CHALMERS

# Feasibility study of hybrid propulsion systems for long-liner fishing vessels

*Master's Thesis in the International Master's Programme Naval Architecture and Ocean Engineering*

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Figure of Jóhanna Gísladóttir GK entering its home port, Grindavík, taken by Vigfús Markússon and is used with his permission.

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## ABSTRACT

Fluctuating and unpredictable fuel prices in combination with new environmental regulations and increased awareness of shipping impact on global greenhouse gas emissions have brought the interest of ship owners into investigating further alternative propulsion and power plant systems for increased efficiency and reduction of emissions. In recent years there has been a growing interest in the shipping industry to apply hybrid propulsion system including batteries.

Fishing and its related activities constitute a significant part of the shipping business, in particular in some countries such as Iceland and Norway. In the past most designs have been performed with focus on the so called design condition for vessels. However, both due to the fishing method and environmental conditions, the vessels are operating in a number of different conditions from what was assumed in the original design process. In this thesis, the operational pattern is investigated for an existing long-liner fishing vessel in the Icelandic fleet, based on an empirical approach along with on board measurements.

The current propulsion and power plant of the long-liner fishing vessel under consideration is compared with alternative designs including hybrid and diesel-electric propulsion in terms of efficiency and bunker consumption. The comparisons are obtained by simulation models of the propulsion systems and use the estimation and measurement of the power requirement as an input data. Finally, an economical comparison based on estimations of the additional costs for the proposed design alternatives is presented. When trends on market, the operational pattern and the economical evaluation are summarized, it indicates future potential for hybrid propulsion for long-liner fishing vessels.

Key words: Diesel-electric propulsion, Emission reduction, Hybrid propulsion, Long-lining fishing, battery

Förstudie av hybrida framdrivningssystem för line-fiskefartyg
Examensarbete inom Naval Architecture and Ocean Engineering
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## SAMMANFATTNING

Fluktationer och oförutsägbara bränslepriser i kombination med nya regler och ökat miljömedvetande kring sjöfartens påverkan kring utsläpp av växthusgaser har väckt intresse bland rederier att undersöka alternativa system för framdrivning samt energiproduktion ombord för ökad effektivitet och minskade utsläpp. På senare år har intresset växt i sjöfartsnäringen att tillämpa hybriddrift där batterier är inkluderat.

Fiske och relaterad verksamhet utgör en betydande del av sjöfartsnäringen, framförallt i länder så som Island och Norge. Förr, så fokuserades mestadels designarbetet på ett så kallat designförhållande för fartyget, men både vad det gäller fiskemetod men också omgivning, så är fartyget oftast verksam i helt andra förhållanden än vad som antogs i designprocessen. I denna uppsats undersöks det operationella mönstret av ett line-fiskefartyg tillhörande den Isländska flottan, baserat på ett empirisk tillvägagångsätt i kombination med mätningar ombord.

Det nuvarande framdrivnings- och energiproduktionssystemet för line-fiskefartyget under beaktning jämförs med de genererade designalternativen för hybrid- samt diesel-elektriskt system i termer av effektivitet och bunkerförbrukning. Jämförelsen görs genom simuleringsmodeller av det nuvarande samt design-alternativen, där uppskattning och mätningar av energibehov används som indata. Slutligen så presenteras kortfattat merkostnaderna för designalternativen samt en ekonomisk jämförelse. När nuvarande marknadstrend, det operationella mönstret och den ekonomiska utvärderingen summeras så finns det en framtida potential gällande hybriddrift av line-fiskefartyg.

Nyckelord: Batteri, Diesel-elektrisk framdrivning, Hybrid framdrivning, Line-fiske, Utsläpps-reduktion

# Contents

# Preface

This thesis is a part of the requirements for the master's degree in Naval Architecture and Ocean Engineering at Chalmers University of Technology, Göteborg, and has been carried out at Navis ehf, Reykjavík, Iceland between January and June 2015.

We would like to acknowledge and thank our examiner, PhD Cecilia Gabrielii, and especially our supervising PhD student Francesco Baldi, at the Department of Shipping and Marine Technology, for their excellent guidance and support throughout the work with this thesis.

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We would also want to thank Visir hf for giving us access to a vessel in there fleet and especially the fleet manager, Kjartan Viðarsson for helping us to get the measurements done and providing us with the data we needed.

Finally we would like to thank Þór Sigfússon at the Icelandic Ocean cluster for his help with establishing contact with the ship owner.

Reykjavík, May 2015

Alexander Andersson

Kári Logason

# List of abbreviations

| | |
|---|---|
| AIS | Automatic Identification System |
| B | Battery Package |
| CAD | Computer Aided Design |
| CFD | Computational Fluid Dynamics |
| CPP | Controllable Pitch Propeller |
| DE | Diesel Engine |
| DNV | Det Norske Veritas |
| EM | Electrical Motor |
| FAO | Food and Agriculture Organization of the United Nations |
| FC | Frequency Converter |
| FPP | Fixed Pitch Propeller |
| G | Generator |
| GB | Gearbox |
| GL | Germanischer Lloyd |
| ITTC | International Towing Tank Conference |
| LCB | Longitudinal Centre of Buoyancy |
| MGO | Marine Gas Oil |
| NOx | Nitrogen Oxides |
| NPV | Net Present Value |
| PC | Power Converter |
| SB | Switchboard |
| SNAME | Society of Naval Architects and Marine Engineers |
| SOx | Sulphur Oxides |
| SECA | Sulphur Emission Control Areas |

# Definitions

| | |
|---|---|
| *Diesel-electric propulsion* | Propulsion system driven by an electrical motor connected through a gearbox to provide power for the propeller via a conventional shafting arrangement. The power production for the electrical motor is produced from an integrated arrangement of diesel generators feeding all consumers of the vessel along with the propulsion system. |
| *Genset* | Power production unit with a combined engine and generator also known as auxiliary engine or generating sets. |
| *Hybrid-propulsion* | Diesel-electric propulsion system combined with energy storage and supply by using batteries. |
| *Long-liner* | Fishing vessel that uses long-lines equipped with baited hooks. |
| *Power plant* | Power production for consumers such as equipment and propulsion. |
| *Secondary Batteries* | Batteries able to discharge/charge a number of cycles compared to primary batteries that only could be used once. |

