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The cost of different propulsion concepts for a product tanker

An investigation of the costs for maintenance, energy and investment

Master's thesis in Naval Architecture and Ocean Engineering

Karl-Johan Hansson

DEPARTMENT OF MECHANICS AND MARITIME SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
www.chalmers.se

MASTER'S THESIS IN PROGRAMME
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KARL-JOHAN HANSSON

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Master's Thesis 2021:30
Department of Mechanics and Maritime Sciences
Division of Marine Technology
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone +46 (0)31-772 1000

Department of Mechanics and Maritime Sciences
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Abstract

When designing a marine propulsion system, there are many alternatives to consider, each with its pros and cons. With the technical development, leading to many new types of propulsion, the conventional propulsion with a two-stroke engine no longer is the obvious choice for the product tankers. Rules and regulations are forcing the shipping companies to invest in more environmentally friendly ships where the energy efficiency is one of the most important parameters. By reducing the consumed energy fuel is saved which leads to less emissions and lower costs.

Different propulsion technologies also have different investment cost and maintenance. The type of propulsion installed is therefore of high importance to study since a lot of money can be saved by studying the three different costs of investment, maintenance and fuel.

The research is looking at five commonly used marine propulsion concepts. The study includes the main components, contributing to the total investment cost and efficiency drop, between the producers and consumers. Where producers are being the engines and the consumers being propellers and electrical consumers such as bow thrusters and fans. Manufacturers are asked to offer individual components or packages of components needed to complete the mechanical and electrical power chains onboard the ship, all with a specific investment price and efficiency.

The investigation leads to an interesting conclusion where it is noted for how the energy consumption is an important parameter but where especially the maintenance costs are seen to differ a lot between the concepts. The very low maintenance cost for the concept with conventional propulsion with a four-stroke engine, referred to as concept 1, is the main reason why it can be stated to be the absolute winner, being more than two million euros in total cheaper than the two closest competitors. It is also shown that the type of fuel chosen is having a big impact on the total cost where it is stated that an extra investment in dual fuel engines is soon paid off with today's LNG fuel prices.

Key words: propulsion, product tanker, cost, maintenance, investment, energy, fuel

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Acknowledgement

The master thesis is a mandatory course in the Master's programme Naval Architecture and Ocean Engineering at Chalmers University of Technology. The thesis was made possible with help of the two companies FKAB Marine Design and Rederi AB Donsötank.

I am extremely grateful to the companies and especially to my supervisors Andreas Hagberg and Stefan Johnsson at FKAB Marine Design for their support throughout this spring. Their expertise within the subject is impressive and I have learnt a lot from them while discussing the different questions that has arisen. A big thanks also to Henrik Lorensen, Mathias Hermansson and Lilian Johnsson at Rederi AB Donsötank who have provided and helped me searching for data and information needed for the project.

My supervisor Per Hogström deserves a big thanks as well since he always supported and helped me when troubles occurred. He has during this time tried to lead me in a direction which finally one day resulted in a finished thesis and Master's degree.

In a ship propulsion system there are many different components from various manufacturers. This thesis would not have been possible to finish without all the representatives of these companies since they have provided me with all the expertise and data needed for the project. As promised I will not mention your names but you know who you are and you should know that I am filled with gratitude, thank you.

Finally, I want to give a big thanks to my family and friends who have supported me in different ways on this journey.

Göteborg, June 2021

Karl-Johan Hansson

List of abbreviations

The following abbreviations have been used once or more in the thesis.

AC	Alternating current
AFE	Active front end
AUX	Auxiliary engine
CPP	Controllable pitch propeller
DC	Direct current
DEE	Diesel-electric engine
DF	Dual fuel
DWT	Deadweight tonnage
ECA	Emission control area
EEDI	Energy efficiency design index
EGR	Exhaust gas recirculation
FPP	Fixed pitch propeller
HFO	Heavy fuel oil
IMO	International Maritime Organization
INU	Inverter unit
LBG	Liquid biogas
LNG	Liquid natural gas
MARPOL	International Convention for the Prevention of Pollution from Ships
ME	Main engine
NO _x	Nitrogen oxides
PM	Particulate matter
PSC	Propeller shaft clutch
PTI	Power take in
PTO	Power take out
SO _x	Sulphur oxides
SCR	Selective catalytic reduction
ULSFO	Ultra low sulphur fuel oil
VFD	Variable frequency drive
VLSFO	Very low sulphur fuel oil

1 Introduction

Choosing an appropriate propulsion system for a given operational pattern of a vessel involves many uncertain choices. The system comes with costs related to each component and quickly add up with increased complexity. A great concern is the energy efficiency, which has implications on both costs as well as environmental impact. Thus, the design choices must be addressed in a structured way.

1.1 Background

The ship owning company Rederi AB Donsötank are in 2021 taking delivery of two 22000 DWT tanker ships built in Wuhu, China and designed by the Swedish company FKAB Marine Design. The company FKAB Marine Design have during the last years had many orders on tanker ships. The shipowners are asking for energy efficient ships which means lower economical cost and a smaller environmental footprint. Also the International Maritime Organization (IMO) and the Marine Environment Protection Committee (MEPC) are by their EEDI (Energy Efficiency Design Index) making sure that all new built ships are keeping a specific standard depending on size and ship type when it comes to the ships energy usage (International Maritime Organization, 2011). The machinery setup is one of the areas where progress can be made to reduce the energy consumption and so on costs and emissions.

Different needs in shipping such as manoeuvrability, fuel economy, redundancy etc. have developed into many different propulsion concepts. The propulsion concepts consist of many different components such as engines, electrical motors, shaft lines, gearboxes, propellers etc. depending on type of concept are some of many investments for a ship owner. These components, building the propulsion concepts, are all negatively contributing to a less energy efficient propulsion chain. It is therefore of high interest to study the components energy efficiency and investment cost, to see which concepts that are more or less environmentally friendly and economically beneficial.

1.1.1 Ship propulsion

The shipping industry have for many years been dominated by the conventional propulsion systems where an internal combustion engine provides mechanical power to a propeller. According to McCoy (2002) electrical propulsion solutions started to develop during the 1980's and electric propelled ships started to be built. McCoy describes that the difference between the concepts is that the mechanical connection between the prime mover and propeller is removed in an electrical setup. Instead a number of smaller engines are generating electricity that powers an electrical motor running the propeller. Hansen & Wendt (2015) describes in their article that the main reason to install a diesel-electric propulsion concept is since it is more energy efficient. The energy saving is according to Hansen & Wendt because the engines can be operated at their optimum running of prime movers.

In shipping many different propulsion concepts are used for different reasons. Hansen & Wendt (2015) states that most of the cruise vessels, DP offshore vessels, Icebreakers and LNG carriers uses diesel-electric propulsion. In tanker ships it is known that conventional two-stroke propulsion is the most used type of propulsion even if others are used as well, where Donsötank for example have both conventional two-stroke and four-stroke propelled ships as well as diesel-electric propelled ships. The type of propulsion installed onboard the ship is chosen dependent on need as redundancy, manoeuvring etc. but where the energy

efficiency has become one of the most important parameters in order to save costs and the environment.

1.1.2 Economical earnings

When designing a ship there are many different costs to consider. Typically a higher investment cost leads to lower fuel consumption since equipment as heat recovery systems, more efficient engines etc. that are meant to reduce energy consumption tends to increase the investment cost.

The energy consumption on board the ship is one of the largest operating expenses. Lilian Johnsson, Financial Manager at Donsötank, describes that about 20 – 30 % of the operating expenses has been bunker costs for the period 2017 – 2020. She says that the bunker cost is depending on several parameters such as the distance of the voyages, number of days off-hire, bunker price and the American dollar exchange rate. The consumption is to a big extent dependent on the losses in the propulsion system. Shi, Grimmelius, & Stapersma (2010) mentions that the losses of the power chain in a conventional propulsion system can be divided into three areas: engine efficiency, transmission efficiency and propulsive efficiency. Whereas the transmission efficiency is the efficiency of the gearbox and the shaft, and the propulsive is the propeller efficiency and hull efficiency. In an electrical concept the same areas can be expected but where the transmission losses instead consist of electrical equipment as converters and generators instead of the mechanical gearbox and shaft.

McCoy (2002) is describing the efficiency of the components in a mechanical concept to be better than the electrical but the real benefit with an electrical system comes with the fact that the prime movers also can be used for the electrical loads onboard such as heating, pumps, lights etc. hence no need for the extra auxiliary engines that are installed on a mechanical propelled ship. This means that investment cost can be reduced since less total engine power is installed.

In this project different propulsion concepts are investigated, thus different components and manufacturers is not investigated. Instead the different propulsion concepts is studied to see which concept that has the highest or lowest investment costs, best efficiency and so on to decide which one in a life cycle perspective that is the optimal concept.

1.1.3 Environmental regulations

The shipping industry is the most used way of transportation for external goods freight for the European countries (European Commission, 2021). According to the European Commission almost 90 percent of the goods transport is transported via the maritime industry. To secure that the shipping industry is well regulated the International Maritime Organization sets up regulations. The regulations regard all kinds of subjects within the maritime industry such as energy efficiency and emission control.

The maritime industry is already one of the absolute most environmentally friendly ways of transportation. In the report written by Litwin et. al (2019) the different transportation modes and the carbon dioxide emissions in grams per ton-kilometre is presented. It can be seen that road transport is the worst way of transportation with up to 180 CO₂ [g/tonkm] compared to the chemical tankers which have a maximum of 30 CO₂ [g/tonkm]. The values for hybrid ships are also presented where it is shown that up to 55 CO₂ [g/tonkm] can be emitted, more than the tanker, but also as little as 0 CO₂ [g/tonkm] can be released in a hybrid ship. The

source of the electrical energy used in the hybrid case is of high importance, where green energy such as wind have very small amounts of emissions while coal or oil power plants emits to much larger extent (analys.se, 2021).

One of the main indexes that is used by IMO is the Energy Efficiency Design Index, EEDI, which measures the emissions in gCO₂ per tonne nautical mile. The allowed EEDI value is dependent on the size and ship type and covers all new built ships or if the ship has had a major conversion (International Maritime Organization, 2011). The regulations are valid for all ships larger than 400 gross tonnages. Neither are ships with unconventional propulsion as diesel-electric, turbine or hybrid affected by the regulations with the exception of cruise passenger ships and LNG carriers (International Maritime Organization, 2011).

According to International Maritime Organization (2011) the regulations regarding the EEDI will be stricter each year starting 2013 with a reference level, built on the existing fleet. During the four phases, starting 2013 with phase 0, the emission level will be reduced by 10 % for each phase.

Table 1. The EEDI regulated reduction in gCO₂ per tonne nautical mile, in percent, for a tanker larger than 20000 dwt (International Maritime Organization, 2011).

Ship type	Size	Phase 0 1 Jan 2013 – 31 Dec 2014	Phase 1 1 Jan 2015 – 31 Dec 2019	Phase 2 1 Jan 2020 – 31 Dec 2024	Phase 3 1 Jan 2025 and onwards
Tanker	20000 dwt ≤	0	10	20	30

The Northern Europe which is the main area where the investigated ships are to be operated is a part of the emission control area controlled by IMO. Rules for the allowed sulphur content in the fuels and nitrogen oxide emission per produced kilowatt is presented in (International Maritime Organization, 2008) and is mandatory for ships operating in the ECAs. This have led to the usage of better and more environmental fuels as well as more efficient machinery systems.

The stricter regulations regarding exhaust emissions together with the increased fuel costs are according to McCoy (2015) “forcing ship owners to implement a number of new technologies, such as exhaust catalysts, electronically injected common rail diesels, waste heat energy recovery and more hybrid and electrical power and propulsion systems”.

1.2 Purpose of the work

The aim of the project is to investigate different propulsion and machinery concept setups and their costs, investment and operational, for a product tanker within the range of 20 000 – 25 000 DWT. This to find the most optimal design with the lowest total cost for the ships life cycle.

1.3 Objectives

The objectives of the master thesis:

- Define and set up, in Autocad, different machinery concepts with individual components suitable for the ship design.
- Find investment cost and efficiency data for the different concepts components.

- Calculate the total energy consumption of the components with help of manufacturer component data.
- Identify the change in maintenance cost with changed propulsion.
- Compare the different costs for the ships lifecycle to decide the most economical alternative.

1.4 Limitations

The following boundaries are set for the project:

- Only conventional internal combustion engines operating on fuel oil or gas are used as prime movers.
- The study is only valid for tankers in the 20 000 – 25 000 DWT range operating on the North European spot market.
- The study only considers the components in the power chain. The hydromechanical and structural changes of the hull and structure are not included in the investigation.
- Assumptions and simplifications considered in the research are presented in Chapter 10.1.

2 Methodology

This study makes a comparison between different propulsion concepts. The concepts have been chosen by relevance after discussion with the supervisors where the FKAB Marine Design T29 have been used as a reference design. A literature review regarding the main categories conventional propulsion and diesel-electric propulsion was implemented to get an understanding of the theory behind the concepts and to find out about cons and pros. To secure that the ship with the different propulsion concepts is complying to all regulations and requirements documents published by the International Maritime Organization and the Swedish Maritime Administration was studied.

It was noted for how the rules related to the propulsion and engine regarding the protection of the environment are focusing on the sulphur oxide, nitrogen oxide, particulate matter and energy efficiency. These rules are then used as a basis when choosing the type of engines and fuel.

The total power output requirement onboard for the different concepts are regulated by the Finnish-Swedish ice class rules published by the Swedish Maritime Administration. The size of the individual engines was chosen according to the ice class requirements and the electrical load balance as well as by discussion with supervisors and by looking at similar sized ships. The same principle was used when choosing the manufacturers and the specific products, where experience from previous projects including the reference ship became a cornerstone in the decision process.

Prices and efficiencies were collected from the chosen manufacturers. They have all provided with either initial prices or prices from earlier projects that they have participated in. The efficiencies and consumption numbers were obtained from public documents or by mail contact with representatives of the manufacturers.

The calculations leading to the final energy consumption numbers were performed in Excel where collected engine energy consumption, component efficiencies, propulsion power- and ship service power requirements were used as a basis. The power needs were obtained from documents from the reference ships design stage. An electrical load balance study was made by FKAB Marine Design and the propulsion power was achieved from the propeller tests performed at SSPAs facility in Gothenburg. One of Rederi AB Donsötanks existing ships were studied to obtain the time spent on the different operating conditions. The time spent and power needed during the different operating conditions can therefore be specified. With known power values, operating profile, efficiency losses and energy consumption of the engine the total energy consumption for the ship could be calculated.

The cost of the energy consumption was then summarised with the maintenance costs and investment costs for the different propulsion concepts. The maintenance costs are obtained by investigating the actual costs of Rederi AB Donsötanks existing ships. The investment cost was obtained by summarising the required main components in the propulsion chain.

3 Theory

In this section the theory behind the different propulsion systems is covered. The project is based on the FKAB Marine Design ship design T29 which is being built as Rederi AB Donsötanks two ships named Prospero and Pacifico. The design is from now on referred to as the “reference ship”.

3.1 Propulsion concepts

In the marine industry today the most common propulsion concept is a conventional shaft connected to either a four-stroke or two-stroke engine. This can be done in various ways with or without gearbox, shaft generator etc. This type of ship propulsion can be configured with either a low speed two-stroke engine or with a medium/high speed four-stroke engine. The tanker ships are with its big “house” a good candidate to the two-stroke engines which requires height because of its much larger size compared to the four-stroke engine. The benefit with the large two-stroke engine is that its more efficient than the four-stroke engine. Electrical alternatives have also gained market share where internal combustion engines connected to generators produces electricity, which is provided to the propulsor.

In this chapter the five investigated propulsion concepts are introduced, where two concepts are mechanical and three electrical.

3.1.1 Conventional propulsion

The conventional propulsion method for ship and the most used concept, are via mechanical connection between engine and propeller. As stated the prime mover can be either two-stroke or four-stroke which both will be investigated in this thesis.

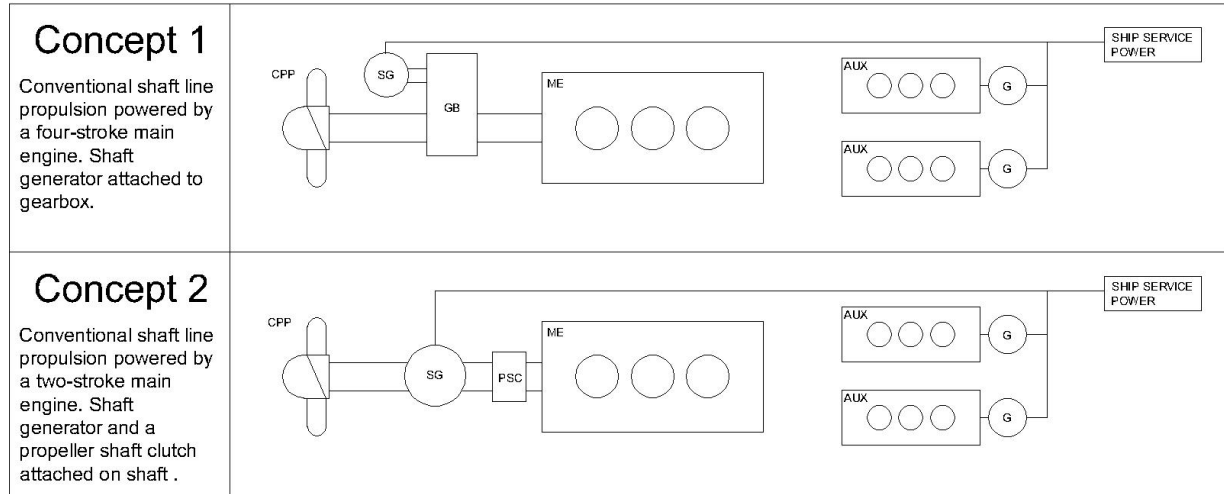


Figure 1. A basic schematic of the two investigated conventional propulsion concepts. Abbreviations: AUX – Auxiliary engine, CPP - Controllable pitch propeller, G - Generator, GB - Gearbox, ME – Main engine, PSC – Propeller shaft clutch, SG - Shaft generator.

The first concept can be seen as the reference concept since it is the concept that the actual design is being built with. The propulsion concept is a concept conventional shaft line with a medium speed four-stroke engine, Wärtsilä 10V31DF. Connected is a shaft generator that is attached to the gearbox. When a medium speed engine is used a reduction gear is necessary to

reduce the speed of the propeller shaft. The shaft generator has the opportunity to both boost the shaft as well as generate electricity to the hotel and other equipment.

The second conventional concept that is being included in this project is a similar setup with the four-stroke engine replaced by a slow running two-stroke engine. With the much slower running main engine and shaft withdraws the need of a reduction gear since the same rotational speed is used for the propeller and the engine shaft. Since no gearbox is needed a propeller shaft clutch is installed instead. The clutch is required to have the opportunity, in case of emergency, to unclutch the propeller shaft from the engine and operate the propeller by just the shaft generator, if for example the engine would fail.

3.1.2 Diesel-electric propulsion

Another very popular way of propulsion is the so called “diesel-electric propulsion”. Instead of having mechanical connection an electrical motor runs the propeller, the motor which is powered by the prime mover running as an electric generator.

The diesel-electric propulsion has mainly been used for ships in need of good manoeuvrability and flexibility such as cruise ships and ice breakers. By installing a diesel-electric system weight can be reduced since the electricity is produced by the smaller four-stroke engines. Also because of the flexibility by having an electrical system the weights can be easily distributed in the machinery room. The generating sets can also produce the ship service electricity, so no need of the “extra” auxiliary engines needed in a conventional concept. One major benefit with diesel-electric propulsion is that the engines can be operated at its most efficient load. This is possible since the engines either can be started or stopped depending on the power need. At lower loads for example one smaller diesel-electric engine can provide power to the propeller while in a mechanical connection the big engine will operate at an inefficient load.

The ship can by electrical power be propelled in different ways, either by rotatable pods or a conventional propeller. In this thesis three different electrical concepts will be investigated: one conventional propeller connected to an electrical motor, one electrical podded propulsor and one electrical driven azimuth thruster.