# Notations

| | |
|---|---|
| $\mathrm{k}_1$ | Form factor describing the viscous resistance of the hull form |
| $\mathrm{R}_\mathrm{A}$ | Model-ship correlation resistance |
| $\mathrm{R}_\mathrm{APP}$ | Resistance of appendage |
| $\mathrm{R}_\mathrm{B}$ | Additional pressure resistance of bulbous bow near the water surface |
| $\mathrm{R}_\mathrm{F}$ | Frictional resistance due to ITTC-57 friction formula |
| $\mathrm{R}_\mathrm{Total}$ | Total resistance |
| $\mathrm{R}_\mathrm{TR}$ | Additional resistance due to immersed transom stern |
| $\mathrm{R}_\mathrm{W}$ | Wave making and wave breaking resistance |
| $A_E$ | Expanded blade area |
| $A_O$ | Propeller disc area |
| $C_p$ | Prismatic coefficient |
| $CF_{PE}$ | Cost factor installed power engines |
| $CF_{PB}$ | Cost factor installed power batteries |
| $C_{PE}$ | Cost power electronics |
| $P_{PE}$ | Installed power engines |
| $P_{PB}$ | Installed power batteries |
| $K_Q$ | Torque coefficient |
| $K_T$ | Thrust coefficient |
| $P_{1-3}$ | Power demand for phase one to three |
| $P_B$ | Engine brake power |
| $P_{E,service}$ | Effective power service allowance included |
| $P_E$ | Effective power |
| $P_{total}$ | Sum of the power demand for all three phases |
| $R_{Total}$ | Total resistance |
| $V_A$ | Advanced velocity |
| $V_s$ | Ships speed |
| P | Propeller pitch |
| $D$ | Propeller diameter |
| $I$ | Current |
| $I$ | Initial investment cost |
| $J$ | Advance Coefficient |
| $N$ | Expected lifetime of the investment |
| $Q$ | Propeller torque |

| | |
|---|---|
| $T$ | Propeller thrust |
| $U$ | Upgrade cost of battery package |
| $V$ | Voltage |
| $\eta_{O}$ | Open-water propeller efficiency |
| $\eta_H$ | Hull efficiency |
| $\eta_R$ | Relative rotative efficiency |
| $\eta_T$ | Transmission efficiency |
| $a$ | Annual cost reduction due to fuel savings |
| $n$ | Propeller revolutions per second |
| $r$ | Discount rate |
| $t$ | Thrust deduction factor |
| $w$ | Wake factor |
| $z$ | Number of blades |
| $\rho$ | Fluid density |

# 1 Introduction

Fluctuating and unpredictable bunker prices in combination with new environmental regulations and increased awareness for shipping contribution to global greenhouse gas emissions are putting a lot of pressure on the shipping industry and the fisheries are not any exception. This situation comes in connection with increased sailing distances in order to keep equal catch levels. Fuel is therefore a major issue in the fishing industry where there is a growing objective to be less dependent on oil (Basurko, 2013).

In the past most of the designs were performed by focusing the so called design condition for the ship, both for technical needs and legal purposes. However, due to both the fishing method and to the environmental conditions, the vessels are operating in a number of conditions which are different from what was assumed in the design process. The method of long-lining fishing consists of several operational modes with significant differences, considering the power requirements for the vessels. Due to this difference it is clear that there is room for improvements when designing the propulsion and power plant where different modes are considered.

As a consequence of the growing concern for fuel prices and environmental awareness, there has been a growing interest by the ship owners to look into new technologies and solutions regarding propulsion and power plant. One solution that is widely used in different types of industries and is experiencing a huge development is the concept of a hybrid propulsion plant. In the shipping industry, hybrid propulsion is often referred to a mechanical/electrical hybridization without batteries. In this thesis, hybrid propulsion is a diesel-electric propulsion plant including batteries. It has been shown today that hybrid propulsion on ships can save up to 20-30% in fuel consumption (DNV GL, 2014a). This is achieved by storing the energy when the power demand is low and using it when the power demand is higher or turn of the engines if the batteries can provide the required power.

The battery technology is developing very fast, both when considering the storage of energy compared to weight but also considering price per unit. For example the unit price of 1 kWh has decreased from 560 USD to 380 USD in 2011-2014 and market specialists within the area claim that the price will decline to 200 USD before 2020. Today the batteries on the market are up to 200 Wh/kg but manufacturers are already testing prototypes up to 400 Wh/kg, which implies large potential since the weight and operational criteria is of great importance, regarding application on ships (Dedes et.al., 2012). Considering quotations from manufactures and market leaders there is a strong enthusiasm regarding the future (Mckinsey&company, 2013).

1. *"I do think that cost per kWh that the cell level will decline below $200, in the not-to-distant future", Elon Musk, CEO Tesla Motors*
2. *"Today there are prototypes out there with 400Wh/kg, the industry is in a period of rapid transformation." Gary Smyth, GM Director of Global Research and Development*
3. *"In the next 3-4 years there will be more progress in battery development than the previous 100 years" Ian Robertson, BMW Board Member*
4. *"Through mass production, we will soon lower production costs to a quarter of what they were […] in 2009", President Makoto Yoda, GS Yuasa Corp (Mitsubishi Motors Corp supplier)*

Several projects have investigated battery electrification of various ship types showing that there is considerable potential to reduce both energy consumption and emissions of sulphur oxides (SOx), nitrogen dioxide (NOx) and particulate emissions (DNV GL, 2006). Even though this thesis is mainly focusing on the Icelandic fleet where regulations, such as SECA not have been put in to practise, it should be kept in mind that prices of fuel that fulfils these regulations might become 30-50% more expensive (DNV GL, 2014a). These regulations could come into practise in the Icelandic waters in coming years.

Since longlining fishing vessels have such a special operational profile due to its fishing method, there is a huge potential in applying hybrid technology including batteries with the aim of a more even power production which will result in reduced fuel cost and emissions. Although the application of hybrid propulsion systems has potential when considering energy savings, it requires an additional investment cost compared to conventional propulsion systems which could be seen as an initial obstacle.

## 1.1 Objective

The main objective of this thesis is to investigate the feasibility of hybrid propulsion system and its application on long-liner fishing vessels. The study considers both retrofitting of existing vessel and the building of new vessels. The existing vessel has its limitations with space and arrangement but new vessel is more of an open book. To be able to accomplish the main objective, the thesis will be divided into the following research questions.

- Is the operational profile of a long-liner fishing vessel compatible with ship types suitable for the application of hybrid-propulsion technologies?
- How will the operational and investment cost change with hybrid and diesel electric propulsion system?
- Is it feasible to invest in hybrid or diesel-electric propulsion system today or will it be in the future?

## 1.2 Methodology

In order to achieve the main objective of this thesis, several steps need to be performed, where the principle of the methodology can be seen in Figure 1.1. These steps included:

- Literature study concerning hybrid propulsion systems applied on ships and its configurations in general and look into recent trends for the propulsion and power plant for new built long-liners. Additionally, an investigation considering battery systems available on the markets today for specific use in marine applications.
- Performing real time measurements of the auxiliary engines on-board the long-liner fishing vessel Jóhanna Gísladóttir GK in order to obtain the auxiliary power requirements and its distribution during operation.
- Using an empirical approach to model the propulsion power requirements of the long-liner fishing vessel Jóhanna Gísladóttir GK and its distribution during operation.
- Developing mathematical models for three different propulsion systems:
    - Baseline system, representing the current design
    - Diesel-electric system

    - Hybrid propulsion system
- Concept generating of alternative propulsion and power plant system applied to Jóhanna Gísladóttir GK, based on the information gained from the literature study.
- Evaluation and comparison of the current and generated alternative designs by using a modelling tool.

*Figure 1.1 The method procedure*

## 1.3 Limitations

This thesis is primarily based on measurement and estimation of the Icelandic long-liner fishing vessel Jóhanna Gísladóttir GK. Due to the nature of this thesis, some limitations and assumptions were to be made. More technical and detailed limitations are discussed in Section 3.

Limitations and assumptions;

- Maintenance requirements are excluded out of the system comparisons.
- Environmental effects of the systems are not considered. The issues related to the end-of-life handling of batteries and other system components is not taken under consideration.
- Human factors are not considered.

# 2 Background

In this section, fishing methods are described briefly. Further, the concept of diesel-electric and hybrid diesel-electric propulsion and power plant is discussed. Finally, general requirements and characteristics for lithium-ion batteries are presented.

## 2.1 Fishing and fishing vessels

Fishing vessels are defined as a vessel with a special purpose. In order to obtain profit from the catch, fishing operators need to take risks in a costly and complicated business. The fuel consumption of a fishing vessel depends on the operational profile of the vessel and on the fishing method, but the fuel cost could be as much as 20-30% of the total value of the catch (Van Beek and Van der Steenhoven, 2005). The main focus has not been to evaluate the actual power usage of different types of fishing vessels where the energy consumption of the propulsion system and auxiliary system has been assessed (Thomas et.al. 2009). The dependency on fossil fuels, the need to reduce emissions and the changes in migration routes for target species are some parameters that have changed energy efficiency from an option to a necessity, in order to maintain the industry’s competitiveness (Basurko et.al. 2013).

The traditional propulsion system for fishing vessels today is a mechanical shaft line arrangement. The design and type of the propeller and the presence of a nozzle depends on the fishing method, including fishing gear of the vessel, as well as if delivering frozen or fresh catch. (Van Beek and Van der Steenhoven, 2005).

There are several fishing methods used today in the commercial fishing industry. The choice of the method employed is based on a number of parameters such as target species, seasonality, quality of the products, quotas etc. Some of the major fishing methods and gear for the commercial fishing used today are pure seines, trawling, gillnets and lines outfitted with baited hooks (Nédélec and Prado, 1990).

Purse seining is a fishing technique that catches fish trough a surrounding net from both sides and underneath, which prevents the fish to escaping by diving downwards. It is the purse line that closes the net at the bottom, and in general, these nets are supported by a float line at the surface. Usually, these nets are operated by a single vessel, but could also be operated by two, dependent on size of the nets as well as the size vessels (Nédélec and Prado, 1990).

Trawling is a fishing method where the nets are towed, either by one or two vessels. In general, trawling could be subdivided into two different types of fishing dependent if it is in use at the bottom or in mid-water. The nets are in general cone shaped where they are closed by a bag or are extended by wings at the end of the net opening. Bottom trawls are designed so they can work near the bottom where the lower edge of the net opening is outfitted with a thick protection line ballasted with weights, usually covered by some sort of rubber disc or equivalent (Nédélec and Prado, 1990). Mid-water trawls are often designed to be operated in various depths included surface where the depth often is controlled by a net sounder. These trawls are in general larger than bottom trawls and may be towed by two vessels (Nédélec and Prado, 1990).

Gillnets and entangling nets are used as a fishing method, often in coastal waters. General usage could either be as drifting gillnets or as gillnets fix positioned thru weights and assessable by a floating buoy. This method is generally used by boats or smaller vessels and only in a minor scale in the commercial fishing industry.

The fishing method including lines outfitted with baited hooks is often referred to as long-line fishing. This method is used in a number of variations regarding the hook and line configurations and is employed by a number of different vessels. It could either be small boats where the line hauling and dropping is performed by hand or by large vessels outfitted with mechanical processing lines. This method is in general considered to be environmentally friendly with a catch of very high quality (Basurko et.al. 2013).

In this thesis, propulsion systems for long-lining fishing vessels will be investigated. The choice of this type of vessels as subject of this thesis depends on their complex operational profile. Speed variety is quite large and some energy storage or steps in its power production might make it more efficient. Therefore the feasibility of a diesel electric and hybrid systems will be investigated for this fishing method.

## 2.2 Diesel-electric propulsion

Diesel-electric propulsion could be suitable when there are large variations in power demands during operation. Often, the design of this kind of systems differs between different ship types due to different purposes and operational profiles. This implies that the propulsion and power arrangement needs to be considered case by case, but the common objective is to increase efficiency with the goal of lower fuel consumption and reduced emissions and operational cost (MAN Diesel and Turbo, 2014).

The reason why it is possible to increase the efficiency is simply that the generating sets are designed in such way that they are able to operate at as a high load as possible during the operational time. For example, at low loads and dependent on configuration, one generating set could be shut down so the remaining genset or gensets runs at as high loads as possible, instead of a system that in overall runs at part loads. Other advantage of diesel-electric system could increase redundancy in case of a breakdown, flexibility in the arrangement of the system and maintenance could be performed without disturbing operations. Further, the electrical motors could be run precisely in terms of speed, which make it possible to operate the propeller in its best condition (Molland, 2008)

Disadvantages of diesel-electric propulsion is on the other hand higher transmission losses compared to a diesel mechanical system due to the increased amount of components in the power train, i.e. generators, power converters and electrical motors. Values in Table 2.1 are typical transmission losses for common components. In general the increased amount of components also results in higher initial investment cost. It should also be noted that the flexibility as well as the efficiency gain of a diesel-electric system is limited due to the amount of gensets installed with a question of space and capital cost of the system. It is therefore essential to have detailed information about the vessel and its operation (Woud and Stapersma, 2002).

*Table 2.1 Table showing typical transmission losses for different components (MAN Diesel and Turbo, 2014 and SNAME, 1990).*

| Typical transmission losses Components | |
|---|---|
| Generator | 3% |
| Switchboard | 0.2% |
| Frequency Converter | 1.5% |
| Electrical Motor | 4% |
| Gearbox | 1% |
| Shafting | 1% |

## 2.3 Hybrid propulsion

The definition of hybrid propulsion[1] in this thesis is referring to a system that combines energy storage and energy supply to the propulsion and power plant. The energy storage is here referring to batteries and is chosen due to the possibility to store a large amount of energy at reasonable cost compared to other storages methods (Dedes et.al., 2012). Hybrid technology where a prime mover is combined with energy storage and supply possibilities is in use in variety of areas, such as in the locomotive industry and the automotive industry. In the marine industry historically, there are primarily submarines that have used electrical power supply and storage in their propulsion plants (DNV GL, 2013).