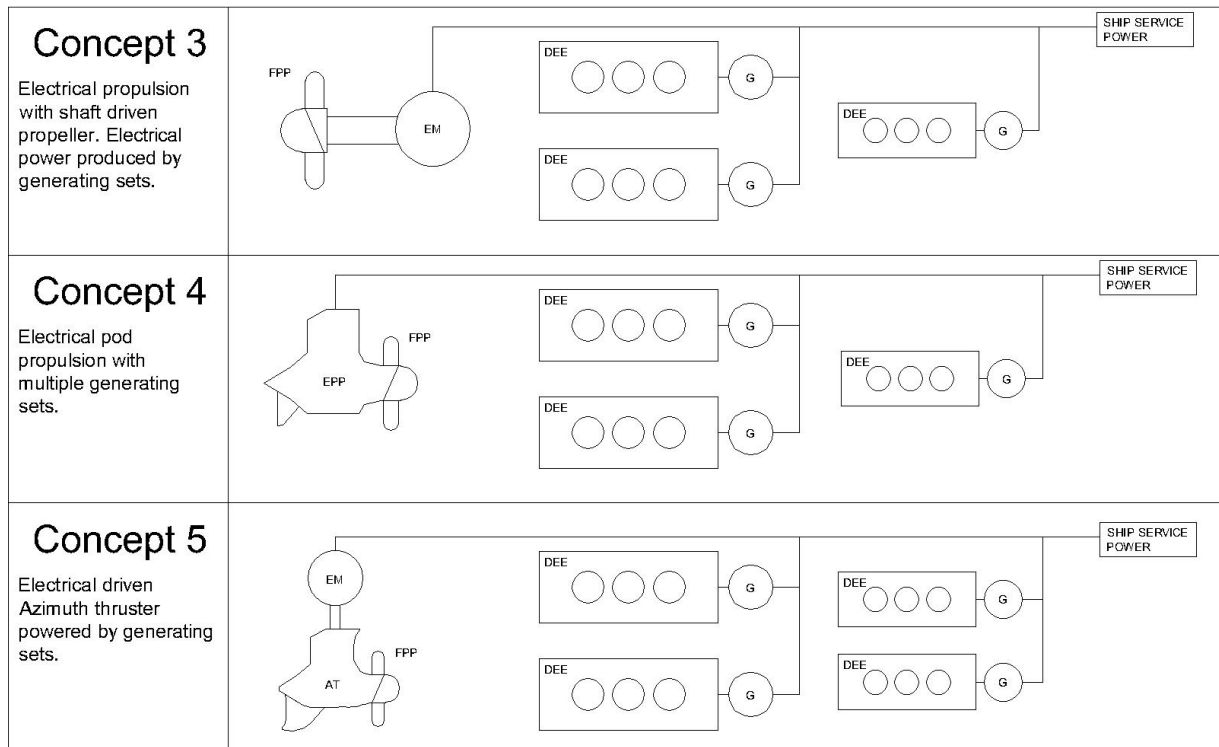


Figure 2. A basic schematic of the three investigated electrical propulsion concepts. Abbreviations: AT – Azimuth thruster, DEE – Diesel-electric engine, EM – Electrical motor, EPP - Electrical podded propulsor, FPP - Fixed pitch propeller, G – Generator.

3.2 Power requirements

In this section the various requirements on the propulsion power and ship service power are further investigated. A model test for the reference ship was made at SSPA where it showed that the effective power for design speed 13.5 knots is 2800 kW. The total efficiency of the propeller and hull then decides the required power delivered to the propeller. With equations provided by Ramne (2018) following equation for delivered power, P_D , is derived:

$$P_D = \frac{P_E}{\eta_0 \eta_R \eta_H}$$

Where P_E is the effective power, η_0 the open water efficiency, η_R the relative rotative efficiency and η_H the efficiency of the hull.

With known delivered power, efficiency of the propulsion line and shaft generator load then the brake power, P_B , is calculated as:

$$P_B = \frac{P_D}{\eta_s} \cdot (1 + SM) + SG$$

Where P_D is the delivered power, η_s the efficiency, SM the sea margin (normally 15%) and SG, the shaft generator load (Ramne, 2018). For the different propulsion concepts differences in the ship service power can be assumed because of the different need of cooling pumps, fuel pumps etc. but the same loads are used for all concepts in the electrical balance presented in Chapter 3.2.2.

The power provided by the engines hence, are relying on the mentioned parameters. The effective power and shaft generator load is varying for the different types of ship operation.

The time spent and required power during the operational modes are presented in Appendix 10.2.1.

3.2.1 Ice class

One of the areas where the ship is to be operated is in the Baltic Ocean where winters can be harsh. Ice class 1A is therefore a requirement from the shipowners to be able to operate even in very hard conditions. In this chapter the different propulsion concepts and their required engine power will be investigated. The Swedish Maritime Administration (2009) provides information about how the engine power requirement is calculated and dependent on the total resistance of the ship, the propeller/machinery type and the propeller diameter. The minimum engine effect can be calculated with Equation 1:

$$P = K_e \frac{(R_{CH}/1000)^{3/2}}{D_P} [kW] \quad (1)$$

Where D_P is the propeller diameter in meter and R_{CH} is the resistance of the ship in a channel with brash ice and a consolidated layer, in newtons. K_e is dependent on number of propellers and type of propeller or machinery system:

Table 2. The constant K_e for different propeller characteristics used in Equation 1 (Swedish Maritime Administration, 2009).

Propeller type or machinery	Controllable pitch propeller or electric or hydraulic propulsion machinery	Fixed pitch propeller
1 propeller	2.03	2.26
2 propellers	1.44	1.60
3 propellers	1.18	1.31

Since no change in the hull form is to be investigated in this study the R_{CH} can be assumed to be constant. The resistance is attained by using the known ice class effect and propeller from concept 1. Hence it can be used to calculate the other concepts required engine effect.

In the initial design by FKAB the propeller diameter was 6.1 m in diameter and the machinery output calculated to be 6300 kW in order to reach required ice class. For the investigated concepts controllable pitch propeller (CPP) or electric propulsion is assumed in all cases. With this information known a linear relation can be found between the machinery output and propeller diameter if only 1 propeller alternatives are to be investigated.

$$P_{CPPorElectricFPP,i.im} = P_{CPP,6.1m} \frac{6.1}{D_{i,i}} [kW] \quad (2)$$

Where $P_{CPPorElectric,i.im}$ is the new effect in kilowatts with the other propeller, $P_{CPP,6.1m}$ is the effect, in kilowatts, of concept 1 with CPP with 6.1 m diameter and $D_{i,i}$ is the diameter of the new propeller in meters.

For the two conventional concepts, 1 and 2, the same propeller diameter and type can be used, CPP with 6.1 m diameter. Concept 3 can have either CPP or fixed pitch propeller (FPP) but since it is diesel-electric propulsion the engine effect requirement remains the same. The two other diesel-electric concepts, 4 and 5, have either electrical podded propulsor or azimuth thruster which means that a smaller FPP normally is used. The two pod manufacturers ABB

and Schottel were contacted to provide data for their electric podded propulsors respectively azimuth thrusters. The representatives of both companies proposed to have two propellers instead of one. Hence the required ice class effect of the engine will be calculated with K_e as 1.44 for these two concepts while being 2.03 for the other three.

Table 3. The required engine output in kilowatts for the different concepts, attained from Equation 1 and 2 (Swedish Maritime Administration, 2009). Details on how propellers for concept 4 and 5 where chosen is presented in Chapter 4.4 and 4.5 (*)

Concept	Propeller/Machinery	Number of propellers	Diameter [m]	Ice class propulsion power required [kW]
1	CPP	1	6.1	6300
2	CPP	1	6.1	6300
3	FPP/Diesel-electric	1	6.1	6300
4	FPP/Diesel-electric	2*	4.1*	6650
5	FPP/Diesel-electric	2*	3.3*	8260

The numbers presented in Table 3 are the required propulsion power to reach the ice class. It is important to have in mind that the additional ship service power needs to be considered as well, especially for the diesel-electric concepts. This is needed to secure that all necessary equipment can be provided with electricity in the most extreme ice conditions. This is further investigated in Chapter 3.2.2.

3.2.2 Electrical balance

The ice class engine output is the power output needed for propulsion, but hence also some additional electrical loads for hotel, equipment and others needs to be taken in consideration when choosing the size of auxiliary engines and diesel-electric engines. The system also needs to be prepared/sized for the lower loads when the ship is not being propelled. For the reference ship the power presented in Table 5 was calculated by FKAB. In this thesis the same ships service power is assumed for all concepts. The ship service power is considered to dimension the size of the different concepts diesel-electric engines.

For this some different gensets and generators are studied:

Table 4. The gensets and the shaft generator used in the electrical balance study. The genset power numbers are the standard numbers presented by Wärtsilä (<https://www.wartsila.com/>).

Concepts	Component	Details
Conventional	Auxiliary engine	Wärtsilä 8L20, 1405 kWe, 60 hz
	Shaft generator	The Switch, 1500 kWe
Electrical	Diesel-electric engine	Wärtsilä 8L20DF, 1420 kWe, 60 hz
	Diesel-electric engine	Wärtsilä 6L34DF, 2770 kWe, 60 hz

The electrical power output of the electrical generators can then be compared to the required power during the different conditions. In Table 5 the different conditions are investigated for both the conventional and electrical concepts. For the electrical concepts and the conditions when the ship is also being propelled the electrical power easily can be distributed between the diesel-electric engines, hence “not of interest” is stated in the table.

Table 5. Attained loads on the electrical gensets and generators during the ships various conditions.

Condition	Power consumption [kW]	Source of power for conventional / electrical	Load [%]
Sea going	620	SG / not of interest	41 / -
Sea service with tank washing and cargo handling	980	SG / not of interest	65 / -
Manoeuvring/docking	1690	SG & W8L20 / not of interest	58 / -
In harbour/cargo discharging/ballast loading	2036	2xW8L20 / 2xW8L20DF or 1xW6L34DF	72 / 72 or 74
In harbour/cargo loading/ballast discharging	694	W8L20 / W8L20DF	49 / 49
Take me home	2024	2xW8L20 / not of interest	72 / -
In harbour, stand by	328	W8L20 / W8L20DF	23 / 23

As mentioned in Chapter 3.2.1 is the importance of some considered additional ship service power to the engine maximum continuous rating for the diesel-electric concepts because of the extreme ice conditions that the ship will experience. The data presented in Table 5 and the numbers especially for the conditions “sea going” and “sea service with tank washing and cargo handling” are further investigated. Together with representatives at FKAB 400 kW is then assumed to be a reasonable number for the additional electrical load that needs to be considered during extreme ice conditions. This since some loads as heating, pumps etc. could be shut off during that short period of time if needed.

3.3 Environmental regulations

The International Maritime Organization are regulating the maritime industry to secure an environmentally friendly industry. In this section the Energy Efficiency Design Index (EEDI) and emission limiting standards for Sulphur Oxides (SOx), Nitrogen Oxides (NOx) and Particulate Matter (PM) is studied and considered to make sure that the ship and propulsion complies with the regulations.

3.3.1 Energy Efficiency Design Index

The International Maritime Organization developed and published the EEDI to reduce the energy consumption onboard the ships and so on the carbon dioxide emissions. As mentioned in Chapter 1.1.3 the EEDI calculation is applicable for all ships with conventional propulsion and larger than 400 gross tonnage. Hence the investigated tanker needs to be controlled only for concept 1 and 2 since the other concepts are diesel-electric, which not are covered by the rules for tankers. The EEDI formula is as follow (International Maritime Organization, 2018):

$$\frac{(\prod_{j=1}^n f_j) (\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FAE} \cdot SFC_{ME(i)}) + (P_{AE} \cdot C_{FAE} \cdot SFC_{AE}^*) + ((\prod_{j=1}^n f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{Aeff(i)}) C_{FAE} \cdot SFC_{AE}) - (\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}^{**})}{f_i \cdot f_c \cdot f_i \cdot Capacity \cdot f_w \cdot V_{ref}}$$

- * If part of the Normal Maximum Sea Load is provided by shaft generators, SFC_{ME} and C_{FME} may – for that part of the power – be used instead of SFC_{AE} and C_{FAE}
- ** In case of $P_{PTI(i)} > 0$, the average weighted value of $(SFC_{ME} \cdot C_{FME})$ and $(SFC_{AE} \cdot C_{FAE})$ to be used for calculation of P_{eff}

The calculated EEDI is then compared to the reference value which is provided by IMO guidelines. As presented in Table 1 the reference weighted emission value is tightened for each new phase. In Figure 3 the requirements for the four phases are shown as well as FKAB previously built ships and their attained EEDI values. The reference value are according to International Maritime Organization (2011) calculated by the formula:

$$Reference\ value = a \cdot b^{-c}$$

Where a and c are constant factors relying on ship type, for tanker set to 1218.8 and 0.488. The b is the deadweight of the ship. This means that the maximum allowed EEDI for the ship is 7.41 in phase 2 and 6.49 in phase 3 which will entry in to force in 2025 (International Maritime Organization, 2011).

As can be seen in Figure 3 FKAB have a tradition of designing more efficient ships than the regulations require.

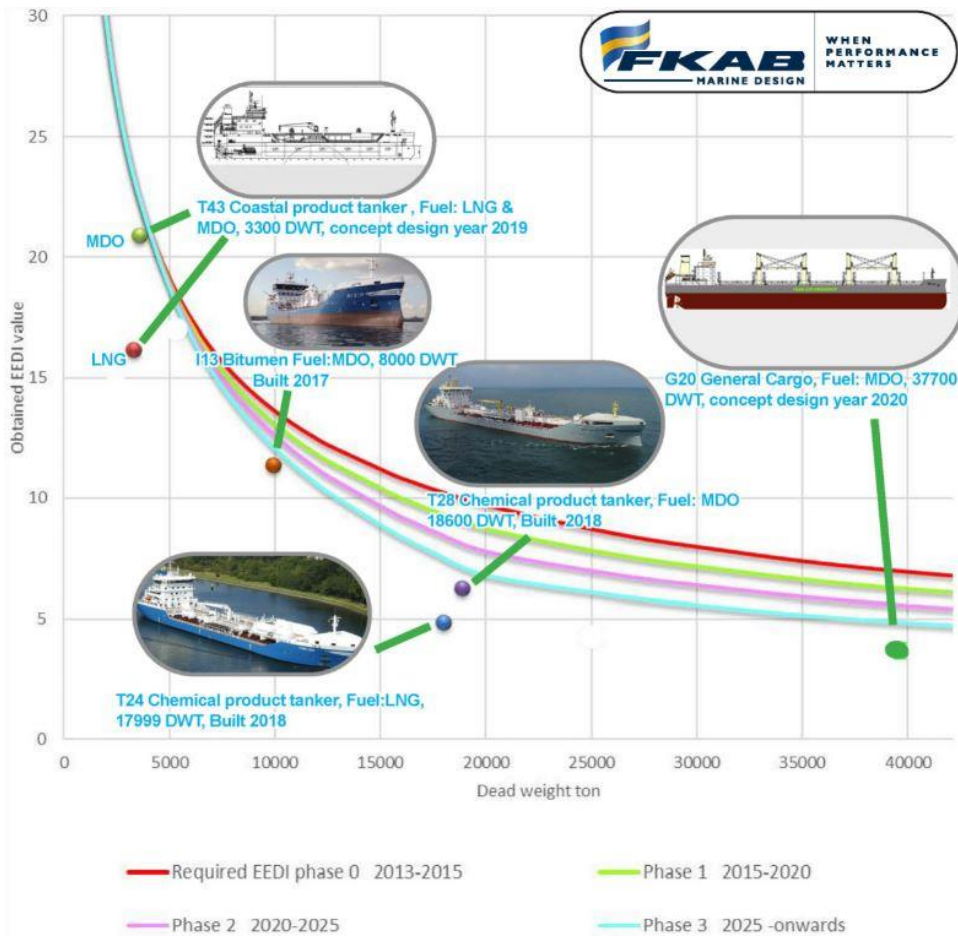


Figure 3. The EEDI limits together with the FKAB designed ships (FKAB Marine Design, 2020).

The reference ship is in the design phase calculated to have an EEDI of 4.50 which is way below the required phase 2 for a 22000 DWT tanker ship. The two concepts covered by the

EEDI regulations is expected to have the same specifications, with the exception of the main engine, so a similar EEDI value can be expected also for concept 2.

3.3.2 Nitrogen Oxide, Sulphur Oxide and Particulate Matter

In the MARPOL Annex VI, Prevention of Air Pollution from Ships, which went in effect the 19 of May 2005 regulations how to minimize airborne emissions were established (International Maritime Organization, 2013). The International Maritime Organization have with the goal to minimize the emissions decided on what they call Emission Control Areas (ECA’s). These areas are used to regulate the NOx emissions of the marine diesel engines as well the SOx and PM. The coordinates of the emission control areas existing today are presented in MARPOL and consists of the following areas: North American Sea, United States Caribbean Sea, North Sea and Baltic (International Maritime Organization, 2017). The United States Caribbean Sea ECA, which is a small area around Puerto Rico and the American Virgin Islands. The ECA shown close to Hawaii belongs to the North American Sea ECA.

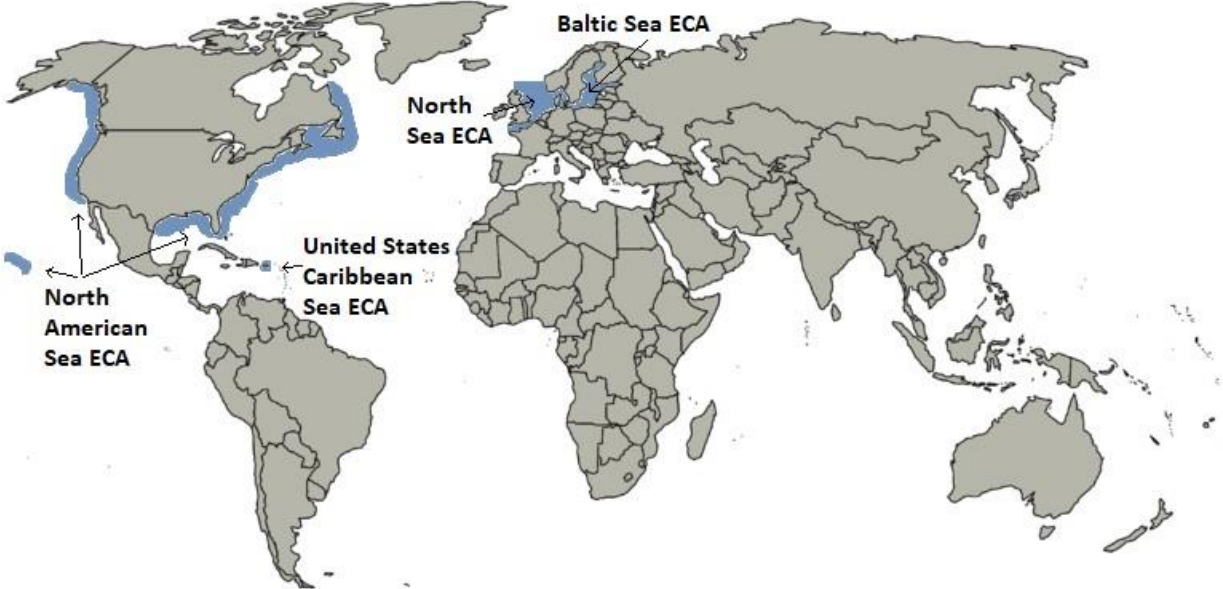


Figure 4. The ECA’s for NOx and SOx. Revised picture. Original by Artista~commonswiki (2006).

Since the MARPOL Annex VI went into force 2005 the total weighted cycle emission (g/kWh) have been limited by Regulation 13 and divided into three phases, Tier I, Tier II and Tier III (International Maritime Organization, 2013). The first requirement went into force for ships built on or after the 1st of January year 2000 with Tier I and is applicable for all diesel engines larger than 130 kW with the exception of emergency generators, with emergency situations as its only purpose.

Table 6. The NOx limits, Regulation 13, for ships inside the NOx ECA’s (International Maritime Organization, 2008). The limit was adopted to the Baltic Sea and North Sea with start 1st January 2021 for ships operating in North Sea and Baltic Sea ECA (International Maritime Organization, 2019).

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh)		
		n = engine’s rated speed (rpm)		
		n < 130	n = 130 – 1999	n ≥ 2000

I	1 January 2000	17.0	$45 * n^{(-0.2)}$	9.8
II	1 January 2011	14.4	$44 * n^{(-0.23)}$	7.7
III	1 January 2016*	3.4	$9 * n^{(-0.2)}$	2.0

The NOx and PM standards went into force the 1st of January 2000 in the North American and United States Caribbean Sea ECA's (International Maritime Organization, 2008) but not until 1 January 2021 in the North Sea and Baltic Sea ECA's (International Maritime Organization, 2019). Hence the ships operating in that area must comply with Tier III, if built on or after the 1st of January 2021.

The ships can according to Wärtsilä (2017) comply with the rules in two different ways, either by choosing a dual fuel engine, running on gas, where NOx is not released in the same extent. Second solution is an NOx reducer which can be installed in the exhaust gas system, a reduction system built on the Selective Catalytic Reduction (SCR) technology (Wärtsilä, 2017). The reference ship is built prior the introduction of the new Tier III regulations, hence Tier II compliance is required and attained, but is complying also with the stricter regulations if operated on gas.

The SOx and PM are regulated by Regulation 14 (International Maritime Organisation, 2017). The regulations are different for ships inside and outside the ECA's. As the NOx the SOx and PM are harder regulated inside than outside the ECA's. The sulphur oxide limitations inside the ECA's, including North Sea and Baltic Sea where the ships are to be operated, is presented in Table 7.

Table 7. The SOx regulations for ships inside and outside the ECA's (International Maritime Organization, 2008).

SOx emission limits	
Outside an ECA	Inside an ECA
4.50 % m/m prior to 1 January 2012	1.50 % m/m prior to 1 July 2010
3.50 % m/m on and after 1 January 2012	1.00 % m/m on and after 1 July 2010
0.50 % m/m on and after 1 January 2020	0.10 % m/m on and after 1 January 2015

The International Maritime Organization (2021) have decided that ships operating in North Sea ECA and Baltic Sea ECA are not a part of the PM restriction while ships in the North American ECA and the United States Caribbean Sea ECA need to upfill all three requirements.

The regulations are upfilled by either installing an exhaust gas cleaning system as the scrubber which removes the SOx and PM content. Wärtsilä (2017) says that their scrubbers can reduce the SOx emissions from 3.5% to 0.1% if conventional fuels are used. Another solution is to use other fuels, where the sulphur content is lower than the conventional fuels.

Deng et al. (2021) are saying that the emissions can be reduced a lot if Liquefied Natural Gas (LNG) is used as main fuel. Compared to Heavy Fuel Oil (HFO) the emission numbers can be reduced by following numbers for a high-speed engine: NOx by 86%, SOx by 98%, CO2 by 11% and PM by 96%. With a low speed engine the emission reduction is even better, as much as: NOx by 90%, SOx by 100%, CO2 by 20% and PM by 99%. The article states that LNG

has the highest reduction rate as well as the highest potential rate compared to other reduction technologies as SCR and EGR.

This taken in mind together with Wärtsilä (2017) promise that all of their dual fuel engines complies with the NO_x and SO_x regulations, on gas mode, results in that dual fuel engines is used for the prime movers. The SCR are also installed on all engines so the ship also complies with Tier III also when not being operated on gas.

4 Conceptual design

In this project five different concepts are investigated. This section is describing the power lines of each concept as well as the specific components such as engines and propulsors. The concepts are equipped with components of suitable size, either chosen from manufacturer catalogues or recommended by representatives at the companies. The engines are chosen according to the power requirements in Chapter 3.2 where both ice class and electrical loads are considered.

The electrical components are provided by WE Tech and ABB. WE Tech is the manufacturer in the conventional alternatives and ABB the manufacturer in the diesel-electric concepts. In WE Techs solutions a DC-link is used to minimize losses in the system and the representative of WE Tech describes that the components of interest where losses can be found are the INU, AFE and LCL. The INU is an inverter unit which converts direct current (DC) to alternating current (AC) and the AFE is a rectifier which uses active front end technology, a popular technology used for DC to AC conversion (Kamala et al., 2018). The AFE rectifier is instead of traditional rectifiers with diodes using Insulated Gate Bipolar Transistors (IGBTs) (ABB, 2019). In the report by ABB (2019) it is described that the rectifier creates high frequency noise and to reduce this a LCL filter is used. Dependent on if there is a conventional propulsion system or diesel-electric system the electrical power system schemes will have some differences. The representative of WE Tech says that we can save energy by putting some consumers on the DC-link instead of running the electric all the way to the main switchboard. This is because the electricity generated by the shaft generator in the conventional concepts then just needs to be converted once.

ABB do also use the AFE technology in their frequency converters. In the diesel-electric concept the DC-link is not as beneficial as in the conventional since all electricity is produced by the diesel-electric gensets. The solution provided by ABB is therefore without the DC-link.

The frequency converters provided by WE Tech and ABB do use the same technology but since WE Tech uses the DC-link the components are divided into the three components LCL, rectifier and inverter. In the ABB frequency converter these three technologies are all included but it is referred and shown in Figure 5 as one. In the schematic drawings presented in each concept the symbols shown in Figure 5 are used.

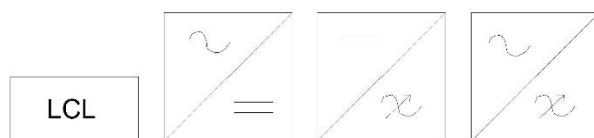


Figure 5. The electrical components within WE Techs and ABBs scope of supply. From left: LCL filter, AFE rectifier, INU (inverter unit) and frequency converter.

The representative at WE Tech describes that the electrical components need to be strong enough to handle the electrical power. This means that the diesel-electric concept uses much larger sized INUs, AFEs and LCL filters than the conventional concepts because of the electrically powered propulsors.

4.1 Concept 1

As can be seen in Figure 6 the first concept is using a four-stroke main engine with a mechanically connected controllable pitch propeller. A gearbox is used to reduce the engine speed to a suitable propeller speed and to the gearbox also a shaft generator is attached to generate electricity when the main engine is running. It is more beneficial than using the smaller and less efficient auxiliary engines.

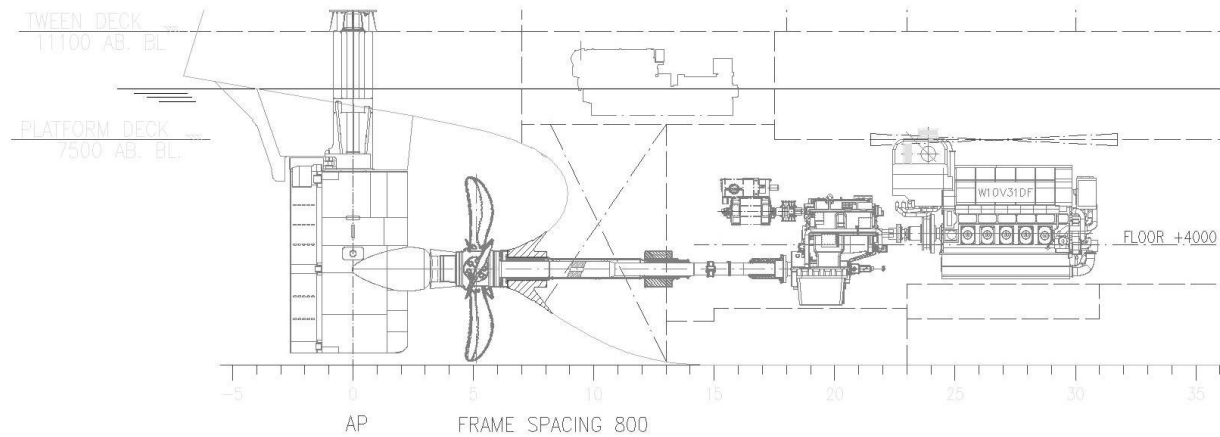


Figure 6. The propulsion layout of concept 1. From right, Wärtsilä main engine (four-stroke), gearbox, shaft generator, shaft, propeller. The auxiliary engine is seen above the propulsion line.

The reference design is being built with this set up today. The main engine is a Wärtsilä 31DF, which is recognised as the world’s most efficient four-stroke engine (Wärtsilä, 2021). The engine is a dual fuel engine which means it can operate on either diesel or gas such as LNG or Liquid Biogas (LBG). The installed engine has ten cylinders and produces in total 5500 kW of mechanical power brake power. For electric production two Wärtsilä 8L20 auxiliary engines equipped with AVK generators are used, each generating approximately 1430 kWe.

For this concept, a reduction gear (gearbox) is needed to reduce the engine speed at 750 r/min to a more suitable speed for the propeller. The shaft generator which can both take out (PTO) and take in (PTI) power to the propulsion line operates under variable speeds where a reduction gear is needed.

The mechanical components seen in Figure 6 are summarised in Table 8. It can be stated that Wärtsilä are the provider of the major part of the power line.

Table 8. The mechanical components of concept 1.

Component	Manufacturer	Product	Details
Main engine	Wärtsilä	10V31DF	5500 kWm, 750 r/min, Gvu & SRC
Auxiliary engine with generator	Wärtsilä, AVK	8L20	1480 kWm, 900 r/min, SCR
Gearbox	Wärtsilä	Two stage	5500 kW + 1100 kW
Shaft generator	The Switch	Permanent magnet	1500 kWe PTO & 1100 kW PTI
Shaft	Wärtsilä	-	Length 9.5 m
Propeller	Wärtsilä	Controllable pitch	Diameter 6.1 m & four blades

Rudder	Becker	-	-
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In Figure 7 all the components considered in the investigation is shown. The largest electrical consumer on the DC side is the shaft generator, 1500 kWe, which becomes the load that the electrical components need to be dimensioned for.

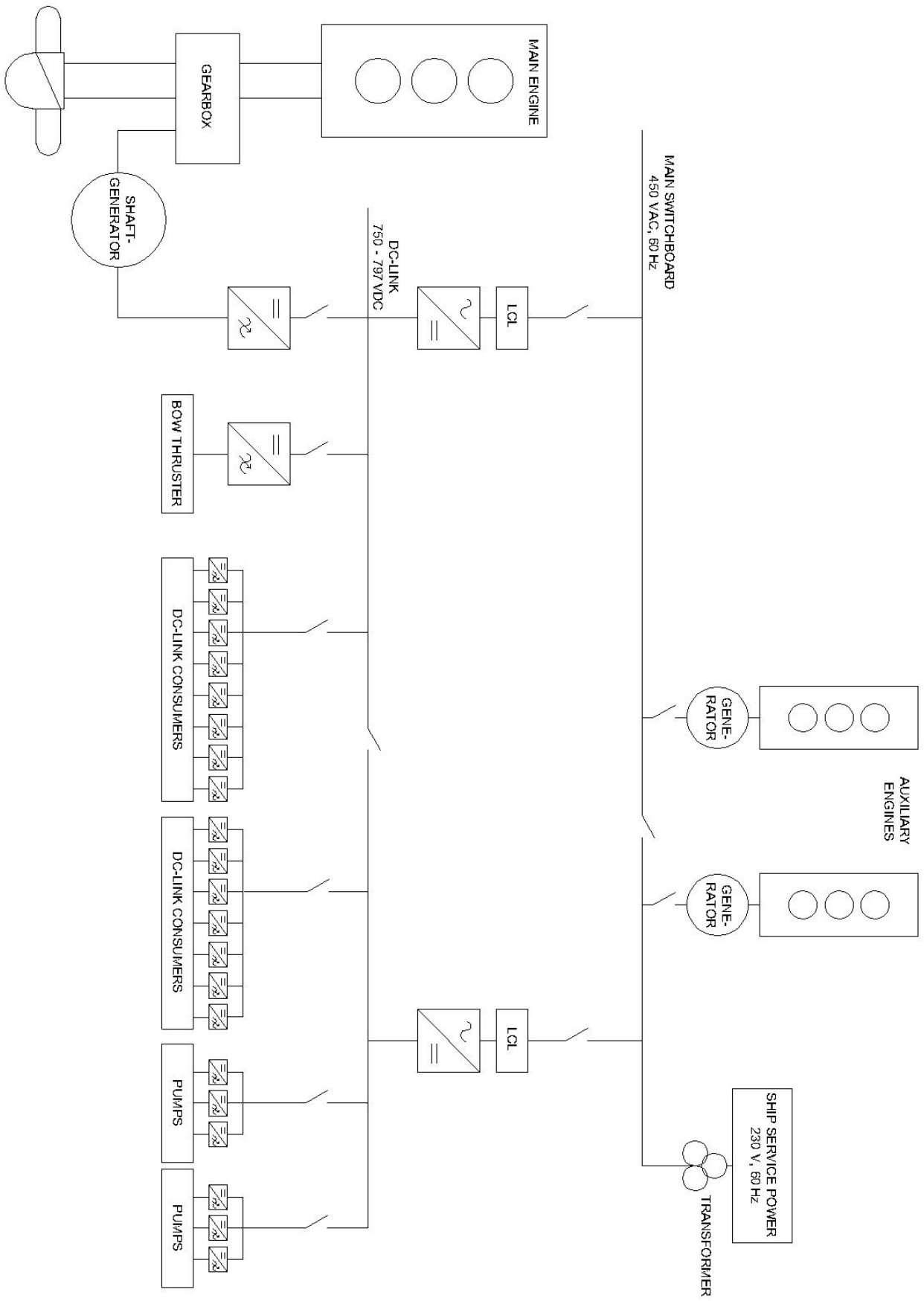


Figure 7. The single line diagram for concept 1.

4.2 Concept 2

The second concept is as mentioned in Chapter 3.1.1 also a mechanically connected power line where the four-stroke engine is replaced by a larger two-stroke engine.

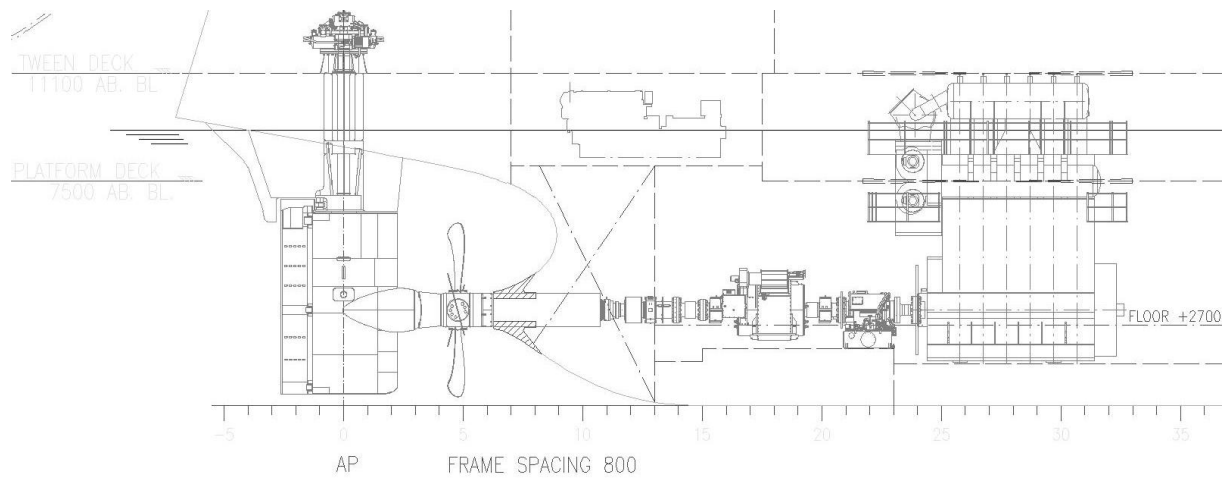


Figure 8. The propulsion layout of concept 2. From right, the MAN main engine (two-stroke), propeller shaft clutch, shaft generator, shaft, propeller. The auxiliary engine is seen above the propulsion line.

Since the same propeller diameter is used there is no change in ice class effect so the same main engine effect can be used. All other engines in this thesis are manufactured by Wärtsilä but this two-stroke engine is the exception with MAN as the manufacturer. The decision therefore landed in using a MAN 6G45ME-C9.5, producing 5500 kW, with dual fuel possibilities. The engine has been used earlier in projects similar to the reference ship which FKAB Marine Design have been participated in. The auxiliary engine type Wärtsilä 8L20 with attached AVK generator is used and two of these are needed to reach the required ship service power during manoeuvring and discharging presented in Chapter 3.2.2. In Figure 8 a propeller shaft clutch (PSC) is seen to left of the main engine. The PSC is required for the “take me home” option. This means that in case of engine failure the engine shaft can be disconnected so the propeller shaft instead can be driven only by the shaft generator.

Table 9. The mechanical components of concept 2.

Component	Manufacturer	Product	Details
Main engine	MAN	6G45ME-C9.5-GI	5500 kWm, 95 r/min, HPSCR and GVU.
Auxiliary engine with generator	Wärtsilä, AVK	8L20	1480 kWm, 900 r/min, SCR.
Propeller shaft clutch	RENK	Fully automatic	5500 kW, 95 r/min, Ice 1A
Shaft generator	-	Permanent magnet	1500 kW _e PTO & 1100 kW PTI.
Shaft	Wärtsilä	-	Length 9.5 m
Propeller	Wärtsilä	Controllable pitch	Diameter 6.1 m & four blades.
Rudder	Becker	-	-

The electrical components INU, AFE and LCL filter need to be sized to handle the electrical load coming from the shaft generator which in this case is 1500 kW_e.

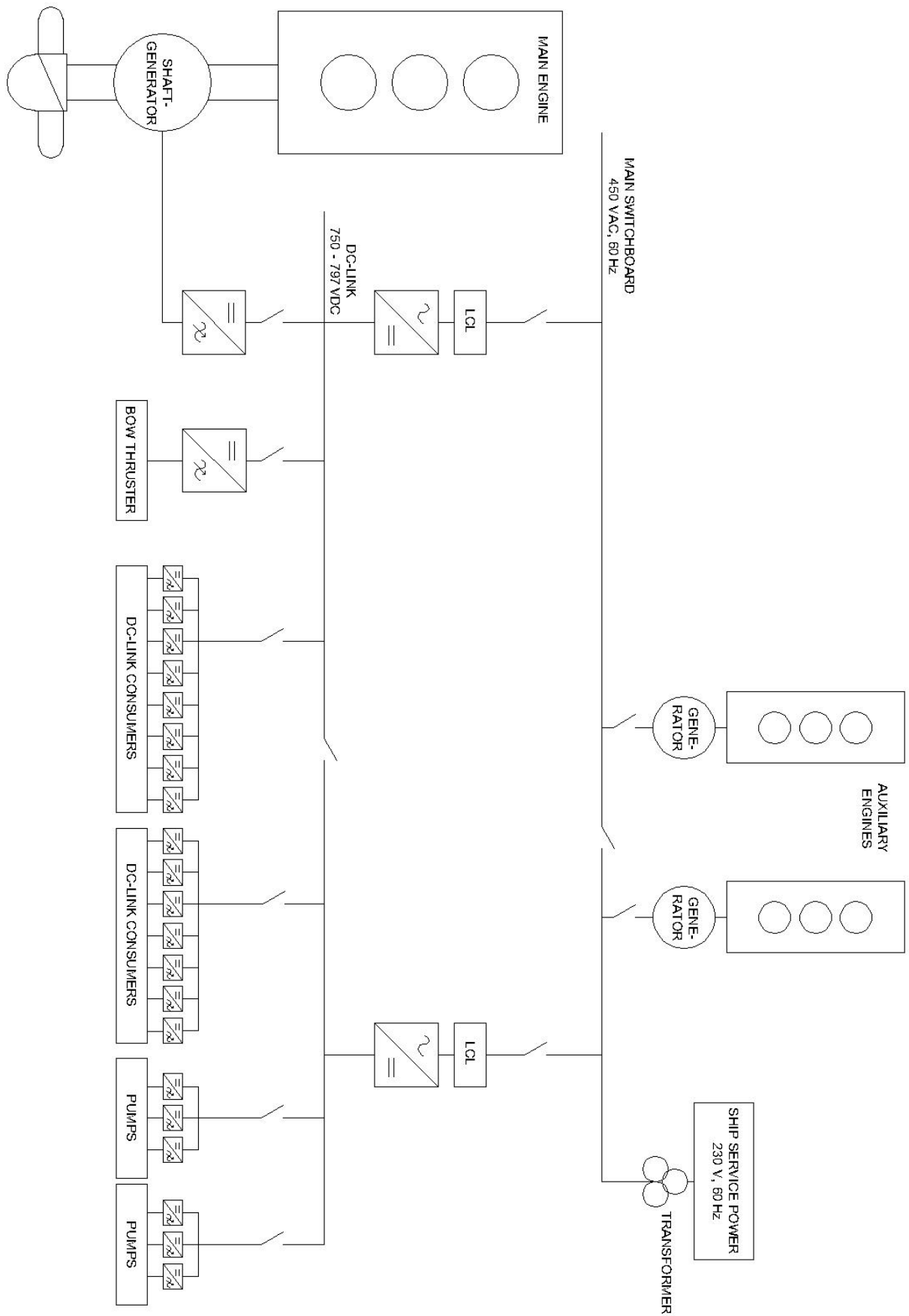


Figure 9. The single line diagram for concept 2.

4.3 Concept 3

The diesel-electric concept with a shaft line connected to an electrical motor is in a machinery effect point of view the best alternative. It is shown that this concept requires a low amount of total engine effect which both saves investment cost, maintenance cost and space.