Due to the rapid development in battery technology, possibilities of larger hybrid diesel-electric systems including batteries for application on ships have occurred. The principle of hybrid systems for propulsion and power plant is to provide energy as efficient as possible in terms of optimized combination of genset and battery usage. This combination could be performed in several ways, either by operating the genset or gensets as close to peak efficiency as possible and boost the system if needed with a help of a battery. Another way is to provide energy from the battery slowly until it is discharged and then switch to genset use for power supply and charge in an alternating mode during operation.

The hybrid diesel-electric system has the same initial drawbacks as for the diesel-electric system regarding additional components and higher transmission losses compared to a diesel mechanical propulsion system. This implies that the knowledge of the operational pattern in combination of a well-designed propulsion and power plant is crucial.

Some recent projects were different hybrid propulsion and power plant systems have been applied are listed below (DNV GL, 2014b):

---

[1] In the shipping industry, hybrid propulsion is often referred to a mechanical/electrical hybridization without batteries. In this thesis, hybrid propulsion is a diesel-electric propulsion plant including batteries.

- Scandlines, has converted four of their passenger ferry’s into hybrid battery systems, 2013
- NORLED, has converted two of their passenger ferry’s into hybrid battery systems, 2013 and 2014,
- Eidesvik, has converted one of their offshore supply vessels into a hybrid battery systems, 2013
- Østensjø, new built offshore supply vessel with hybrid battery systems, 2013
- Fafnir Offshore, is building an new offshore supply vessel with hybrid battery systems, 2015

The different vessels that are listed above operate in a variety of areas and the hybrid configuration is thereby individually designed. A recent trend in the shipping industry when considering energy storage is to utilise lithium-ion batteries and their technology.

## 2.4 Lithium-Ion Batteries

The market for lithium-ion batteries has grown rapidly in the last two decades and stands for almost three-quarter of the sales value for secondary batteries[2] (Reddy, 2011). Applications for lithium-ion batteries range from mobile phones and laptops to cars and to hybrid locomotives. The use of lithium-ion has come to be the standard for a broad range of products and industries which implies that the battery performance is continuously improving.

The price for battery packages in the automotive industry is predicted to drop from the current price of 500 USD/kWh to 200 USD/kWh before 2020 and down to 160 USD/kWh by 2025, see Figure 2.1. Today a typical cost for battery package for marine applications is 1000 USD/kWh for a battery with similar qualities as in the automotive industry (DNV GL, 2014a).

The price trend predictions of lithium-ion batteries in kWh are based on increased manufactured volumes and decreased cost in the supply chain. Further, the technology is improving constantly where the energy density is increasing with the result of decreased cost in kWh. It should also be mentioned that additional cost reductions normally occur when entering new markets. As could be seen in Figure 2.1, the trends can be visualized for the automotive industry, where the blue dots are based on the current and future predicted price.

---

[2] Batteries able to discharge/charge a number of cycles compared to primary batteries that only could be used ones.

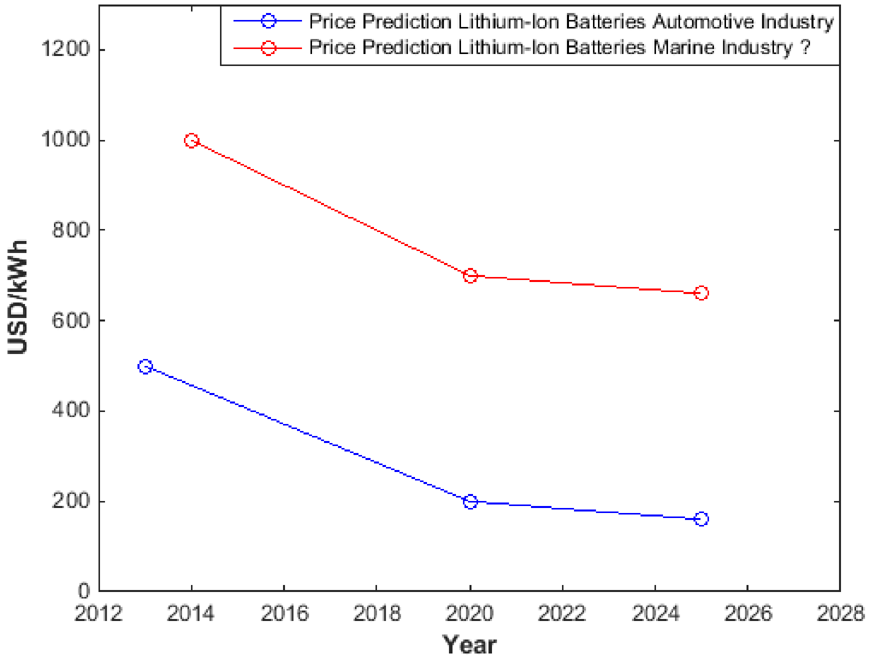

*Figure 2.1 Current price along with a price prediction for Lithium-Ion Batteries(DNV GL, 2014a)*

In Figure 2.1 it should be noted that the only number found on battery prices for the marine industry is the number for current price in 2014. The forecasted price in the graph for the marine industry follows the predicted price for the automotive industry and the current difference between the industries. This price difference could be assumed to be because of environmental requirements and lower production volumes compared to the automotive industry.

Some general advantage and disadvantage of lithium-ion batteries are presented here below (Reddy, 2011).

Major advantages;

- Battery cells are sealed which implies that no maintenance is required
- Long cycle life
- Broad temperature range when considering operation
- Low self-discharge rate
- Rapid charge capacity
- High specific energy and energy density

Major disadvantages;

- High costs
- Degrades at high temperatures
- Protective circuitry is needed
- Capacity loss when overcharged
- Possible venting when crushed
- May become unsafe if rapidly charged at low temperatures

If a comparison is made between traditional batteries applied on ships such as lead acid and nickel based batteries with water based electrolytes, lithium-ion batteries have two to eight times higher energy per weight unit, see Figure 2.2 (DNV GL, 2013). This combination of high energy density and the usage of flammable electrolytes increases the demands with regards to the design for a safe and secure operation. When designing a battery system for maritime applications, factors such as safety, reliability and lifetime of the system are of outmost importance. This requires good quality of components in the system, where it is as important to secure the quality of the total integrated system as it is for each individual component.