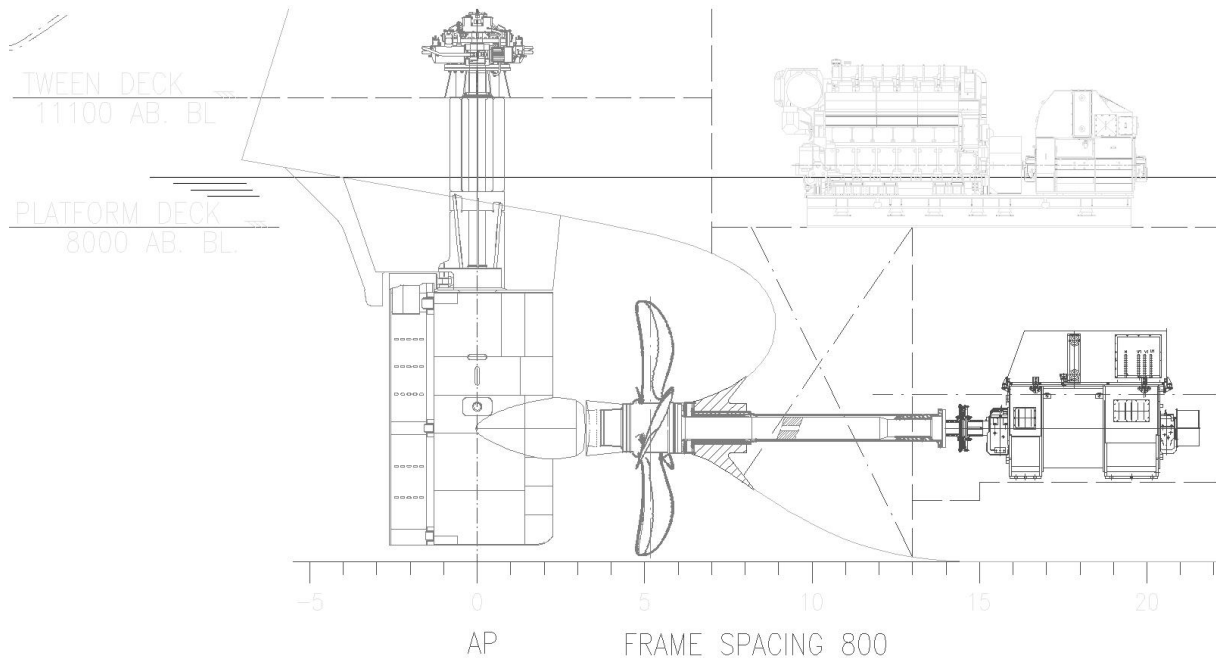


Figure 10. The propulsion layout of concept 3. From right, the electrical motor, shaft line and propeller. One of the diesel-electric engines (Wärtsilä 6L34DF) is seen above the electrical motor.

In the ice class investigation, Chapter 3.2.1, it is noted that the same low machinery effect is required for this concept as the reference design. The difference from the two conventional concepts is that the same machinery system can be used also for the ship service power which is stated in Chapter 3.2.2. These two facts combined means that concept 3 requires a lower amount of total power compared to the other concepts. This resulted in having three diesel-electric engines of various size. Two Wärtsilä 6L34DF each providing approximately 2780 kW_e and one Wärtsilä 8L20DF at 1430 kW_e, all equipped with AVK generators.

The size of the electrical motor needs to be larger than the required ice class power presented in Table 3. For the diesel-electric concepts also the 400 kW_e extra power need to be considered as described in Chapter 3.2.2 and hence the total required brake power becomes 6700 kW_e which is less than the total power output from the engines.

Table 10. The mechanical components of concept 3.

Component	Manufacturer	Product	Details	Number	Total power [kW]
Diesel-electric engine with generator	Wärtsilä, AVK	6L34DF	2880 kW _m , 720 r/min, SCR and GVU.	2	7240 kW _m
	Wärtsilä, AVK	8L20DF	1480 kW _m , 1200 r/min,	1	

			SCR and GVU.		
Electrical motor	ABB	-	6300 kW	1	6300 kW
Shaft	Wärtsilä	-	Length 4.5 m	1	-
Propeller	Wärtsilä	Fixed pitch	Diameter 6.1 m & four blades.	1	-
Rudder	Becker	-	-	1	-

The electrical AFE drives provided by ABB are dimensioned to handle the electrical motor. The electrical motor also needs to be sized for the ice class effect which in Table 3 is presented to be 6300 kW, a motor which ABB provided.

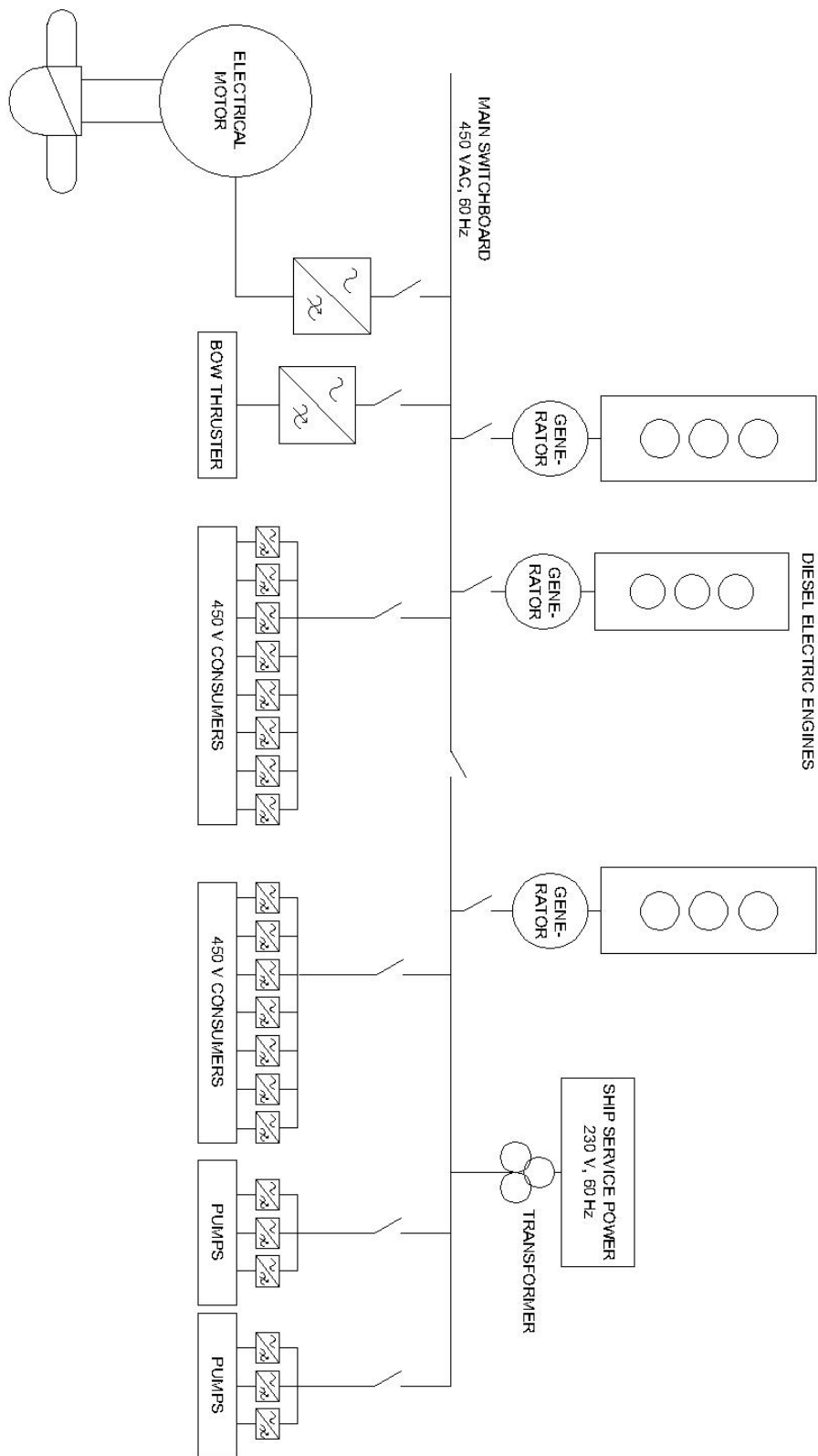


Figure 11. The single line diagram for concept 3.

4.4 Concept 4

Concept 4 is a podded type of propulsion where diesel-electric engines provide electricity to the electrical motors seated inside the ABB Azipods. The electrical podded propulsors are built for smaller propellers and instead higher rotative speed, this decreases the diameter of the propeller and as described in Chapter 3.2.1 the machinery effect to reach the ice class changes. The benefit is as previously mentioned that the “total effect” might be reduced since the generators are both used for propulsion and ship service power, and hence no need for the “extra” auxiliary engines in the conventional alternatives.

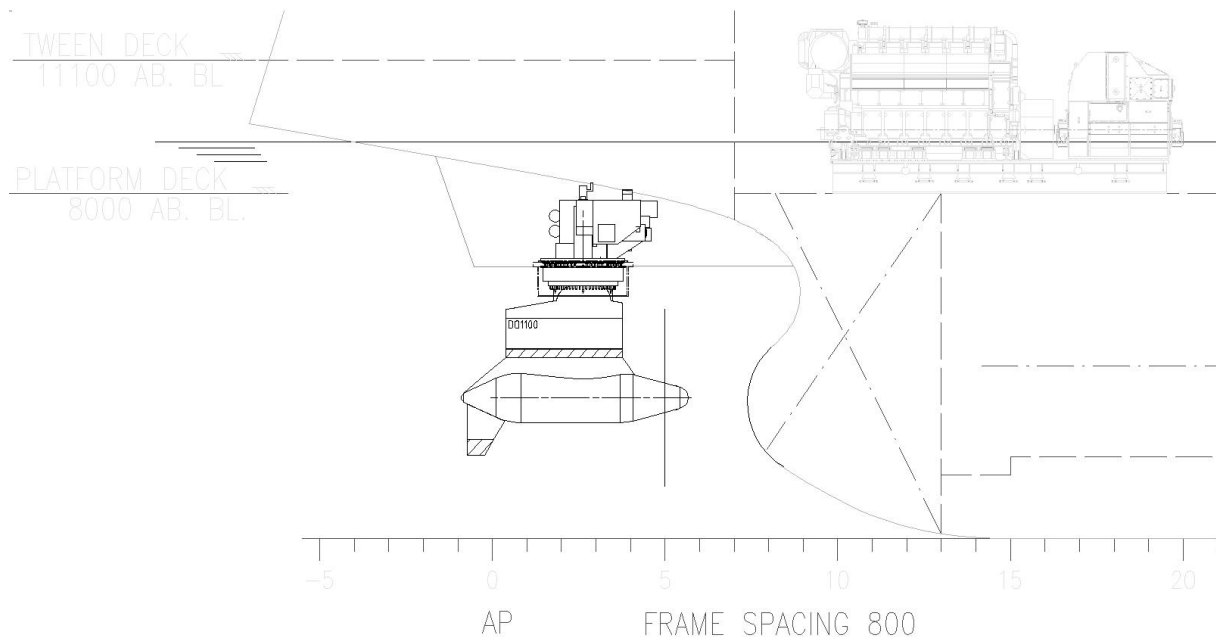


Figure 12. The propulsion layout of concept 3. Presented is the diesel-electric engine Wärtsilä 6L34DF and the ABB Azipod DO1100P.

The ABB Azipod department was contacted to support with the Azipod. Representative of the company suggested two pods with fixed pitch propeller, 4.1 m in diameter. The proposed Azipod is called DO1100P and is a polar classed pod which reaches the regulated ice class strength 1A. The effect of the Azipod is 3470 kW, hence a total propulsion power of 6960 kW from the two pods which is more than the required 6650 kW to reach the ice class which is presented in Table 3. The engine effect to reach the ice class is seen to be a little bit higher than concept 3 but the same diesel-electric engine set up works also in this case. The frequency converters used are using AFE technology and are included in the package provided by ABB.

Table 11. The mechanical components of concept 3

Component	Manufacturer	Product	Details	Number	Total output
Diesel-electric engine with generator	Wärtsilä, AVK	6L34DF	2880 kWm, 720 r/min, SCR and GVU.	2	7240 kWm
	Wärtsilä, AVK	8L20DF	1480 kWm, 1200 r/min, SCR and GVU.	1	
POD	ABB	Azipod DO1100P	Fixed pitch, diameter 4.1 m, 3470 kW	2	6960 kW

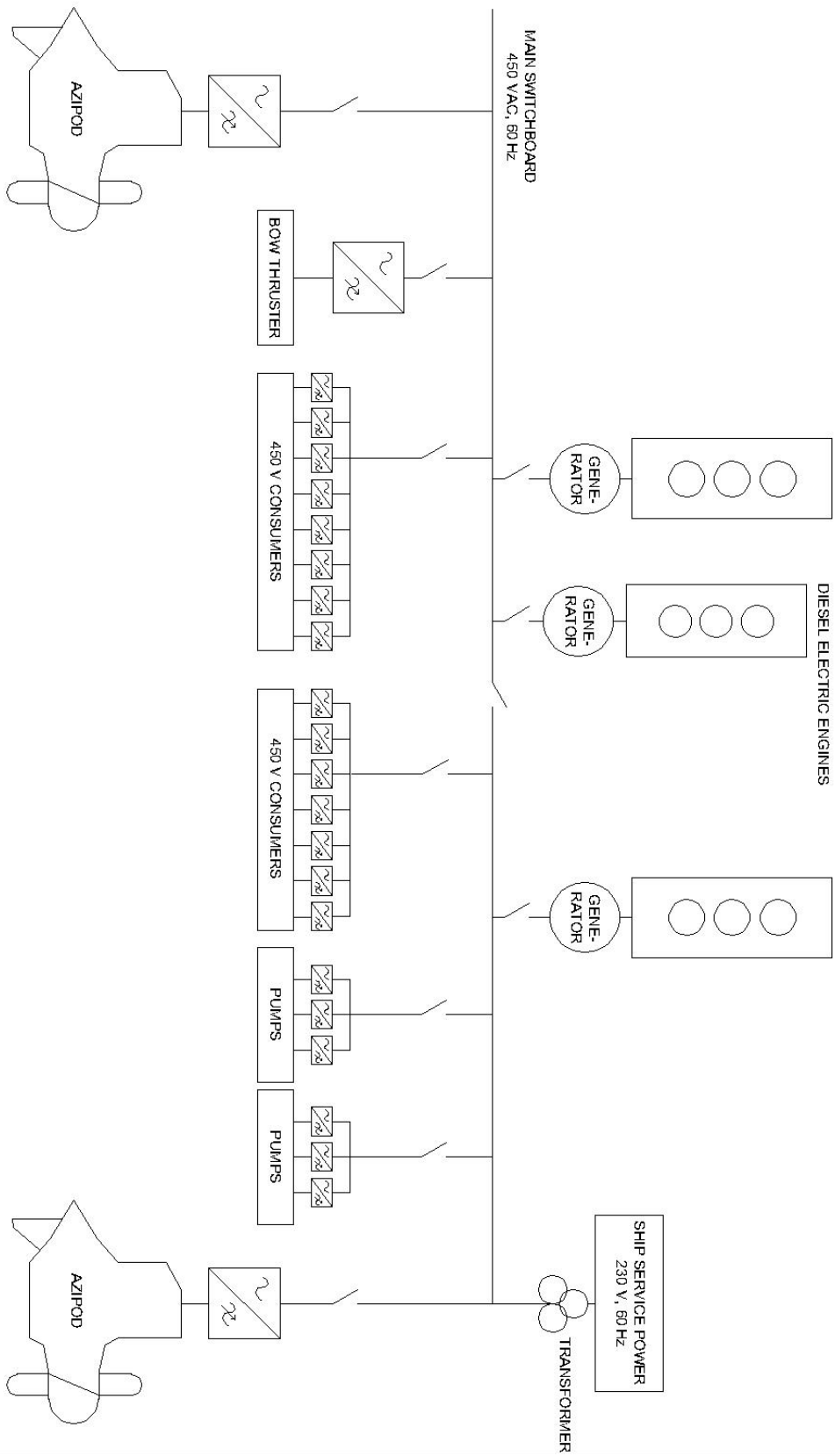


Figure 13. The single line diagram for concept 4.

4.5 Concept 5

Azimuth thrusters is an interesting concept not that commonly implemented on this type of ships. Manufacturer of the Azimuth thrusters used are Schottel which representatives proposed, for the required thrust and stated hydrodynamical data that two thrusters with fixed pitch propellers, 3300 mm in diameter, where to be installed. Each providing approximately 2500 kW of power at a propeller speed of 192 rpm, to attain the design speed.

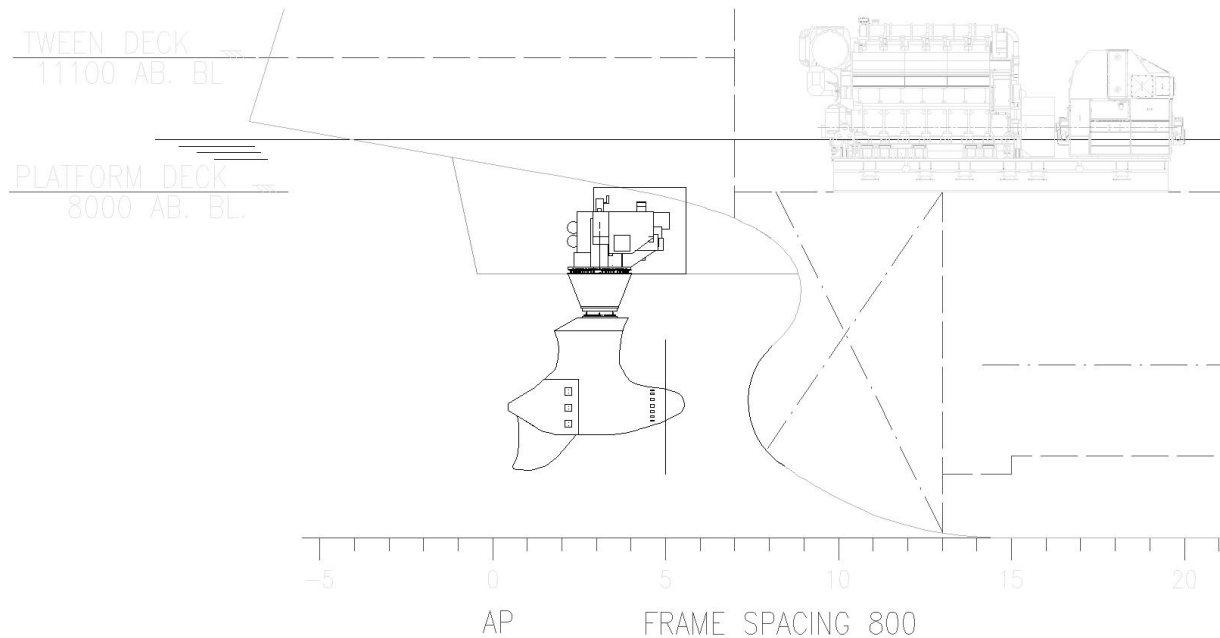


Figure 14. The propulsion layout of concept 5. Shown the diesel-electric engine Wärtsilä 6L34DF and a conceptual sketch of the Azimuth thruster (private).

The thrusters are of a special ice classed design. The small diameter anyhow puts a higher requirement on the engine effect because of the classification rules presented in Chapter 3.2.1. It is stated that the minimum engine effect is 8260 kW plus the additional ship service power. Thus, the previous diesel-electric set up used in concept 3 and 4 with two 6L34DF and one 8L20DF is not since the engine effect becomes too low so one additional 8L20DF is installed. The concept is equipped with two electrical motors, 4000 kW each including AFE drives, provided by ABB. To comply with the ice class 1A requirements also the electrical motors need to be sized for the engine effect 8260 kW. With known generator losses presented in Chapter 4.6.4 it is noted for how the AFE drives and electrical propulsion motors, sized for a total of 8000 kW, can handle the electric power produced by the diesel-electric engines.

Table 12. The mechanical components of concept 5.

Component	Manufacturer	Product	Details	Number	Total output
Diesel-electric engine with generator	Wärtsilä, AVK	6L34DF	2880 kWm, 720 r/min, SCR and GVU.	2	8720 kWm
	Wärtsilä, AVK	8L20DF	1480 kWm, 1200 r/min, SCR and GVU.	2	
Electrical motor	ABB		4000 kW	2	8000 kW
Azimuth thruster	Schottel	Special SRE Ice	Fixed pitch, diameter 3.3 m	2	-

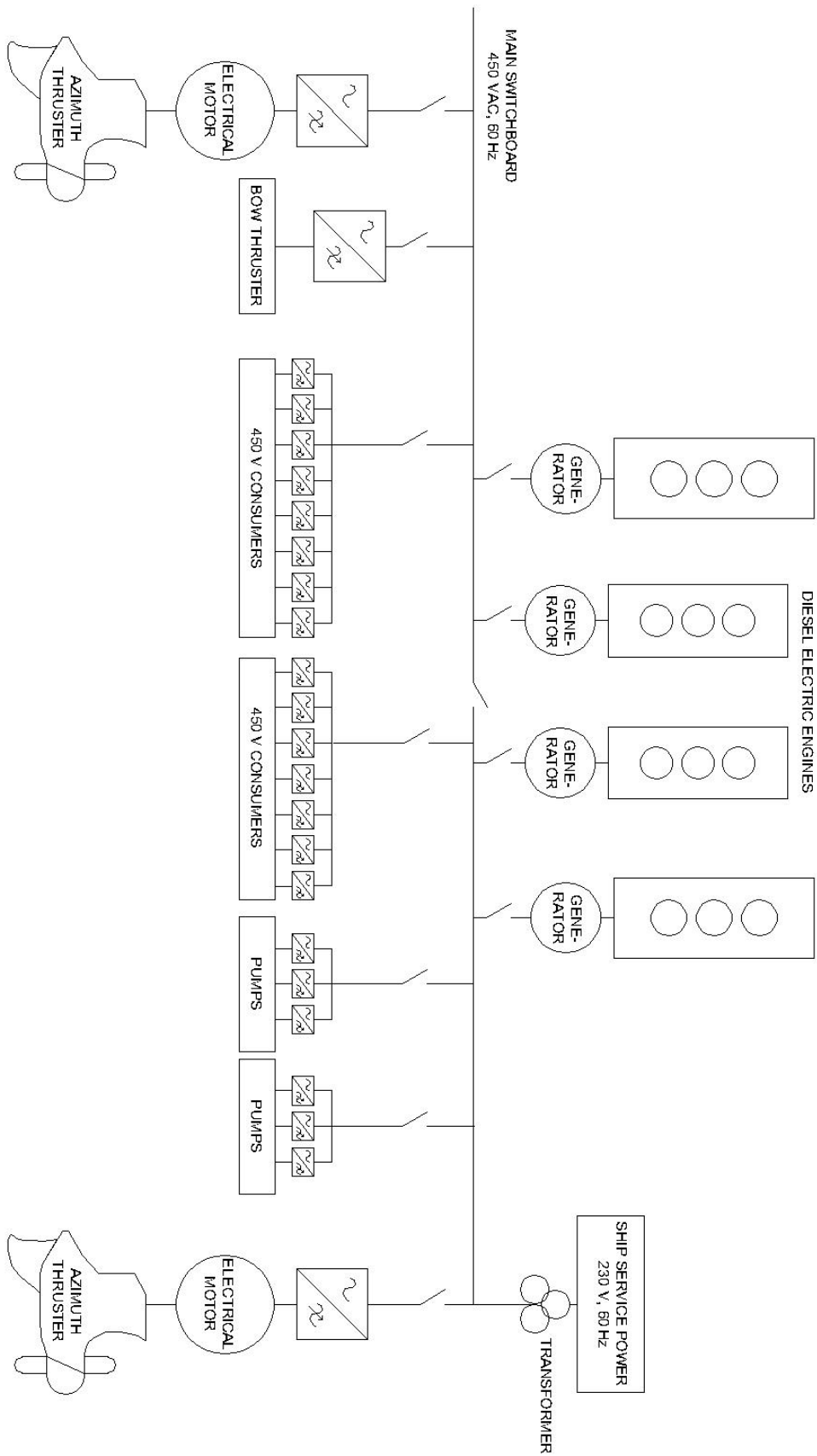


Figure 15. The single line diagram for concept 5.

4.6 Component efficiencies

In each concept numerous components are used. Each contributing to the total losses obtained in the system. This section presents the losses that is covered and included in this study.

4.6.1 Main engines

Main engine is normally used as a term when the engine is mechanically connected to the propeller as in the two conventional alternatives, concept 1 and 2.

The two main engines used is the Wärtsilä 10V31DF and MAN 6G45-C9.5-GI, both equipped with SCR. Generally the larger two stroke engines, in this case the MAN engine, provides better efficiency than the four stroke engines. According to Yao, Qian, Li, & Hu (2019) marine power plants reaches 30 – 45 % in power output of the total energy consumed and Okabe et al. (2013) describes that numbers up to 50 % in efficiency can be reached in two-stroke marine engines.

The four-stroke Wärtsilä 10V31DF and the two-stroke MAN 6G45-C9.5-GI-HPSCR are expected to have energy consumption according to Figure 16, details can be found in Appendix 10.2.2.

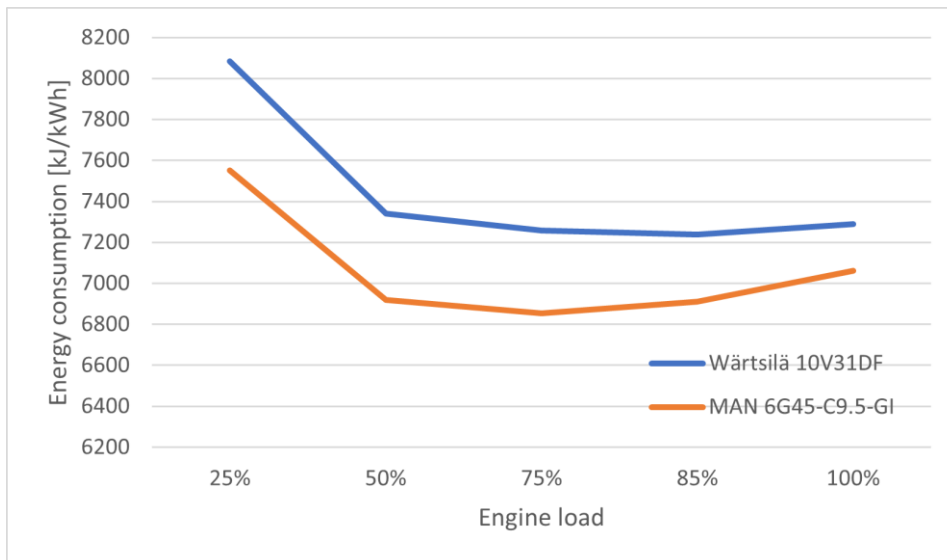


Figure 16. The total energy consumption of the two main engines. Lower calorific value used for fuel oil is 42 700 kJ/kg for both engines and for gas 49 700 kJ/kg is used for Wärtsilä engines and 50 000 kJ/kg for MAN engines. In the numbers presented by MAN the pump losses are excluded, something that is considered below.

Wärtsilä and MAN present their energy consumption in different ways. Wärtsilä includes the influence of the pumps into the energy consumption data while MAN is not. Therefore the energy consumption presented in Figure 16 is without cooling- and lubricating pumps. The power needed for the pumps can be calculated with the formula $P = 0,04 \cdot p \cdot v [kW]$ according to representative at MAN where p is in bar and v in cubic meters per hour. The power is hence calculated with the equation where the pressure and flow are attained from the MAN 6G45-9.5 engine report. The pumps used for lubricating oil, jacket cooling water, central fresh water and sea water for central cooling are the pumps considered. The total effect for these pumps is 68 kW which is added to the ship service power when the main engine is running. Details can be seen in Appendix 10.2.9.

4.6.2 Auxiliary engines and diesel-electric engines

The auxiliary engines in the two conventional concepts have the same energy consumption as the diesel-electric engines in the diesel-electric concepts. The difference from the “main engines” is the smaller size and the attached generator converting mechanical power to electrical power. A smaller engine generally means a less efficient engine.

The four-stroke auxiliary engines 8L20, 8L20DF and 6L34DF from Wärtsilä are expected to have energy consumption according to Figure 17, details can be found in Appendix 10.2.2. The presented numbers are excluding the generator losses which is presented in Chapter 4.6.4.

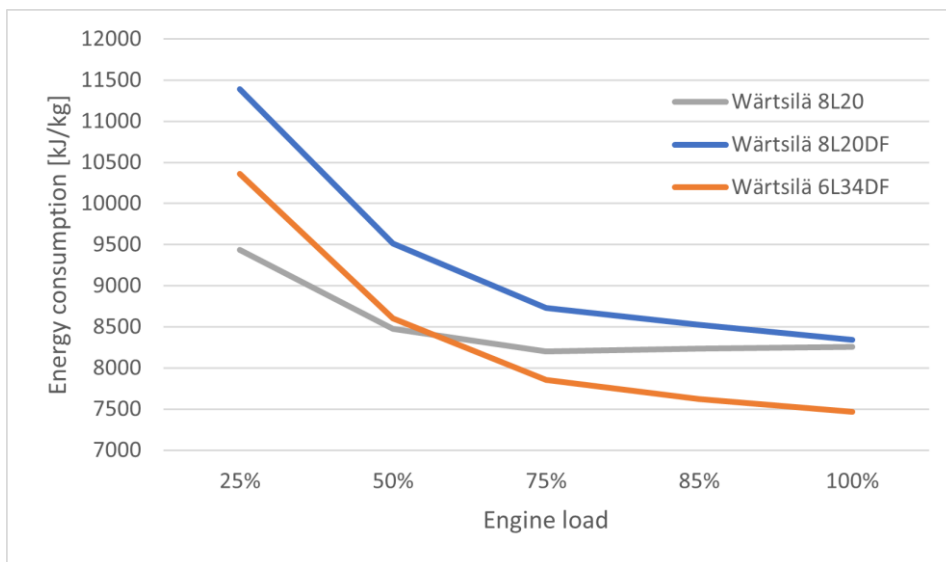


Figure 17. The total energy consumption of the auxiliary- and diesel-electric engines. Lower calorific value 42 700 kJ/kg for fuel oil and 49 620 kJ/kg for gas.

4.6.3 Gearbox

The gearbox is used to reduce the speed of the engine to a suitable shaft speed for the propeller. In Figure 18 it is shown how the efficiency drops with lower loads. It can be stated that the efficiency is quite constant between 50 - 100 % load, where the losses are approximately 2 – 3 %. Since the gearbox is expected mainly to be operating between these loads the losses in the gearbox are set to 2.5 %.

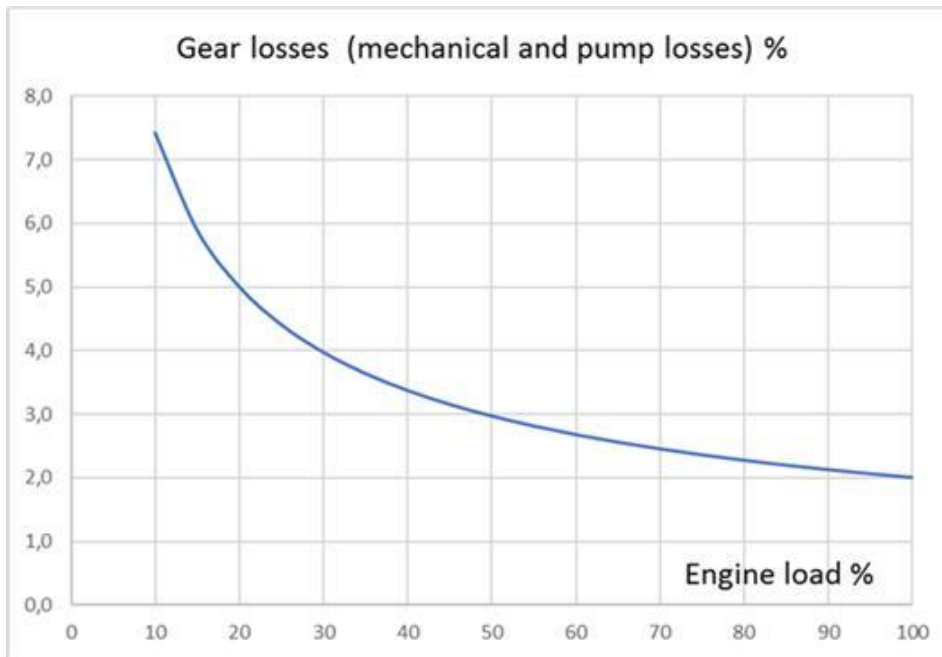


Figure 18. The expected efficiency drop of the Wärtsilä gearbox with varying load. Provided by representatives of Wärtsilä.

4.6.4 Generators and electrical motors

The generators attached to the diesel-electric engines and auxiliary engines are all assumed to have an efficiency of 96.5 % based on the AVK generator used for the 8L20 engine in the reference ship. The number is obtained from the generator factory of acceptance test (FAT) where the efficiency during different load points is tested. The numbers are presented in Figure 19. The generators used for the 8L20DF and 6L34DF engines are assumed to have the same efficiency as the 8L20 engine.

The two first concepts are equipped with shaft generators. The main purpose of the shaft generator is to provide the ship with energy efficient electric power produced by the main engine. It also has the opportunity to boost the shaft, so called peak shaving, which makes the main engine operate smoother but then electric power from another source is required. If an emergency would occur with engine failure as an example, the “take me home” mode can be used where the engine shaft is disconnected and the propeller shaft is fully operated by the shaft generator.

The shaft generator in concept 1 uses the permanent magnet technology which is a more efficient type of electricity generation. Documents related to the generator presents generator efficiency numbers of 97.3 - 97.8 % for loads between 50 and 100 %, where the best efficiency point is shown to be at 80 and 90 % load which can be seen in Figure 19. The efficiency in this study is set to 97.5 % based on the efficiency curve. MAN where not able to provide any data for the shaft generator. The data from the shaft generator by The Switch, used in concept 1 is therefore also used in concept 2. The losses in the shaft generator is only of interest for the power taken out or taken in by the generator.

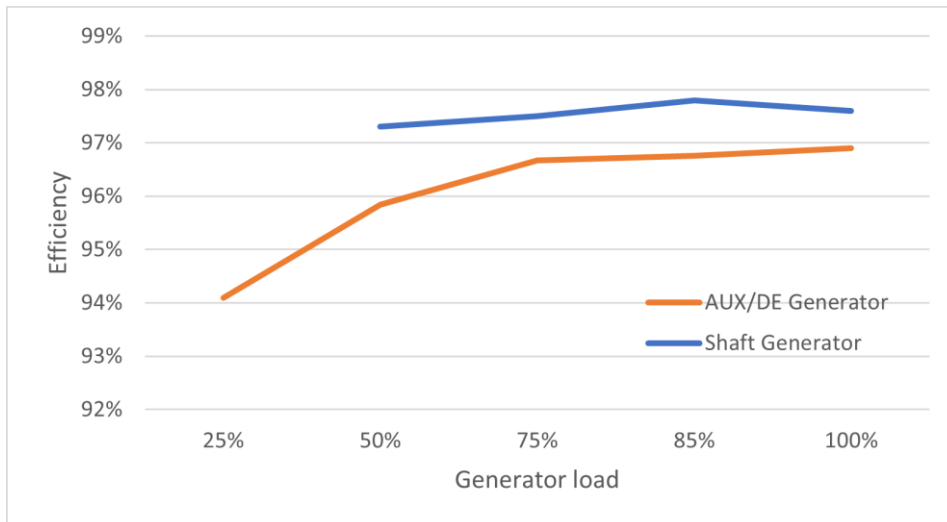


Figure 19. The different generator and their efficiency for the different load points.

The electrical motors used for propulsion in the three diesel-electric concepts are all provided by ABB. In concept 3 and 5 the electrical motor is attached inside the hull while in concept 4 the motor is inside the Azipod. All electrical motor including the Azipod uses permanent magnet technology and the efficiency can hence according to representatives of ABB be assumed to be 98 %.

4.6.5 Shaft

The losses in the shaft are mainly found in the stern tube bearings and according to representatives of Wärtsilä they assume the losses to be 1 %. Concept 3 uses a shorter shaft than concept 1 and concept 2. The statement of the representative anyhow indicates that the losses should be similar since the stern tube bearing set up are the same for both concepts regardless of the shorter shaft.

4.6.6 Propellers and pods

Shi, Stapersma, & Grimmeliuss (2009) are describing the propeller efficiency to be the relative rotative efficiency times the open water efficiency. Then the total efficiency is: $\eta_D = \eta_0 \eta_R \eta_H$, where also the hull efficiency is included.

The three conventional propellers, two controllable pitch and one fixed pitch, are all relying on the data from the model test for the reference ship. The fixed pitch propellers total efficiency is set to be 2 % more efficient than the CPP after discussion with representatives at FKAB Marine Design. Efficiencies for concept 4 and 5 is provided from the manufacturers ABB and Schottel where a suitable pod/thruster, propeller diameter- and speed was chosen.

Table 13. The total efficiency and obtained delivered power for design speed, 13.5 knots, during loaded condition.

Concept	Total efficiency at design speed [-]	Delivered power at design speed, loaded condition [kW]
1	0.768	3406
2	0.768	3406
3	0.788	3320
4	0.713	3669
5	0.54	4844

The delivered power numbers for loaded- and ballast condition can be seen in Figure 20 and Figure 21. Schottel and ABB provides estimations only for design speed during loaded condition. The efficiencies for the other speeds are therefore calculated with the same percentage change as the propeller efficiency in the reference ship. The model test of the reference ships actual propeller design is only providing data for EEDI- and design condition. Therefor the data from the stock propeller is investigated and compared to give a good estimation of the efficiencies during ballast condition.

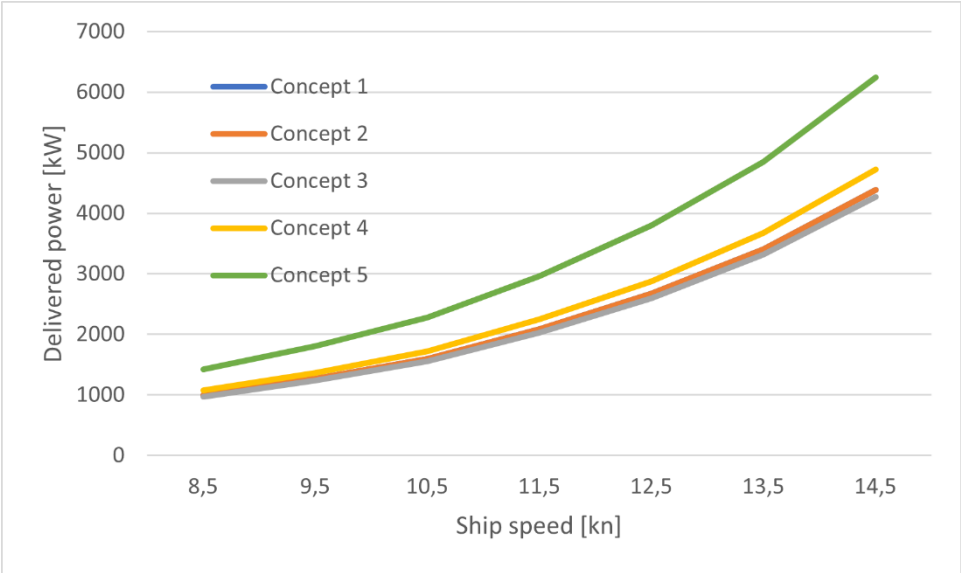


Figure 20. The delivered power required for the ship in design (loaded) condition. Concept 1 equals concept 2 and is therefore hidden behind the orange line.

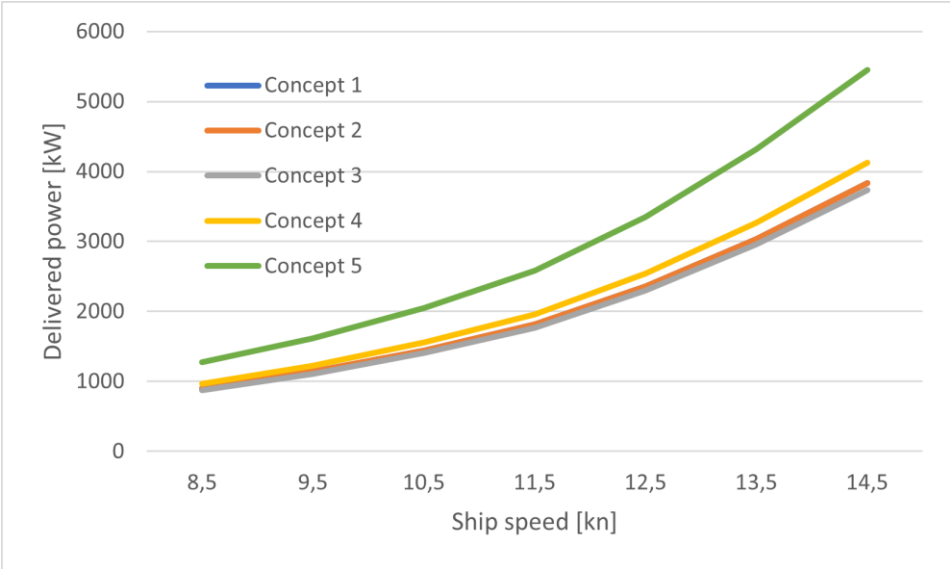


Figure 21. The delivered power required for the shop in ballast condition. Concept 1 equals concept 2 and is therefore hidden behind the orange line.