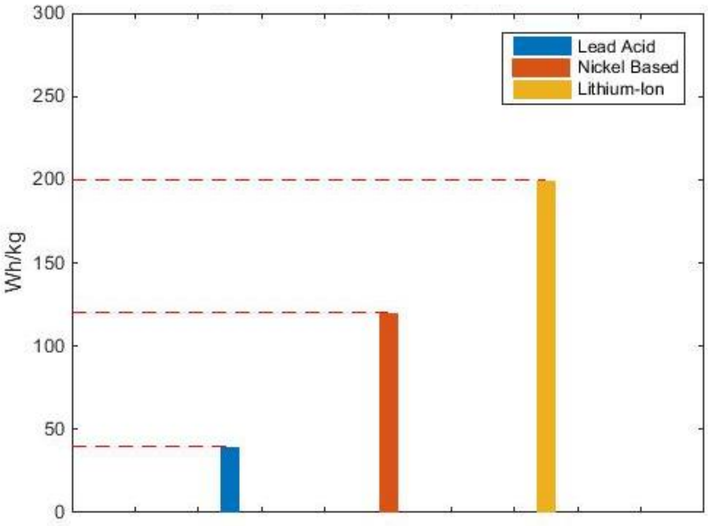

*Figure 2.2 Specify energy of battery systems.*

Lithium-ion systems require monitoring of each cell in the system at all times where voltage, current and temperature are crucial factors. Further, it is of great importance to implement cells with equal properties into the battery package. The reason why it is so important with equal properties of the cell is that the package needs to be designed with the weakest cell in mind (DNV GL, 2014a). Large variations on properties of cells will result in overdesign and make the cell balancing even more challenging.

Due to the characteristics of lithium-ion cells, extensive consideration needs to be done when putting the cells into battery modules and designing the battery system. Battery management system should control the following parameters quoted from the Tentative Rules for Battery Power:

- Internal charge/discharge of the battery
- Battery temperature
- Cell balancing

Further, the following parameters shall be measured and indicated at local control panels or in remote workstations:

- Cell voltage
- Cell temperature
- Battery string temperature
- Ambient temperature
- Electrical insulation resistance

It is also of great importance that the battery management system communicates with the external power management system, where normal operations and situations when faults occur are well specified (DNV GL, 2012).

As can be seen the battery management system is of great importance to ensure safe operations and to maintain a battery system that is able to fulfil its intended function during its operational lifetime.

When the arrangement of the batteries is designed it should be done in a way it will not lead to a loss of propulsion or auxiliary power if explosions or other breakdowns occur. General recommendations for the battery system include the choice of a location that protects it from heat and other harmful sources that could influence the system and its component. If possible the battery space should be in an enclosed room. (DNV GL, 2012)

General aspects that need to be considered when designing the battery system to ensure safe, reliable and cost effective operation of the vessel could be summarized as follows;

- Experience of the battery supplier and their system
- High quality cells, where the battery system is well documented
- Extensive temperature and thermal management system

When sizing the battery system it is of great importance to identify patterns of relevant load, charge and discharge cycles. The battery systems lifetime is the main driver when deciding how the batteries could be used and the lifetime is directly connected to the cell temperature of the batteries. For example if the battery is cold, it is possible for high discharge for a short time, but the same procedures would result in degradation of the battery system and its lifetime when the cells are warm. For designing battery systems where it is assumed that they will be operated for 24 hours without any cool down, the following initial assumptions should be made;

- Range of use is 60-90% of the battery
- Maximum charge is 90% of the battery package
- Maximum long time discharge is 30%
- Storage temperature of the battery package is 15°C

The assumption is based on a planned lifetime of ten years of the battery system and could be used as initial design parameters in a conservative manner. [3]

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[3] Jóhannes Jóhannesson(Naval architect currently working on a ferry project that includes battery system)

# 3 Method

In this section, the vessel under consideration, Jóhanna Gísladóttir GK, is presented. The methods used for the measurements of auxiliary power and estimation of propulsion power are described. Finally, the input for modelling the current design together with the alternative designs is presented.

## 3.1 Description of the case study

The vessel that is under consideration, Jóhanna Gísladóttir GK, see Figure 3.1 is an Icelandic long-liner fishing vessel and is owned and operated by the ship-owner Visir hf. The vessel was originally built in the late 60´s as a purse seiner for the booming herring fishing in Iceland. Due to the collapse of the domestic herring stock in the late 60´s the vessel was converted a few times and operates currently as a long-liner. The history of modifications and upgrades on this vessel is largely due to changes in regulations and different fishing quotas being associated with the vessel[4]. This approach has on paper resulted in an ageing fishing fleet in Iceland, with an average age of 27 years (The Icelandic Ocean Cluster, 2014).

*3.1 Jóhanna Gísladóttir GK in the port of Grindavík.*

Recently, the vessel´s steel structure was upgraded and in 2005 the vessel was equipped with a new and more effective processing line. According to the fleet manager of Visir hf, the processing line is considered to be similar to if the same investment was made today. Therefore the company sees great opportunities to invest further in the ship[5]. The next step is to invest in a new and more efficient propulsion plant. The investment concerns both the auxiliary engines and main engine.

The reason Jóhanna Gisladóttir GK was chosen as a reference model is that according to Vísir hf the processing line on board is very close to what would been put on-board today[4]. For a new long-liner the main particulars, propeller and other things that affect the propulsive power would be different but the operational mode would be similar and therefore this study should be a good starting point in a new design.

---

[4] Karl Lúðvíksson(Naval Architect at Navis ehf)

[5] Kjartan Viðarsson(Fleet manager at Visir hf)

*Table 3.1 Main Particulars of Jóhanna Gísladóttir GK.*

| | |
|---|---|
| Type | Long-liner Fishing vessel |
| Flag | Iceland |
| Length over all, LOA | 56.80 m |
| Length between perpendiculars, LPP | 50.70 m |
| Draft | 3.70 m |
| Depth to main deck | 4.00 m |
| Depth to shelter deck | 6.20 m |
| Moulded Breadth | 8.00 m |
| Displacement | 842 m³ |
| Fish hold | 550 m³ |
| Accommodation | 16 |
| | |
| Design speed | 10 knots |
| Max speed | 12 knots |
| | |
| Main Engine | 1x Wichmann 1007 kW (1350 Hp) |
| Auxiliary Engine | 2x Mitsubishi 6D24-TC 181kW |
| | |
| Propeller | 1x Finnoy CP-Propeller |
| Tunnel Thrusters | 2x Hydraulic, type and size unknown |

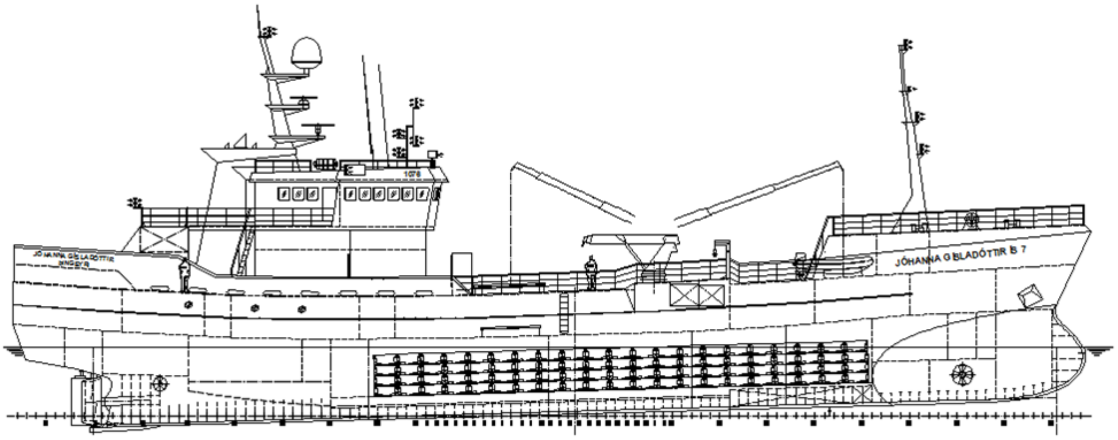


*Figure 3.2 Side view from Jóhanna Gísladóttir GK GA-Plan.*

## 3.2 Estimation of required main and auxiliary power

A ship model is made to investigate the operational pattern of Jóhanna Gisladóttir GK, which will make it possible to estimate and calculate the bunker consumption.