In addition to this mechanical losses can be found in the Azimuth thruster. Representatives of Schottel describes that these losses can be expected to be around 3 %.

4.6.7 Electrical transmission

The WE Tech representative describes that the loss in the electrical transmission comes mainly from the LCL filter, AFE rectifier and LCL filter. The representative of WE Tech means that the AFE and LCL filter combined contributes to an efficiency drop of 2.7 %. In the conventional systems there is plenty of inverters (INU's), each one with an efficiency of about 1.5 %. Representatives of ABB means that 3 % in losses can be assumed in their AFE drives (frequency converters including LCL filter, AFE rectifier and INU) which is slightly better than WE Techs given numbers.

The representative of WE Tech says that AFE technology is mainly used instead of ordinary Variable Frequency Drives (VFD) to reduce harmonics. The harmonics which for example increases the losses in the electrical cables since they get heated by the harmonics. According to the representative the losses in a VFD is lower than an AFE converter, estimated to be around 3% but the AFE drive is still preferred because of its benefits, at least for larger applications. The representative of ABB describes that the transformers are not needed when using AFE drives, something that the WE Tech representative agrees on.

Losses from the main switchboard is neglected since they are known to be very small. According to Bastos, Branco, & Arouca (2021) the loss in the switchboard is as low as 0.01 %. Bastos, Branco and Arouca describes the efficiency of the transformers to be around 99.1 – 99.7 %, where 99.5 % is chosen for this study.

5 Results

In this section the results are presented. The section is divided into the two categories energy consumption and investment cost.

5.1 Energy consumption

The total energy efficiency of each concept is dependent on the losses for the prime mover, the power chain between the producer (prime mover) and consumer (motors or propellers) and the propulsive efficiency.

Table 14. The total efficiency losses found in the conceptual power chains.

Producer to consumer	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
Main engine to propeller	0.965	0.990	-	-	-
Main engine to AC/230V ship service power	0.907	0.930	-	-	-
Main engine to DC/450V ship service power	0.922	0.946	-	-	-
Auxiliary/diesel-electric engine to propeller	-	-	0.908	0.917	0.890
Auxiliary/diesel-electric engine to AC/230V Ship service load	0.960	0.960	0.960	0.960	0.960
Auxiliary/diesel-electric engine to DC/450V ship service load	0.925	0.925	0.936	0.936	0.936

The engine is producing the power required for the propeller, Figure 20 and Figure 21, and ship service power, Table 5. The total produced power is found by considering the ships operational profile, where the time spent in the different operating conditions, and the power required during the different operating modes have been further studied, see Appendix 10.2.1. The losses in the system, Table 14, are considered so enough power is produced. The produced engine power is presented in Figure 22.

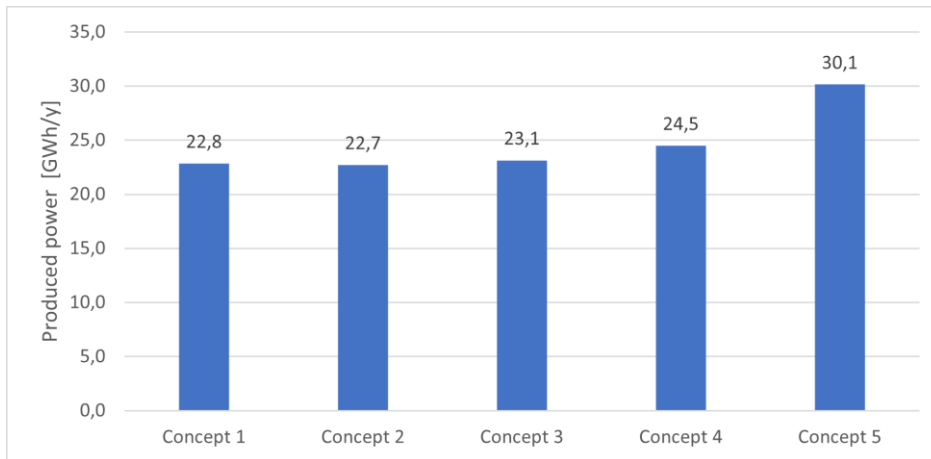


Figure 22. The power produced by the engines of each concept in giga watt hours per year.

The power produced by the engines are produced by engines with various energy fuel- and energy consumption per produced kilo watt hour. The amount of fuel and energy consumed to produce the power is presented in Figure 23 and Figure 24.

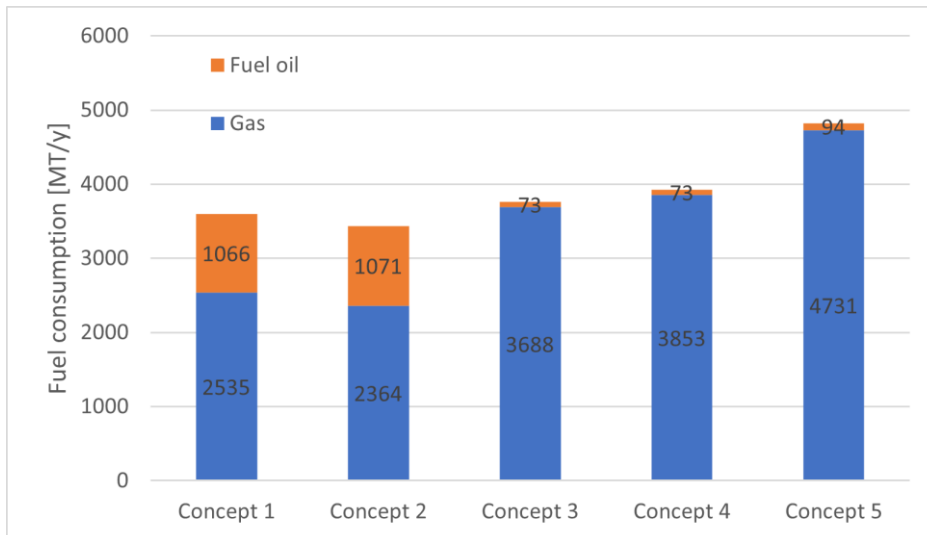


Figure 23. The fuel consumption in metric tonnes per year for the different propulsion concepts. The lower heating values used for conversion are the ones provided by manufacturer for the specific engine presented in Chapter 4.6.1 and Chapter 4.6.2.

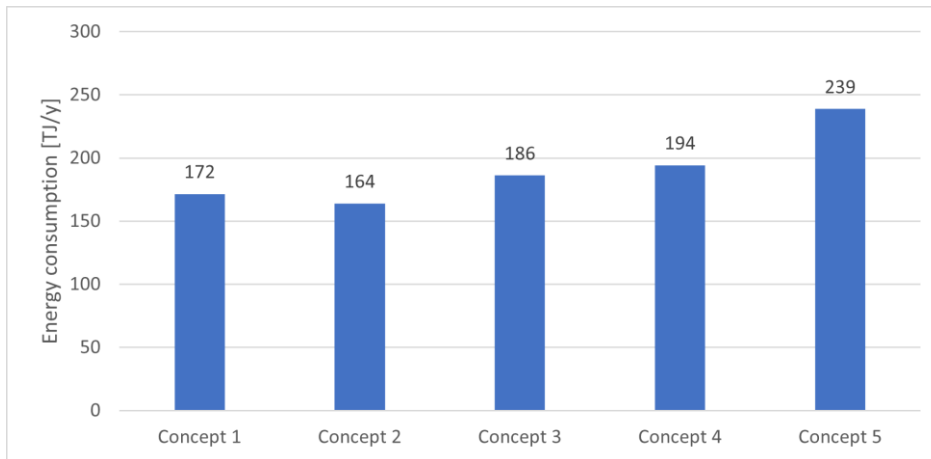


Figure 24. The energy consumption of the different propulsion concepts in tera joules per year. The lower heating values used for conversion are the ones provided by manufacturer for the specific engine presented in Chapter 4.6.1 and Chapter 4.6.2.

5.2 Cost

In this chapter the obtained and calculated costs for investment, fuel and maintenance are presented.

5.2.1 Investment cost

The investment costs are based on the components presented in Chapter 4 and includes all mechanical- and electrical components presented except for all the switchboards and transformers. All investment costs are either proved by manufacturers or estimated with help of discussions with representatives at Rederi AB Donsötank and FKAB Marine Design as well as with the manufacturers.

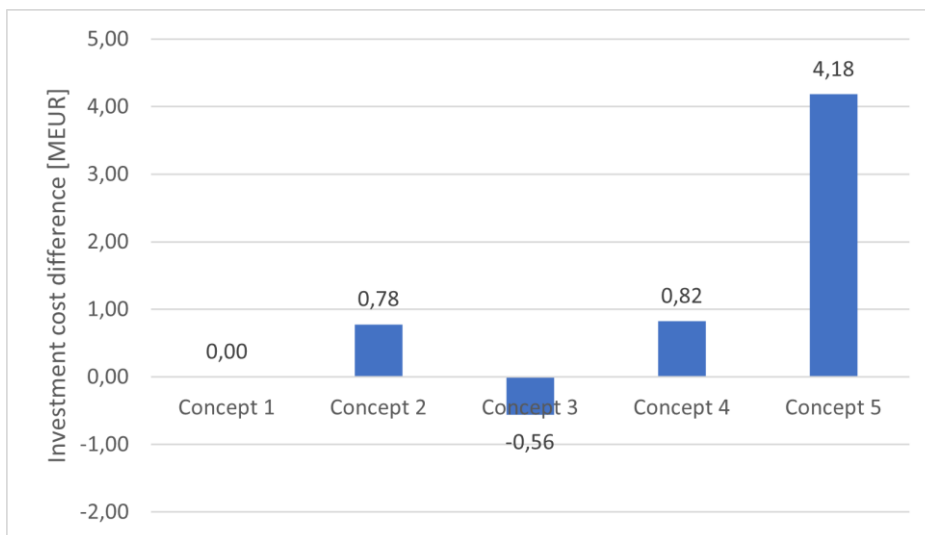


Figure 25. The difference in investment cost for the various propulsion concepts. The presented costs are how the concepts differs from the reference concept 1. The costs are presented in million euros.

5.2.2 Fuel cost

The fuel costs have been calculated with known fuel consumption presented in Figure 23. The fuels used are Ultra Low Sulphur Fuel Oil (ULSFO) and Liquid Natural Gas (LNG). The fuel price used is obtained from Ship & Bunker (<https://shipandbunker.com/>) and Titan LNG (<https://titan-lng.com/>) in Rotterdam the 19th of April, ULSFO = 432 EUR/MT and LNG =

430 EUR/MT. The exchange rate 1 EUR = 1.2037USD from 19th of April have been used for the ULSFO price. The exchange rate is obtained from Bloomberg (<https://www.bloomberg.com/quote/EURUSD:CUR>).

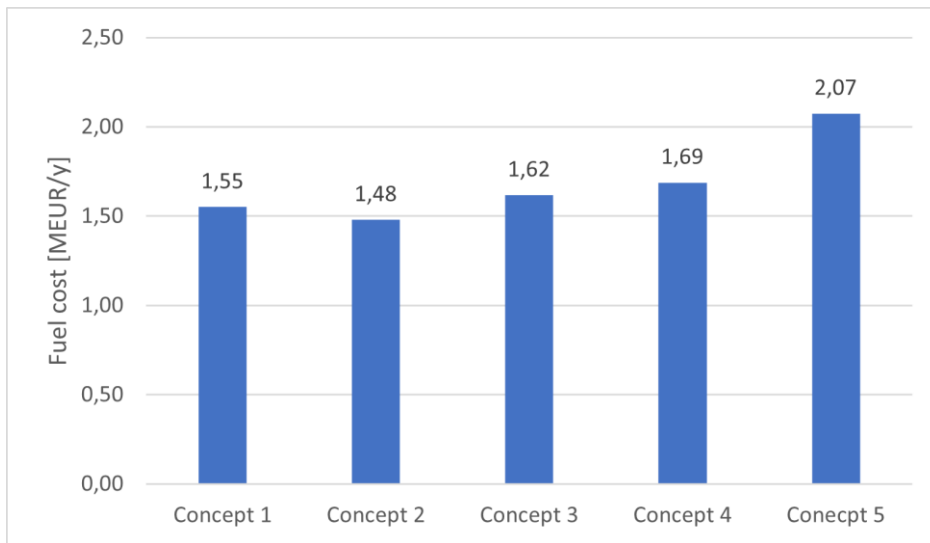


Figure 26. The fuel cost of the different propulsion concepts. Fuel prices: LNG = 430 EUR/MT and ULSFO = 432 EUR/MT. The costs are presented in million euros per year.

5.2.3 Maintenance cost

The maintenance costs are obtained from the actual maintenance costs for Rederi AB Donsötanks existing ships. The years 2016 – 2020 were investigated for the five different ships which each are equipped with one of the concepts represented by a blue bar chart in Figure 27.

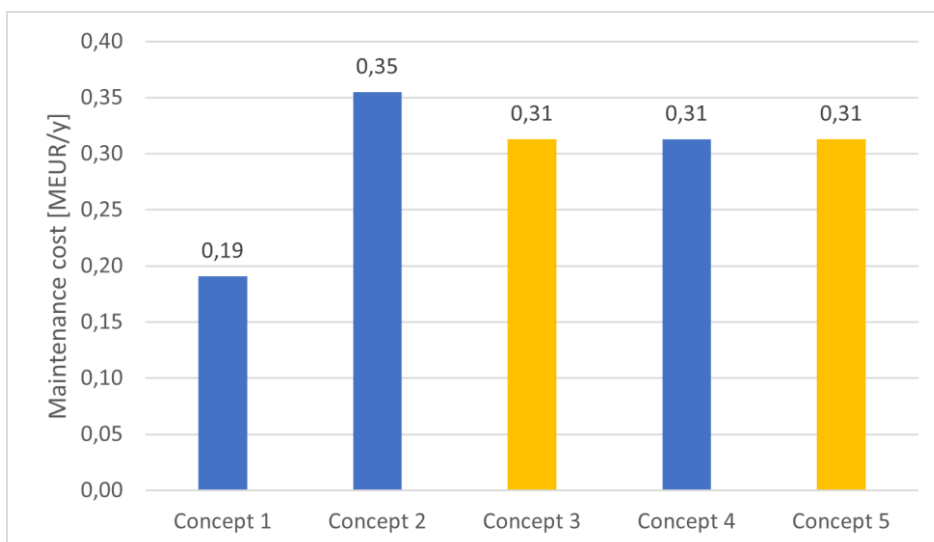


Figure 27. The maintenance cost of the different propulsion concepts. The costs are presented in million euros. The blue stacks are actual costs from existing ships with the actual propulsion concept installed. Bars with the colour yellow are estimated because of its similarities to one of the existing concepts.

5.2.4 Total cost

The costs for investment (Figure 25), fuel (Figure 26) and maintenance (Figure 27) are summarised into Figure 28. The figure shows the total cost of the concepts in relation to concept 1.

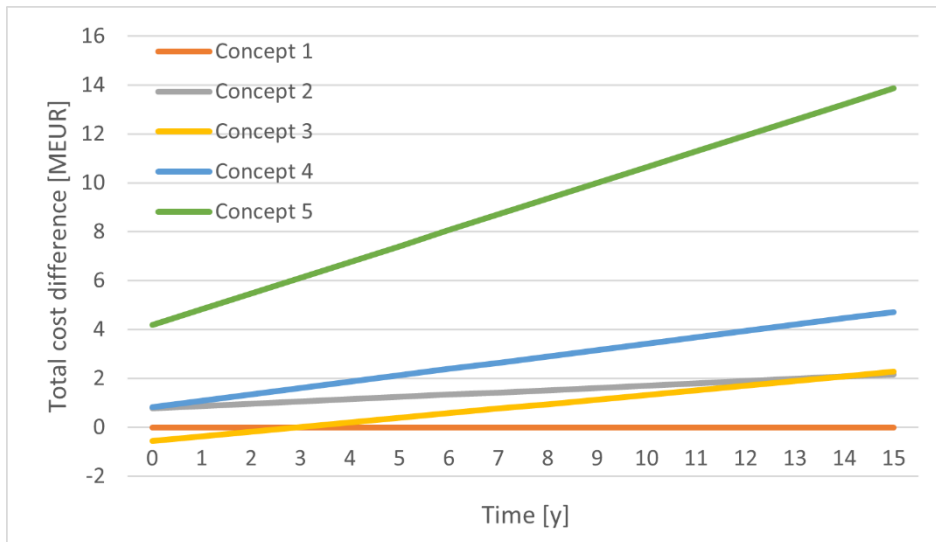


Figure 28. The cost difference for the different propulsion concepts. The presented costs are how the concepts differs from the reference concept 1. The costs are presented in million euros.

6 Discussion

The observed results need to be discussed since a lot of assumptions is made in this investigation. In this section questions as the price validity, electrical- and hydrodynamical simplifications and other is discussed.

6.1 Energy consumption

The uncertainty of the propeller studies for the different concepts needs to be covered. Generally a larger diameter gives a better efficiency (Ramne, 2018). For the two podded concepts there are two smaller propellers which reduces the efficiency compared to the three conventional propeller concepts. The designed propellers for the two podded concepts are also designed upon request, with the same hull as the reference ship, where only the required power to propel the ship was provided to the manufacturers. The combination with hull and propeller is hence not fully optimized for all concepts and it can be assumed that the efficiency can further be increased for some concepts. Interesting and remarkable is the big difference in propulsion efficiency, presented in Table 13, where it is noticed that the electrical pod in concept 4 seems to be much more efficient than the azimuth thruster in concept 5.

Many simplifications are made in this thesis work. For example, the efficiency of the different components changes with the load on the component, but in this thesis it is set to a specific point. The gearbox is according to a diagram provided by representatives of Wärtsilä between 0.925 and 0.98 for the loads 10 % to 100 %. In this case a simplification is made and the efficiency 0.975, presented in Table 8, at operating load 70 % is chosen. This since it is shown that the efficiency is not changing that much between the loads 50 % (eff. = 0.97) and 100 % (eff. = 0.98).

On the market many different fuels are available and the energy content in the fuels varies a lot. In this thesis the lower heating values used by the engine manufacturers are used. Wärtsilä for example used 42700 kJ/kg for liquid fuel and 49620 kJ/kg or 49700 kJ/kg for gas dependent on engine. The lower heating value, or lower calorific value as it is also called, can anyhow vary very much for different fuels as well. Marsh & Shamray (2019) describes in their article that the energy content within the fuels is varying a lot. From 300 000 samples it was discovered that the mean lower heating value of Very Low Sulphur Fuel Oil (VLSFO) is 41.6 MJ/kg, but it was also seen that the energy content in VLSFO could vary by 3 - 5 %. Gas and especially LNG is used as the prime fuel in this study. LNG is anyhow a fuel which methane content is varying, between 87 % to more than 99 % according to Kuczynski, Laciak, Szurlej, & Wlodek (2020) and hence is the energy content in the fuel as well which means that the actual consumption might be higher or lower. This means that even within the same fuel categories large differences in quality can be observed and the energy cost for the ship will vary dependent the fuel bought.

During the investigation one strong argument for the diesel-electric alternatives have been that since many smaller engines are used it is easy to operate them at their most efficient load. Hansen & Wendt (2015) even meant that this is the reason why the diesel-electric concepts are the most energy efficient concepts. The results anyhow shows that the load optimisation is not good enough to compete with the more efficient power chain in the mechanical setups as well as the larger and more efficient main engine. This can be seen when comparing the numbers in Figure 22 and Figure 24. It is seen how the difference in mechanical energy

produced by the diesel-electric and conventional concepts are much smaller than the total energy used. The only difference between the two figures is the engines fuel consumption which is clearly better in the conventional concepts. So the question is if it really is that beneficial to have small diesel-electric engines. What if two larger engines and one very small is used instead? Or one large engine and one small? Figure 17 anyhow indicates that the 34DF needs to be at quite low engine loads and the 20DF very high engine loads before it is beneficial to run the smaller one. The efficiency for the 31DF engine compared to 34DF is quite similar at higher loads, 49.7 % and 47.2 % respectively at 85 % load. The problem is when the diesel-electric engines run at lower loads where the 31DF still reaches 49.0 % efficiency at 50 % load while the 34DF have dropped to 41.9 %.

The study shows the strength of the conventional power chain, where the losses between main engine and propeller is just 3.5 % respectively 1 % for concept 1 and 2. The large two-stroke main engine used in concept 2 is in addition to this producing mechanical power at a very good energy consumption which makes it the most energy efficient concept. In this manner the diesel-electric concepts are far behind, since the efficiency both in system and engines are lower, but where it is noted for the very energy efficient electric production by the large generators.