### 3.2.1 Measurement and estimation procedure

The model consists of two main parts: the propulsion power and the auxiliary power. The propulsion power estimation consists of a power requirement assessment for the propulsion system by using empirical formulas in conjunction with speed data received from AIS data where service allowance is added to account for weather and operational related parameters. Further, calculations and estimations of the propeller efficiency and transmission losses are included as can be seen in Section 3.2.2. The auxiliary power estimation is based on real-time measurements of the vessels power consumption see Section 3.2.3. These two main parts are then combined into a ship model as can be seen in Figure 3.3.

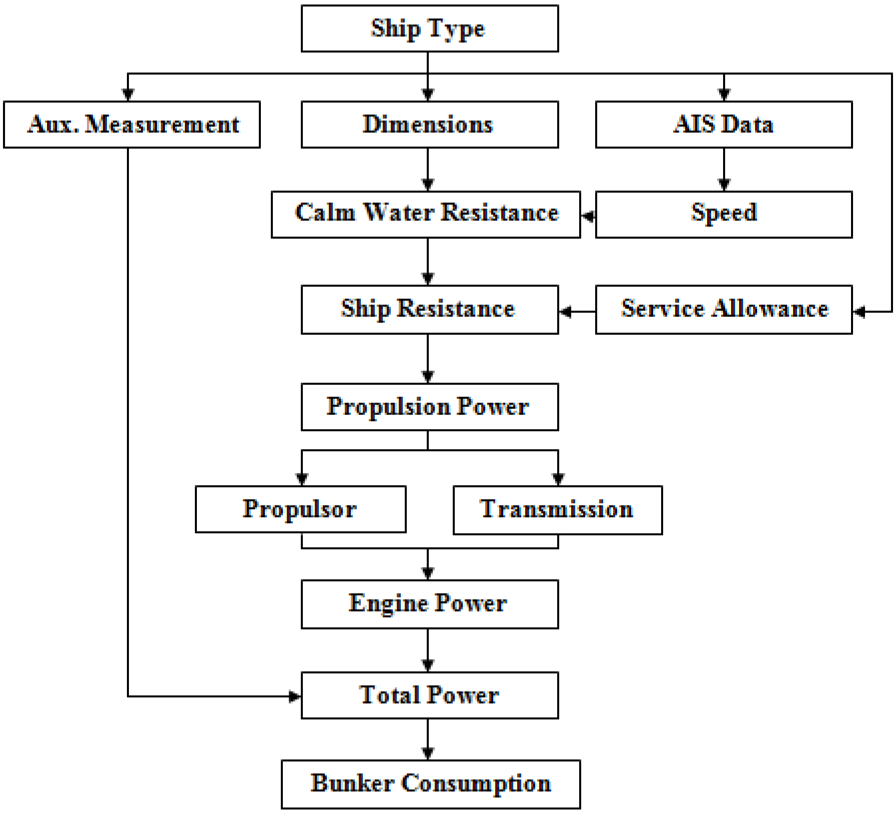


*Figure 3.3 Measurement and estimation procedure.*

### 3.2.2 Ship resistance and propulsion systems

There are several ways to estimate the propulsion power requirements of a vessel and thereby estimate the power distribution. The method chosen is dependent on a number of parameters such as time, cost and accuracy, if the vessel to be analysed is a completely new design or an existing vessel.

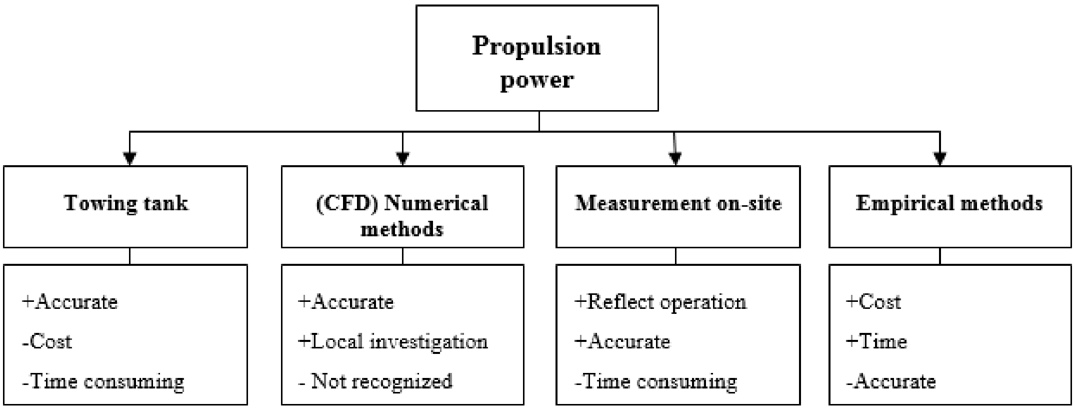


*Figure 3.4 Methods to estimate required propulsion power.*

Towing tank tests can be done on a model of the vessel, numerical methods can be used by utilizing CFD tools or the delivered power can be measured on-site if an existing vessel is analysed. Further, empirical methods can be used based on statistical data. The different methods presented above have advantages and disadvantages when considering their applicability and are in general used at different stages in the design process. For a schematic presentation see Figure 3.4.

Towing tank test of models to evaluate the resistance of ships has a long history and the basic principles used today were used in the same manner in the middle of the 19th century during the days of William Froude. There have however been developments over time where procedures for model scaling and measurement devices have improved. The method of a towing tank test is still considered to be the most accurate method for resistance prediction and power estimation of vessels, but it is an expensive method due to the somewhat extensive cost of model building and testing, which also is rather time consuming (Larsson and Raven, 2010).

The method of numerical predictions of the resistance and power prediction of ships by using CFD tools has been growing rapidly. The reason for this development is largely the revolution in computational power during the last two decades, combined with huge development and progress in numerical techniques and modelling of ships. The advantages of the method are its accurate results and suitability for local investigations of the hull, but is still considered to be too inaccurate compared to a towing tank test (Larsson and Raven, 2010). It should be mention that the method requires work when considering meshing the hull in combination with the simulation of the case for a number of conditions.