The electrical schematics is another area where discussion is of importance. It is seen how the conventional concepts uses a DC-link to reduce the losses in the electric system. In the diesel-electric it was chosen not to use a DC-link since some of the benefits disappears with the shaft generator generated electricity. The electrical schematics are designed after discussion with professionals and by studying actual installed systems. It is anyhow noticed how opinions vary and the solutions are many, so the perfect system is still to be found and requires further research.

6.2 Cost uncertainties

Most probable the biggest uncertainty in this thesis work is the cost of the investment for the different components. When discussions are being made between buyers and sellers often a lot can be done on the initial price. This project is both being dependent on “actual” investment prices as well as “initial” prices provided by manufacturers on request. Therefore, some uncertainty can be assumed, and the actual investment cases can in the most cases be assumed to be lower than stated in Chapter 5.2. It is anyhow shown that as McCoy (2002) described the costs can be reduced in a diesel-electric propulsion concept since less engine effect is installed which is especially seen in concept 3 being the cheapest alternative. The quite expensive propulsors, electrical pods and azimuth thrusters with electrical motors, used in concept 4 and 5, are on the other hand more expensive than just having a conventional shaft line with propeller.

Representatives of WE Tech provided with investment costs for their whole systems including shaft generator, DC-link, smaller frequency converters DC consumers, AFE drives etc. The prices provided by ABB is also including all propulsion motors and AFE drives but excluding smaller converters. On the other hand, the price is including project management, engineering and commissioning. Prices between the different manufacturers as Wärtsilä and MAN or WE Tech and ABB is therefore hard to compare but can still be used as a good indication.

One benefits with having a diesel-electric concept is that the cargo hold can be extended. This since the conventional propulsion line with propeller, shaft, gearbox (if 4-stroke), shaft generator and main engine requires a longer engine room than the diesel-electric concepts. This would lead to more cargo onboard and so on more freight income.

It is noted that the largest cost during the ships lifetime is the energy cost. The fuel cost varies a lot and was according to Ship & Bunker (<https://shipandbunker.com/>) and Titan LNG (<https://titan-lng.com/>) in Rotterdam the 19 of April 2021 430 EUR/MT and 432 EUR/MT for LNG and ULSFO. Noted is that the costs for the two fuels are quite similar. Historically the prices have varied a lot. All fuels normally follow the oil indexes WTI crude and Brent crude. Ship & Bunker presents that the 22 of April 2021 Brent crude oil equalled 65.40 USD per barrel compared to one year earlier the 22 of April 2020 when it was down to 20.37 USD per barrel (<https://shipandbunker.com/>). The crude oil and bunker are as understood very much volatile as the price fluctuates a lot which have a big influence on the final fuel cost of the ship.

Liquid natural gas is as mentioned also stated to have a larger energy content than ULSFO. This means that it is beneficial to run as much as possible at LNG as long as the price per metric ton between the two fuels do not exceed the percentual gain in LNGs energy content.

The maintenance costs are obtained from Donsötanks existing ships. The ships are all built year 2009 or earlier which means that the equipment probably have developed and become better. How the costs have changed is anyhow hard to tell since the concepts are similar even some parts might be different as well as the fact that prices of spare parts changes and service contracts changes by time. In the diesel-electric concept the same maintenance costs have been used for all three diesel-electric concepts. The two diesel-electric ships owned by Donsötank are both having electric podded propulsors, one with one pod and the other with two pods, both having four diesel-electric engines. The number of engines and pods of course changes the maintenance cost, for example concept 5 resulted in having four engines compared to the two other diesel-electric alternatives which has three engines. The conventional shaft line with fixed pitch propeller used in concept 3 is also of a less complicated and detailed design than the Azimuth thrusters or Azipods and can therefore be expected to require less maintenance. In this comparison it is anyhow assumed that all three diesel-electric concepts have the same maintenance cost.

7 Conclusion

In the result section, Chapter 5.2.4, it is noted that the concept installed in the reference ship is the most cost-efficient alternative. The two most used and conventional alternatives are the two that are fighting for the top spot together with the diesel-electric concept 3. Concept 2 proves its good reputation for energy efficiency but the savings in fuel do not overcome the more expensive maintenance costs compared to the much less costly four-stroke set up used in concept 1. Concept 3 is seen to be relatively low in investment but the maintenance cost is the problem also for this set up. The diesel-electric concepts do have less efficient engines because of their much smaller size and older technology. Concept 1 is therefore calculated to be the most economical concept since it is having low cost both in fuel and investment as well as being the clear winner when it comes to maintenance.

The study has shown the importance of the fuel used. The diesel-electric concepts are having higher energy consumption compared to the conventional concepts. Anyhow it is seen how the fuel cost difference is relatively small. The fuel price is as stated in Chapter 5.2.2 very similar for LNG and ULSFO if the unit euros per metric tonne is used. If the energy content per invested euro instead were to be used it is noted how the LNG is significantly cheaper. If the auxiliary engines in the winning concept 1 were to be exchanged into dual fuel engines instead it is shown that the extra investment for that would soon be paid off, within approximately two years, if the fuel prices were to be unchanged from now and the ships is to be operated on LNG instead of ULSFO.

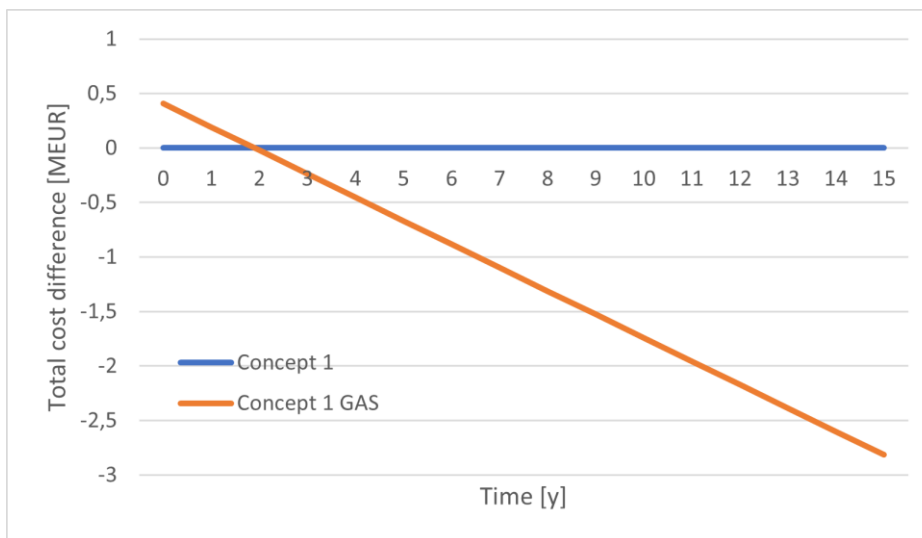


Figure 29. The total cost difference between concept 1 and the modified concept 1 with full gas operation. The cost is presented in million euros and the error bars shows the total cost when the fuel price, presented in Chapter 5.2.2, increases and decreases by 25%.

The fuel prices cannot be forecasted but as shown in Figure 29 not much time is needed before the investment is paid off and in a cost perspective the fuel could always be changed into ULSFO or similar if wanted with a dual fuel engine since SCR makes it Tier III compliant.

This study anyhow shows that size is of major importance where the larger propeller and engines in conventional propulsion results in a more energy efficient concept. If the diesel-electric engines can be developed into more energy efficient engines, then the diesel-electric concept 3 for sure is a good candidate to the conventional propulsion used in concept 1.

8 Future work

This study has been looking at a reference ship with a hull built for a specific type of propulsion. In a future investigation it would therefore be of high interest to also compare the different hulls, optimised for its propulsion, to make a fair comparison between the different propulsion concepts.

In shipping the income comes from the cargo, which means that the more cargo the more money. How much cargo that can be loaded depends to a large extent on the position of the transverse bulkhead separating the engine room/fuel tanks and the cargo tanks. This study has not investigated in detail how the engine room layout changes with the different propulsion concepts. It has been discussed that space is saved with the diesel-electric alternatives but how much more cargo can be fitted into the ship? What economical winnings can be obtained?

The costs and earnings related to the change of engine room layout could also be further studied where different concept means different amounts of equipment, structure etc. This study has only included the main components in the power chain.

As discussed in the Chapter 6.1 one of the strong arguments for diesel-electric concepts is the load optimisation that is possible while having many smaller engines. It would be interesting to further investigate the engine set-up and try different diesel-electric engine alternatives with different amounts of engines and sizes.

In this study the maintenance cost is seen to be a very important parameter when looking at costs. This research based the maintenance costs on a quite small sample of ships. It would therefore be very much interesting to study a bigger number of ships to see how the total costs of the concepts are changing with more precise maintenance data.

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10 Appendix

10.1 Assumptions and simplifications

Energy consumption:

1. Engine data used is either from the engine product guides or from their web-based tools. According to manufacturers these values are only for the early design phase. The presented fuel consumption numbers for the engines 8L20DF, 6L34DF and 10V31DF at 25 % load is without SCR since the numbers at 25 % load have not been obtained. See Chapter 4.6.1 and Chapter 4.6.2.
2. The gearbox efficiency as well as the generator efficiency varies with load, in the calculations it is set to constant numbers. See Chapter 4.6.3.
3. Efficiency data for the shaft generator in concept 2 where not obtained and hence the same shaft generator efficiency numbers as concept 1 was used for concept 2. The cost difference was provided. See Chapter 4.2.
4. The losses in the main switchboard are neglected.
5. The reference ship model test only provides data for 10.5 – 16.5 kn. For speeds lower than 10.5 kn excel inbuilt tool EXPTREND was used to provide the power numbers required. The same effective power number are used in all concepts. See Chapter 4.6.6.
6. Propulsion data for ballast condition is only obtained for the reference ship stock propeller, for speeds 11.5 – 17.5 kn. Excel's EXPTREND is used also in this case to calculate effective power numbers for speeds lower than 11.5 kn. See Chapter 4.6.6.
7. The total efficiency for ballast condition for the design propeller in concept 1 and concept 2 is calculated with known difference in total efficiency between design and ballast condition for the stock propeller. Extrapolation is used for speeds lower than 10.5 kn, where efficiencies from 10.5 kn and 11.5 were used as reference. See Chapter 4.6.6.
8. The fixed pitch propeller in concept 3 were assumed to be 2 % more efficient than concept 1 and concept 2. See Chapter 4.6.6.
9. For concept 4 and concept 5 the total efficiency was only provided for design speed by the manufacturers. Hence the same percentual change is used for these two concepts as the other three. See Chapter 4.6.6.

Investment costs:

1. The investment cost for the AVK generator used for the 6L34DF engine is assumed to have the same price per USD as the AVK generator used for the 8L20 engines.
2. The price of the shorter shaft used in concept 3 is calculated with a cost per meter price found that was used for shaft extension when designing the reference ship. See Chapter 5.2.1.
3. The investment cost of the main switchboard and transformers are not included in the study. See Chapter 5.2.1.

Maintenance costs:

1. The maintenance costs are obtained by looking at Donsötanks existing ships. The costs of years 2016 – 2020 have been investigated where maintenance and service related to

the propulsion and engine room have been included. Also the cost of the lubricating oil have been added. See Chapter 5.2.3.

2. The maintenance costs are assumed to be the same for all diesel-electric concepts. See Chapter 5.2.3.

Others:

1. When ice class effect is calculated an additional 400 kW is considered for the diesel-electric concepts for ship service power which is lower than the normal sea service power. This since some electrical consumers can be turned off if the ship is in need of full propulsion power. See Chapter 3.2.1.

10.2 Excel calculations and summations

Excel have been the major calculation tool in this thesis. The work is divided in to ten different sheets numbered 1-10 which are presented in this appendix. In some tables it refers to another chapter for details, like in the first table where “5 Propeller calculation” written.

10.2.1 Fuel consumption

Concept 1			5 Propeller calculation	4 Electric balance AC-DC		
			Power		Ship service load	
Type of action	Total time (days)	Total time (hours)	Propulsion, Pd [kW]	Ship service load [kW]	W8L20 [kW]	Shaft generator [kW]
Manoeuvring	1,8	42,9	1000,0	1690,0	190,0	1500,0
Port in/out	15,0	359,1	2512,4	800,0	0,0	800,0
At sea Ballast	72,5	1739,4	3033,9	620,0	0,0	620,0
At sea Loaded	85,1	2043,4	3406,3	980,0	0,0	980,0
Tight passages	6,5	156,9	1362,4	800,0	0,0	800,0
Loading	52,6	1262,3	0,0	694,0	694,0	0,0
Discharging	59,3	1423,3	0,0	2036,0	2036,0	0,0
Anchored/Moor ed Ballast	35,3	847,5	0,0	328,0	328,0	0,0
Anchored/Moor ed Loaded	41,2	987,8	0,0	688,0	688,0	0,0

ME load	ME gas cons. [kJ/kWh]	ME pilot [g/kWh]	AUX load	Aux load per engine	AUX fuel cons. [g/kWh]
49%	49%	7197,5	4,4	14%	14%
63%	63%	7117,2	4,2	0%	0%
69%	70%	7098,5	4,1	0%	0%
84%	84%	7062,0	4,2	0%	0%
42%	42%	7387,7	4,7	0%	0%

0%	0%	0,0	0,0	50%	50%
0%	0%	0,0	0,0	147%	73%
0%	0%	0,0	0,0	23%	23%
0%	0%	0,0	0,0	49%	49%

		Fuel consumption [MT]		
Power production [kWh]		ME gas consumption	ME pilot consumption	AUX fuel consumption
Main Engine	Auxiliary Engines			
114405,4	17463,4	16,6	0,5	3,9
1249382,0	0,0	178,9	5,2	0,0
6649047,9	0,0	949,7	27,6	0,0
9406027,6	0,0	1336,5	39,4	0,0
358995,7	0,0	53,4	1,7	0,0
0,0	933600,0	0,0	0,0	185,3
0,0	3087946,8	0,0	0,0	594,5
0,0	294191,5	0,0	0,0	65,0
0,0	719197,9	0,0	0,0	143,3
17777858,5	5052399,7	2535,0	74,4	992,0
	Total gas cons. [MT]	2535,0		
	Total oil cons. [MT]	1066,4		

Concept 1 with DF auxiliary engines					
				Fuel consumption [MT]	
AUX load	Aux load per engine	AUX gas cons. [kJ/kWh]	AUX pilot [g/kWh]	AUX gas consumption	AUX pilot consumption
14%	14%	10730,0	15,4	3,8	0,3
0%	0%	0,0	0,0	0,0	0,0
0%	0%	0,0	0,0	0,0	0,0
0%	0%	0,0	0,0	0,0	0,0
0%	0%	0,0	0,0	0,0	0,0
50%	50%	9212,6	7,0	173,3	6,5
147%	73%	8542,0	5,6	531,6	17,3
23%	23%	10730,0	15,4	63,6	4,5
49%	49%	9259,9	7,3	134,2	5,2
				906,5	33,9
			Total gas	3441,6	
			Total oil	108,2	

Concept 2			5 Propeller calculation	4 Electric balance AC-DC & 8 MAN Pumps		
			Power		Ship service load	
Type of action	Total time (days)	Total time (hours)	Propulsion, Pd [kW]	Ship service load [kW]	W8L20 [kW]	Shaft generator [kW]
Manoeuvring	1,8	42,9	1000	1758,3	258,3	1500,0
Port in/out	15,0	359,1	2512	868,3	0,0	868,3
At sea Ballast	72,5	1739,4	3034	688,3	0,0	688,3
At sea Loaded	85,1	2043,4	3406	1048,3	0,0	1048,3
Tight passages	6,5	156,9	1362	868,3	0,0	868,3
Loading	52,6	1262,3	0	694,0	694,0	0,0
Discharging	59,3	1423,3	0	2036,0	2036,0	0,0
Anchored/Moored Ballast	35,3	847,5	0	328,0	328,0	0,0
Anchored/Moored Loaded	41,2	987,8	0	688,0	688,0	0,0

ME load	ME gas cons. [kJ/kWh]	ME pilot [g/kWh]	AUX load	Aux load per engine	AUX fuel cons. [g/kWh]
47%	6672,6	7,3	19%	19%	221,0
63%	6650,6	5,5	0%	0%	0,0
69%	6657,9	4,9	0%	0%	0,0
83%	6728,4	4,0	0%	0%	0,0
42%	6748,5	8,8	0%	0%	0,0
0%	0,0	0,0	50%	50%	198,5
0%	0,0	0,0	147%	73%	192,5
0%	0,0	0,0	23%	23%	221,0
0%	0,0	0,0	49%	49%	199,2

		Fuel consumption [MT]		
Power production [kWh]		ME gas consumption	ME pilot consumption	AUX fuel consumption
Main Engine	Auxiliary Engines			
111545,2	11869,6	14,9	0,8	2,6
1244347,3	0,0	165,5	6,8	0,0
6609743,5	0,0	880,1	32,6	0,0
9319986,8	0,0	1254,2	37,3	0,0
361468,5	0,0	48,8	3,2	0,0
0,0	933600,0	0,0	0,0	185,3

0,0	3087946,8	0,0	0,0	594,5
0,0	294191,5	0,0	0,0	65,0
0,0	719197,9	0,0	0,0	143,3
17647091,3	5046805,9	2363,5	80,7	990,8
	Total gas cons. [MT]	2363,5		
	Total oil cons. [MT]	1071,5		

Concept 3			5 Propeller calculation	4 Electric balance AC-DC
			Power	
Type of action	Total time (days)	Total time (hours)	Propulsion, Pd [kW]	Ship service load [kW]
Manoeuvring	1,8	42,9	1000,0	1690,0
Port in/out	15,0	359,1	2448,6	800,0
At sea Ballast	72,5	1739,4	2956,9	620,0
At sea Loaded	85,1	2043,4	3319,8	980,0
Tight passages	6,5	156,9	1327,1	800,0
Loading	52,6	1262,3	0,0	694,0
Discharging	59,3	1423,3	0,0	2036,0
Anchored/Moored Ballast	35,3	847,5	0,0	328,0
Anchored/Moored Loaded	41,2	987,8	0,0	688,0

W6L34 DF load total	W6L34 DF per engine	W6L34D F gas cons. [kJ/kWh]	W6L34D F pilot [g/kWh]	W8L20 DF load	W8L20 DF load per engine	W8L20 DF fuel cons. [kJ/kWh]	W8L20 DF pilot [g/kWh]
101%	50%	8427,2	3,9	0%	0%	0,0	0,0
123%	61%	8119,1	3,3	0%	0%	0,0	0,0
136%	68%	7941,1	3,0	0%	0%	0,0	0,0
163%	81%	7605,1	2,4	0%	0%	0,0	0,0
80%	80%	7635,6	2,5	0%	0%	0,0	0,0
25%	0%	0,0	0,0	50%	50%	9235,1	7,1
75%	75%	7749,2	2,6	0%	0%	0,0	0,0
12%	0%	0,0	0,0	23%	23%	10730,0	15,4
25%	0%	0,0	0,0	49%	49%	9275,3	7,4

		Fuel consumption [MT]			
Power production [kWh]		W6L34DF gas consumption	W6L34DF pilot consumption	W8L20DF fuel consumption	W8L20DF pilot consumption
W6L34DF	W8L20DF				
124147,6	0,0	21,1	0,5	0,0	0,0
1270104,4	0,0	207,8	4,2	0,0	0,0
6797154,5	0,0	1087,8	20,2	0,0	0,0
9575436,7	0,0	1467,6	23,1	0,0	0,0
361221,3	0,0	55,6	0,9	0,0	0,0
0,0	926700,5	0,0	0,0	172,5	6,6
3065235,1	0,0	478,7	8,0	0,0	0,0
0,0	292675,4	0,0	0,0	63,3	4,5
0,0	715491,6	0,0	0,0	133,7	5,3
21193299,6	1934867,5	3318,6	56,8	369,5	16,4
	Total gas cons. [MT]	3688,1			
	Total oil cons. [MT]	73,2			

Concept 4				5 Propeller calculation	4 Electric balance AC- DC
				Power	
Type of action	Total time (days)	Total time (hours)	Propulsion, Pd [kW]	Ship service load [kW]	
Manoeuvring	1,8	42,9	1000,0	1690,0	
Port in/out	15,0	359,1	2706,2	800,0	
At sea Ballast	72,5	1739,4	3267,9	620,0	
At sea Loaded	85,1	2043,4	3669,0	980,0	
Tight passages	6,5	156,9	1467,5	800,0	
Loading	52,6	1262,3	0,0	694,0	
Discharging	59,3	1423,3	0,0	2036,0	
Anchored/Moored Ballast	35,3	847,5	0,0	328,0	
Anchored/Moored Loaded	41,2	987,8	0,0	688,0	