If an existing vessel is under evaluation, propulsion power distribution could be decided by performing a real time measurements of the shaft line on-board. The results of those measurements will be the load of the shaft and its distribution. The advantage of this method is that the measurements are performed in real time and on-site which gives the most accurate results considering the operation of the vessel compared to the other methods presented in this section. The main disadvantage of this method is that it is rather time consuming and cannot be performed if the vessel is yet to be built.

Empirical methods are often used when the power requirements of the vessel need to be investigated at the initial stages of the design process. In general there are two different approaches: empirical methods based on systematic series or methods based on statistic evaluation of unsystematic data (Larsson and Raven, 2010). Methods used depend on the ship type under consideration and what type of hull, e.g. displacement or planning. Advantages by using empirical formulas is that the formulation is often easy, which means that fast evaluation could be accomplished when the main parameters of the hull is known. It is also a convenient method if the main parameters of the hull need to be evaluated quickly, which in general results in a cost and time effective solution (Bertram, 2000). Disadvantages are less accuracy compared to the methods described above and the loss of the ability to select a method that fits the vessel under consideration best.

#### 3.2.2.1 Resistance estimation

In this thesis, the resistance and effective power is estimated by the empirical method proposed by Holtrop and Mennen (Holtrop and Mennen, 1982).The Holtrop and Mennen method is based on regression analysis of model experiments and full scale measurement data from ship trials of 334 different ship types. The method is applicable on displacement hulls type vessels such as tankers, cargo ships, trawlers and ferries etc. (Larsson and Raven, 2010). The input data when using the method is based on the main dimensions and form coefficients of the vessels hull. The Holtrop and Mennen method is widely used in the industry, where it is included in most of the CAD packages used for ship design today (Larsson and Raven, 2010).

The reason why Holtrop and Mennen method is used to model Jóhanna Gisladóttir GK is due to its general applicability (Bertram, 2000). Further, the method provides the possibility to estimate reasonable power prediction results for different operational speeds of the vessel in a time effective manner.

Calm water resistance estimated with Holtrop and Mennen consist of several components (Holtrop and Mennen, 1982) and can be subdivided according to Equation (3.1).

$$R_{Total} = R_F(1 + k_1) + R_{APP} + R_W + R_B + R_{TR} + R_A \qquad (3.1)$$

Where:

$\mathrm{R_F}$ - Frictional resistance due to ITTC-57 friction formula.

$\mathrm{k_1}$ - Form factor describing the viscous resistance of the hull form.

$\mathrm{R_{APP}}$ - Resistance of appendage.

$\mathrm{R_W}$ - Wave making and wave breaking resistance.

$\mathrm{R_B}$ - Additional pressure resistance of bulbous bow near the water surface

$\mathrm{R_{TR}}$ - Additional resistance due to immersed transom stern

$\mathrm{R_A}$ - Model-ship correlation resistance

$R_{Total}$ -Total resistance

The effective power can then be calculated by using the total resistance and the ships speed, as can be seen in Equation (3.2). The effective power is defined as the power needed to tow the vessel at a certain speed.

$$P_E = R_{Total}V_s \qquad (3.2)$$

Where:

$V_s$- Ships speed

$P_E$ - The effective power

#### 3.2.2.2 Service allowance

To determine the installed power for the main engine or alternatively engines, a service allowance needs to be taken into consideration when designing the propulsion system. The service allowance should account for parameters that are weather and operational related such as sea state, wind, current and hull fouling. The service allowance is defined as follows dependent on the operational area of the vessel (Kristiansen and Lützen, 2012);

- North Atlantic route, westbound 25-35%
- North Atlantic route, east bound 20.25%
- Europe alt. Australia, 20-25%
- Europe-Eastern Asia, 20-25%
- The Pacific routes, 20-30%

Notable is that these values should only be seen as tentative values for guidance. These values are also dependent on a number of parameters that relate to the ship type such as size and hull shape. This implies that in general, smaller ships have a relatively higher service allowance compared to larger ships and more slender hull form will result in less service allowance. The formulation of the service allowance can be seen in Equation (3.3).

$$P_{E,,service} = P_E(1 + \frac{Service\ allowance\ \%}{100}) \qquad (3.3)$$

Due to the operational area of Jóhanna Gisladóttir GK, the North Atlantic route and westbound number of 35% is used in a conservative approach.

#### 3.2.2.3 Propeller performance

The Wageningen B-series is used when screw propellers need to be evaluated (Oosterveld and Oossanen, 1975) and is probably the most extensive and widely used propeller series in the ship design process (Carlton, 2007).The Wageningen B-series are based on open-water test of 120 screw propellers analyzed with multiple polynomial regression analysis at the Netherlands Ship Model Basin in Wageningen (Bernitsas et.al, 1981).

The method is mainly used when evaluating FP-propellers but is also used widespreadly when investigating CP-propellers since there is lack of data regarding systematic series of CP-propellers (Dang J. et.al., 2012). By applying the Wageningen series for the vessel under consideration, it is possible to model the propeller in a proper manner considering the pitch of the propeller. This will result in the open-water propeller efficiency at certain speeds for the vessel and thereby define different operational and off-design conditions into the ship model.

Jóhanna Gísladóttir GK is outfitted with a CP-propeller, with some predictions and estimations needed to be done in order to obtain an indication about the usage of the propeller. The result was to use the Wageningen B-series to be able to decide the most efficient pitch for different speeds of the vessel and thereby simulate the gut feeling of the master onboard to get as close to its operation as possible.

The open-water characteristics are expressed in the form of the torque coefficient and thrust coefficient in terms of the polynomial of the advance coefficient, blade area ratio, pitch diameter ratio and number of blades. The input used here when using the model is the propeller diameter, the number of blades, blade area ratio and the revolutions per second of the propeller for the vessel under consideration, where the numbers used can be seen in Table 2-3. It should be noted that the nozzle installed on the vessel is not included in the calculations when estimating the characteristics of the propeller. The simulation is performed using the input conditions of speed and resistance to find the most efficient pitch of the propeller at certain speeds. The conventional expression for the open-water propeller efficiency can be seen in Equation (3.4).

$$\eta_O = \frac{J}{2\pi}\frac{K_T}{K_Q} \qquad (3.4)$$

Where;

$K_Q$- Torque coefficient

$K_T$ - Thrust coefficient

$J$ - Advance Coefficient

The torque, thrust and advance coefficient are conventionally expressed as in Equations (3.5-3.7).

$$K_Q = \frac{Q}{\rho n^2 D^5} \qquad (3.5)$$

$$K_T = \frac{T}{\rho n^2 D^4} \qquad (3.6)$$

$$J = \frac{V_A}{nD} \qquad (3.7)$$

Where;

$T$- Propeller thrust

$Q$- Propeller torque

$\rho$- Fluid density

$n$- Propeller revolutions per second

$D$- Propeller diameter

$V_A$- Advanced velocity

As mention earlier in this section, the thrust and torque coefficient can be expressed in polynomials of the parameters connected to speed and the propeller main particulars here (Oosterveld and Oossanen, 1975).