W6L34 DF load total	W6L34 DF load per engine	W6L34D F gas cons. [kJ/kWh]	W6L34D F pilot [g/kWh]	W8L20 DF load	W8L20 DF load per engine	W8L20 DF gas cons. [kJ/kWh]	W8L20 DF pilot [g/kWh]
100%	50%	8432,5	3,9	0%	0%	0,0	0,00

132%	66%	7997,1	3,1	0%	0%	0,0	0,00
146%	73%	7793,8	2,7	0%	0%	0,0	0,00
175%	87%	7504,4	2,2	0%	0%	0,0	0,00
85%	85%	7531,4	2,3	0%	0%	0,0	0,00
25%	0%	0,0	0,0	50%	50%	9235,1	7,13
75%	75%	7749,2	2,6	0%	0%	0,0	0,00
12%	0%	0,0	0,0	23%	23%	10730,0	15,40
25%	0%	0,0	0,0	49%	49%	9275,3	7,36

		Fuel consumption [MT]			
Power production [kWh]		W6L34DF gas consumption	W6L34DF pilot consumption	W8L20DF fuel consumption	W8L20DF pilot consumption
W6L34DF	W8L20DF				
123675,6	0,0	21,0	0,5	0,0	0,0
1361237,4	0,0	219,4	4,2	0,0	0,0
7330277,1	0,0	1151,4	19,8	0,0	0,0
10278628,9	0,0	1554,5	23,0	0,0	0,0
382934,5	0,0	58,1	0,9	0,0	0,0
0,0	926700,5	0,0	0,0	172,5	6,6
3065235,1	0,0	478,7	8,0	0,0	0,0
0,0	292675,4	0,0	0,0	63,3	4,5
0,0	715491,6	0,0	0,0	133,7	5,3
22541988,7	1934867,5	3483,1	56,3	369,5	16,4
	Total gas cons. [MT]	3852,6			
	Total oil cons. [MT]	72,7			

Concept 5			5 Propeller calculation	4 Electric balance AC- DC
			Power	
Type of action	Total time (days)	Total time (hours)	Propulsion, Pd [kW]	Ship service load [kW]
Manoeuvring	1,8	42,9	1000,0	1690,0
Port in/out	15,0	359,1	3573,1	800,0
At sea Ballast	72,5	1739,4	4314,8	620,0
At sea Loaded	85,1	2043,4	4844,4	980,0
Tight passages	6,5	156,9	1937,6	800,0
Loading	52,6	1262,3	0,0	694,0
Discharging	59,3	1423,3	0,0	2036,0
Anchored/Moored Ballast	35,3	847,5	0,0	328,0

Anchored/Moored Loaded	41,2	987,8	0,0	688,0
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W6L34 DF load total	W6L34 DF load per engine	W6L34DF F gas cons. [kJ/kWh]	W6L34DF F pilot [g/kWh]	W8L20 DF load	W8L20 DF load per engine	W8L20 DF gas cons. [kJ/kWh]	W8L20 DF pilot [g/kWh]
101%	51%	8416,3	3,9	0%	0%	0,0	0,0
169%	84%	7540,8	2,3	0%	0%	0,0	0,0
191%	90%	7479,7	2,2	21%	21%	10730,0	15,4
225%	90%	7479,7	2,2	87%	87%	8295,5	4,7
105%	52%	8368,3	3,8	0%	0%	0,0	0,0
25%	0%	0,0	0,0	50%	50%	9235,1	7,1
75%	75%	7749,2	2,6	0%	0%	0,0	0,0
12%	0%	0,0	0,0	23%	23%	10730,0	15,4
25%	0%	0,0	0,0	49%	49%	9275,3	7,4

		Fuel consumption [MT]			
Power production [kWh]		W6L34DF gas consumption	W6L34DF pilot consumption	W8L20DF fuel consumption	W8L20DF pilot consumption
W6L34DF	W8L20DF				
125120,9	0,0	21,2	0,5	0,0	0,0
1743833,7	0,0	265,0	4,0	0,0	0,0
9016963,2	551479,5	1359,2	19,5	119,3	8,5
10593158,4	2637625,8	1596,8	23,0	441,0	12,4
473586,5	0,0	79,9	1,8	0,0	0,0
0,0	926700,5	0,0	0,0	172,5	6,6
3065235,1	0,0	478,7	8,0	0,0	0,0
0,0	292675,4	0,0	0,0	63,3	4,5
0,0	715491,6	0,0	0,0	133,7	5,3
25017897,7	5123972,8	3800,8	56,8	929,7	37,3
	Total gas cons. [MT]	4730,5			
	Total oil cons. [MT]	94,1			

10.2.2 Engine data

Engine / Load	25%	50%	75%	85%	100%
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	Gas [kJ/kWh]	Gas [kJ/kWh]	Gas [kJ/kWh]	Gas [kJ/kWh]	Gas [kJ/kWh]
Wärtsilä 8L20, 900rpm, 60hz	-	-	-	-	-
Wärtsilä 8L20DF, AUX/DE, 1200rpm, 60hz	10730	9211	8493	8314	8189
Wärtsilä 6L34DF, DE, 720rpm	9880	8435	7743	7526	7387
Wärtsilä 10V31DF, ME, 750rpm	7844	7157	7082	7059	7128
MAN 6G45ME- C9.5-GI-HPSCR, 95rpm	6985	6635	6665	6745	6920

Engine / Load	25%	50%	75%	85%	100%
	Fuel oil [g/kWh]	Fuel oil [g/kWh]	Fuel oil [g/kWh]	Fuel oil [g/kWh]	Fuel oil [g/kWh]
Wärtsilä 8L20, 900rpm, 60hz	221	198,5	192,1	192,8	193,4
Wärtsilä 8L20DF, AUX/DE, 1200rpm, 60hz	15,4	7	5,5	4,9	3,5
Wärtsilä 6L34DF, DE, 720rpm	11,2	3,9	2,6	2,3	1,9
Wärtsilä 10V31DF, ME, 750rpm	5,6	4,3	4,1	4,2	3,8
MAN 6G45ME- C9.5-GI-HPSCR, 95rpm	13,24	6,62	4,41	3,89	3,31

Engine	SMCR [kWm]	Lower calorific value [kJ/kg]	
		Gas	Fuel oil
Wärtsilä 8L20, 900rpm, 60hz	1480		42700
Wärtsilä 8L20DF, AUX/DE, 1200rpm, 60hz	1480	49620	42700
Wärtsilä 6L34DF, DE, 720rpm	2880	49620	42700
Wärtsilä 10V31DF, ME, 750rpm	5500	49700	42700
MAN 6G45ME- C9.5-GI-HPSCR, 95rpm	5500	50000	42700

10.2.3 Efficiencies

Concept 1	Component	Efficiency		ME to prop	ME to AC ship service power	ME to DC ship service power	AUX to AC ship service power
	Gear box	0,975		0,975	0,975	0,975	
	Shaft generator	0,975		-	0,975	0,975	
	Shaft	0,99		0,99			
	LCL Filter + AFE	0,973		-	0,973		
	SG INU	0,985		-	0,985	0,985	
	INU	0,985		-		0,985	
	Transformer	0,995			0,995		0,995
	AUX Generator	0,965					0,965
	Total efficiency			0,965	0,907	0,922	0,960
Concept 2	Component	Efficiency		ME to prop	ME to AC ship service power	ME to DC ship service power	AUX to AC ship service power
	Shaft generator	0,975			0,975	0,975	
	Shaft	0,99		0,99			
	LCL Filter + AFE	0,973			0,973		
	SG INU	0,985			0,985	0,985	
	INU	0,985				0,985	
	Transformer	0,995			0,995		0,995
	AUX Generator	0,965					0,965
	Total efficiency			0,990	0,930	0,946	0,960
Concept 3	Component	Efficiency		DE to prop	DE to 450V ship service power	DE to 220V ship service power	
	AFE drive	0,97		0,97			
	VFD AC drive	0,97			0,97		

	Electrical motor	0,98		0,98			
	Shaft	0,99		0,99			
	Transformer	0,995				0,995	
	DE Generator	0,965		0,965	0,965	0,965	
	Total efficiency			0,908	0,936	0,960	
Concept 4					DE to 450V ship service power	DE to 220V ship service power	
	Component	Efficiency		DE to prop			
	AFE drive	0,97		0,97			
	VFD AC drive	0,97			0,97		
	POD	0,98		0,98			
	Transformer	0,995				0,995	
	DE Generator	0,965		0,965	0,965	0,965	
	Total efficiency			0,917	0,936	0,960	
Concept 5					DE to 450V ship service power	DE to 220V ship service power	
	Component	Efficiency		DE to prop			
	AFE drive	0,97		0,97			
	VFD AC drive	0,97			0,97		
	Electrical motor	0,98		0,98			
	Azimuth	0,97		0,97			
	Transformer	0,995				0,995	
	DE Generator	0,965		0,965	0,965	0,965	
	Total efficiency			0,890	0,936	0,960	

Summation:

Efficiencies	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5
ME to propeller	0,965	0,990	-	-	-
ME to AC/230V ship service load	0,907	0,930	-	-	-
ME to DC/450V ship service load	0,922	0,946	-	-	-

AUX/DE to propeller	-	-	0,908	0,917	0,890
AUX/DE to AC/230V ship service load	0,960	0,960	0,960	0,960	0,960
AUX/DE to DC/450V ship service load	0,925	0,925	0,936	0,936	0,936

10.2.4 Electrical balance

Condition	Power consumption [kW]	Power producer [conventional / electrical]	Load Alt. 1 [%]	Load Alt. 2[%]	Load Alt 3. [%]	DC/ 450 V [%]	AC/ 220 V [%]
Sea going condition	620	SG / not of interest	41%	-		37%	63%
Sea service with tank washing and cargo handling	980	SG / not of interest	65%	-		37%	63%
Manoeuvring/docking condition	1690	SG & W8L20 / not of interest	58%	-		77%	23%
In harbour/cargo discharging/ballast loading	2036	2xW8L20 / 2xW8L20DF or 1xW6L34DF	72%	72%	74%	61%	39%
In harbour/cargo loading/ballast discharging	694	W8L20 / W8L20DF	49%	49%		61%	39%
Take me home	2024	2xW8L20 / not of interest	72%	-		8%	92%
In harbour, stand by	328	W8L20 / W8L20DF	23%	23%		42%	58%

DC consumers (Acc. to WE tech schematics.)	Sea going [kW]	Sea service with tank washing and cargo handling [kW]	Manoeuvring [kW]	In harbour /cargo disch. [kW]	In harbour/ cargo loading [kW]	Take me home [kW]	In harbour/stand by [kW]
Rack cooler pump 20kw	20,8	20,8	20,8	0	0	0	0
HVAC fan 20kW	18	18	18	18	18	18	18
AE cool pump 32kw	25,6	25,6	51,2	51,2	25,6	38,4	19,2

2nd heat circ. 21.5kW	12,9	17,2	5	0	12,9	12,9	5
Cargo pipetrunk vent fan 25kw	0	0	0	0	0	0	0
Engine room fan 40kW	32	32	64	32	32	64	0
ME cool circ. 25kw	20	20	20	0	0	0	0
Rack cooler pump 20kW	0	0	0	0	0	0	0
HVAC fan 20kW	18	18	18	18	18	18	18
AE cool pump 32kW	0	0	0	0	0	0	0
ME HT cool circ. 16kW	8	8	8	0	0	0	0
Engine room fan 40kW	0	0	0	0	0	0	0
Cargo pipetrunk vent fan 25kw	15,4	15,4	15,4	15,4	15,4	15,4	15,4
Cargo tank vent fan 250kW	0	89	0	0	0	0	0
2nd heat circ. Pump 21.5kW	0	0	0	0	0	0	0
Bow thruster	0	0	1080	0	0	0	0
Cargo & ballast pumps	60	100	0	1100	301	0	62,8
Total DC [kW]	230, 7	364	1300, 4	1234,6	422,9	166,7	138,4

10.2.5 Propeller calculation

Concept 1							
Ship speed	Total efficiency	Open water efficiency	Effective Power		Delivered Power	Type of action	Propulsion, Pd [kW]

			Design	Bal last	De sign	Bal last	Manoeuvring	1000,0
8,5	0,74		737	66 3	99 7	89 6	Port in/out	2512,4
9,5	0,748		950	85 0	12 70	11 37	At sea Ballast	3033,9
10,5	0,756	0,657	1209	10 91	15 99	14 43	At sea Loaded	3406,3
11,5	0,764	0,657	1593	13 87	20 85	18 15	Tight passages	1362,4
12,5	0,768	0,658	2049	18 10	26 68	23 57	Loading	0,0
13,5	0,768	0,656	2616	23 30	34 06	30 34	Discharging	0,0
14,5	0,763	0,651	3347	29 25	43 87	38 34	Anchored/Moo red Ballast	0,0
							Anchored/Moo red Loaded	0,0

Concept 2								
Ship speed	Total efficiency	Open water efficiency	Effective Power		Delivered Power		Type of action	Propulsion, Pd [kW]
			Design	Bal last	De sign	Bal last	Manoeuvring	1000,0
8,5	0,74		737	66 3	99 7	89 6	Port in/out	2512,4
9,5	0,748		950	85 0	12 70	11 37	At sea Ballast	3033,9
10,5	0,756	0,657	1209	10 91	15 99	14 43	At sea Loaded	3406,3
11,5	0,764	0,657	1593	13 87	20 85	18 15	Tight passages	1362,4
12,5	0,768	0,658	2049	18 10	26 68	23 57	Loading	0,0
13,5	0,768	0,656	2616	23 30	34 06	30 34	Discharging	0,0
14,5	0,763	0,651	3347	29 25	43 87	38 34	Anchored/Moo red Ballast	0,0
							Anchored/Moo red Loaded	0,0

Concept 3								
Ship speed	Total efficiency	Open water efficiency	Effective Power		Delivered Power		Type of action	Propulsion, Pd [kW]

			Design	Bal last	De sign	Bal last	Manoeuvring	1000,0
8,5	0,76		737	663	970	872	Port in/out	2448,6
9,5	0,768		950	850	1237	1107	At sea Ballast	2956,9
10,5	0,776		1209	1091	1558	1406	At sea Loaded	3319,8
11,5	0,784		1593	1387	2032	1769	Tight passages	1327,1
12,5	0,788		2049	1810	2600	2297	Loading	0,0
13,5	0,788		2616	2330	3320	2957	Discharging	0,0
14,5	0,783		3347	2925	4275	3736	Anchored/Moo red Ballast	0,0
							Anchored/Moo red Loaded	0,0

Concept 4								
Ship speed	Total efficiency	Open water efficiency	Effective Power		Delivered Power	Type of action	Propulsion, Pd [kW]	
			Design	Bal last	De sign	Bal last	Manoeuvring	1000,0
8,5	0,687005208		737	663	1073	965	Port in/out	2706,2
9,5	0,694432292		950	850	1368	1225	At sea Ballast	3267,9
10,5	0,701859375		1209	1091	1723	1555	At sea Loaded	3669,0
11,5	0,709286458		1593	1387	2246	1955	Tight passages	1467,5
12,5	0,713		2049	1810	2874	2539	Loading	0,0
13,5	0,713		2616	2330	3669	3268	Discharging	0,0
14,5	0,708358073		3347	2925	4725	4129	Anchored/Moo red Ballast	0,0
							Anchored/Moo red Loaded	0,0

Concept 5							
Ship speed	Total efficiency	Open water efficiency	Effective Power		Delivered Power [kW]	Type of action	Propulsion, Pd [kW]

			Design	Bal last	Des ign	Bal last	Manoeuvring	1000,0
8,5	0,52031 25		737	66 3	141 7	127 4	Port in/out	3573,1
9,5	0,52593 75		950	85 0	180 6	161 7	At sea Ballast	4314,8
10,5	0,53156 25		1209	10 91	227 4	205 3	At sea Loaded	4844,4
11,5	0,53718 75		1593	13 87	296 5	258 2	Tight passages	1937,6
12,5	0,54		2049	18 10	379 4	335 2	Loading	0,0
13,5	0,54		2616	23 30	484 4	431 5	Discharging	0,0
14,5	0,53648 4375		3347	29 25	623 9	545 2	Anchored/Moo red Ballast	0,0
							Anchored/Moo red Loaded	0,0

10.2.6 Ice class

Concept	Propeller diameter	Number of propellers	Ke	Ice class propulsion power required [kW]	Electric power [kW]	Total effect required [kW]
1	6,1	1	2,03	6300	0	6300
2	6,1	1	2,03	6300	0	6300
3	6,1	1	2,03	6300	400	6700
4	4,1	2	1,44	6649	400	7049
5	3,3	2	1,44	8261	400	8661

Concept	Conceptual propulsion power [kW]	Load [%]
1	6600	95%
2	6600	95%
3	7240	93%
4	7240	97%
5	8720	99%

10.2.7 Component costs

In respect of the sellers the costs are not presented. Following components are included in the cost comparison:

Concept 1		
Main engine	Wärtsilä 10V31DF	5500kW, 750rpm, incl GVU.

Main engine SCR	Wärtsilä	
Auxiliary engine	Wärtsilä 8L20	2x, 1480kW, 60hz, incl GVU.
Auxiliary engine generator	AVK	2x,
Auxiliary engine SCR	Wärtsilä	2x,
Gear box	Wärtsilä	5500 + 1100kW, 750 rpm ME to 95 rpm propeller
Shaft generator & electrical components	The Switch/WE Tech	PTO = 1530kW, PTI = 1100 kW boost, inc. 2x AFE drives 1500kW.
Shaft line	Wärtsilä	9m
Propeller	Wärtsilä	CP, dia. 6.1m
Rudder	Becker	
Concept 2		
Main engine	MAN 6G45-9.5C-GI	5500kW
Main engine SCR	MAN HPSCR	
Auxiliary engine	Wärtsilä 8L20	2x, 1480kW, 60hz, incl GVU.
Auxiliary engine generator	AVK	2x,
Auxiliary engine SCR	Wärtsilä	2x,
Clutch	RENK	1x, 5500kW, 95 rpm, DNVGL, ICE 1A, Fully automatic
Shaft generator & electrical components	WE Tech	PTO = 1530kW, PTI = 1100 kW boost, inc. 2x AFE drives 1500kW.
Shaft line	Wärtsilä	9m
Propeller	Wärtsilä	CP, dia. 6.1m
Rudder	Becker	
Concept 3		
Diesel electric engine 1	Wärtsilä 6L34DF	2x, 2880kW, 60hz, incl GVU.
Diesel electric engine 2	Wärtsilä 8L20DF	1x, 1480kW, 60hz incl GVU.
Generator for DEE 1	-	2x, Manu. not defined.
Generator for DEE 2	AVK	1x,
SCR 1	Wärtsilä	2x,
SCR 2	Wärtsilä	1x,

Shaft line	Wärtsilä	5m
Propeller	Wärtsilä	FP, dia. 6.1m
Rudder	Becker	
Electrical motor	ABB	6300kW
Electrical components	ABB	1x AFE drive 6300kW
Concept 4		
Diesel electric engine 1	Wärtsilä 6L34DF	2x, 2880kW, 60hz, incl GVU.
Diesel electric engine 2	Wärtsilä 8L20DF	1x, 1480kW, 60hz incl GVU.
Generator for DEE 1	-	2x, Manu. not defined.
Generator for DEE 2	AVK	1x,
SCR 1	Wärtsilä	2x,
SCR 2	Wärtsilä	1x,
Azipod	ABB DO1100P	2x, 3470kW
Electrical components	ABB	2x AFE drives 3470kW
Concept 5		
Diesel electric engine 1	Wärtsilä 6L34DF	2x, 2880kW, 60hz, incl GVU.
Diesel electric engine 2	Wärtsilä 8L20DF	2x, 1480kW, 60hz incl GVU.
Generator for DEE 1	-	2x, Manu. not defined.
Generator for DEE 2	AVK	2x,
SCR 1	Wärtsilä	2x,
SCR 2	Wärtsilä	2x,
Azimuth thruster	Schottel	2x,
Electrical motor	ABB	2x, 4000kW
Electrical components	ABB	2x AFE drives 4000kW

10.2.8 Maintenance costs

In respect of the ship owner this is not attached in appendix.

10.2.9 MAN pumps

Pump	Capacity [m3/h]	Pressure [bar]	Power [kW]
Jacket cooling water	45	3	5,4
Central fresh water	180	2,5	18
Sea water for central cooling	210	2	16,8
Lubricating oil	180	3,9	28,08
Total pump effect [kW]			68,28

Engine load	25%	50%	75%	85%	100%
Engine effect [kW]	1375	2750	4125	4675	5500
Engine effect + pump effect [kW]	1443,28	2818,28	4193,28	4743,28	5568,28

10.2.10 Result summation

Since investment costs are included also in this excel sheet it has been chosen not to be presented.

DEPARTMENT OF MECHANICS AND
MARITIME SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
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