$J$ - Advance coefficient

$A_E/A_O$ - Blade area ratio

$P/D$ - Pitch diameter ratio

$z$ - Number of blades

A mathematical model is made where the procedure described above is used. The pitch of the propeller could then be optimised with the input values in Table 3.2.

*Table 3.2 Input values for the Wageningen B-series method.*

| | |
|---|---|
| Propeller diameter | 2.1 m |
| Number of blades | 4 |
| Blade area ratio | 0.7 |
| Pitch/diameter ratio (design value) | 0.8 |

#### 3.2.2.4 Engine brake power

To estimate the final engine brake power is a complex task where many parameters need to be kept under consideration. In general, the engine brake power can be estimated as in Equation (3.7**Error! Reference source not found.**, where it includes efficiencies for different subsystems dependent on configuration. For example gearbox and shaft for a diesel mechanical system or including additional transmission losses from components such as generators, power converters and electrical motors as in a diesel electric system.

$$P_B = \frac{P_{E,service}}{\eta_R \eta_O \ \eta_T \eta_H} \qquad (3.7)$$

$$\eta_R \ = 0.9922 - 0.05908 * \frac{A_E}{A_O} + 0.07424(C_p - 0.0225 * LCB) \qquad (3.8)$$

$$\eta_H \ = \ \frac{1-t}{1-w} \qquad (3.9)$$

Where:

$\eta_R$ – Relative rotative efficiency

$\eta_O$ – Open water propeller efficiency

$\eta_T$ – Transmission efficiency

$\eta_H$ – Hull efficiency

$t$– Thrust deduction factor

$w$ – Wake factor

The thrust deduction factor, wake factor and relative rotative efficiency are calculated according (Holtrop and Mennen, 1982). The open water propeller efficiency is calculated with the Wageningen B-series as could be seen in section 3.2.2.3. For the transmission efficiency, it is dependent on the propulsion system and its configuration and will be defined for each system that will be analysed.

### 3.2.3 Auxiliary Power measurements

The auxiliary power requirements include hotel facilities and all other electrical consumers onboard Jóhanna Gisladóttir GK. To measure the auxiliary power requirement onboard the vessel, a meter of the type UMG-604 from the manufacturer Janitza was installed.

The meter constantly measures the current and the voltage of the auxiliary system which make it possible to gather data about the power demand over that time. The data is stored every fifteen minutes as a mean value during that period with a maximum and minimum value also included (Janitza, 2015).

The meter is designed for low-voltage systems up to 300V and the current measurements are performed by using a transformer. For this specific vessels system the transformation is 400/5A. The electrical system on-board is a three phase 230V system where the voltage and current is measured for each phase. With that information the power demand is calculated as can be seen in Equations (3.10) and (3.11).

$$P_{1-3} = I * V \qquad (3.10)$$

$$P_{total} = \sum P_{1-3} \qquad (3.11)$$

Where:

$I$- Current

$V$- Voltage

$P_{1-3}$- Power demand for phase one to three

$P_{total}$- Sum of the power demand for all three phases.

### 3.2.4 Combined power demand

When the estimations for the propulsion power and measurements for the auxiliary power had been done an “average voyage” was made. The “average voyage” consists of the average of both propulsion and auxiliary power for each phase of the voyage for average length of each phase. Phase is the different operational mode of the vessel, line-hauling or line dropping for example. This is done to get simple schematic view of the “average voyage” of the vessel.

When this “average voyage” is used for the simulations that will be described in Section 3.3 a random value is picked from the data behind each phase but time durations of each phase and the whole voyage are used. This method is used to estimate the operational profile of the engines in a better way. If the mean value would only be used, it would always show the same load on the engines for the whole voyage and would not create a clear image of how the current system is operating in the reality.

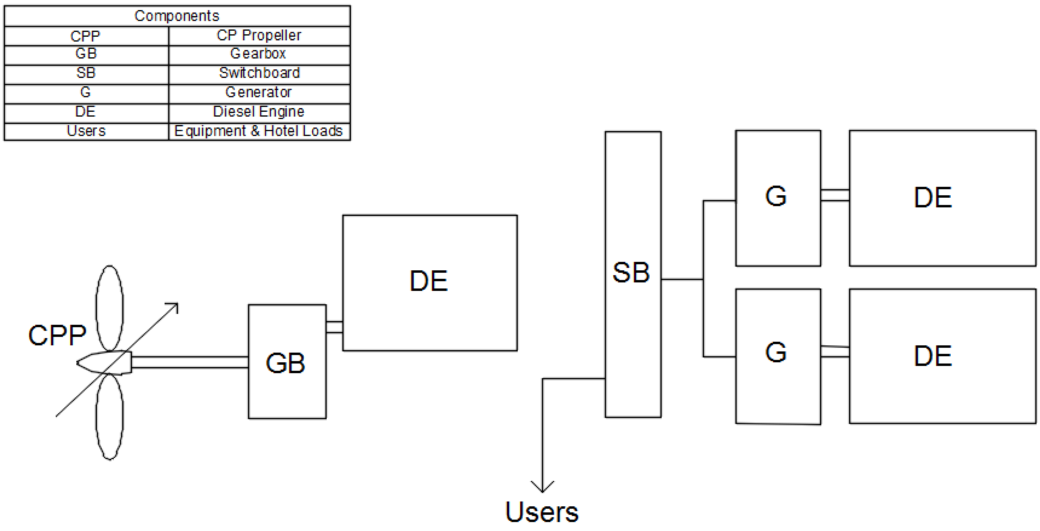
## 3.3 Modelling of propulsion systems

In this sub-section, the propulsion and power plant system will be described. Two alternative systems will be presented, first a diesel-electric and second a hybrid battery system. To be able to compare the current design to alternative designs, a baseline system will also be presented.

## 3.3.1 Modelling of the baseline system

### 3.3.1.1 Description of the base line system

The propulsion and power plant of Jóhanna Gísladóttir GK consist of one main engine and two generating sets. In Figure 3.5 an overview of the engine room layout is shown, where the location for the main engine and the two generating sets is indicated. In Figure 3.6 a principle sketch of the current arrangement is shown which will represent the baseline system that is presented in Section 3.3.1.



| Components | |
|---|---|
| CPP | CP Propeller |
| GB | Gearbox |
| SB | Switchboard |
| G | Generator |
| DE | Diesel Engine |
| Users | Equipment & Hotel Loads |

Figure 3.5 Principle of the current propulsion and power plant system.

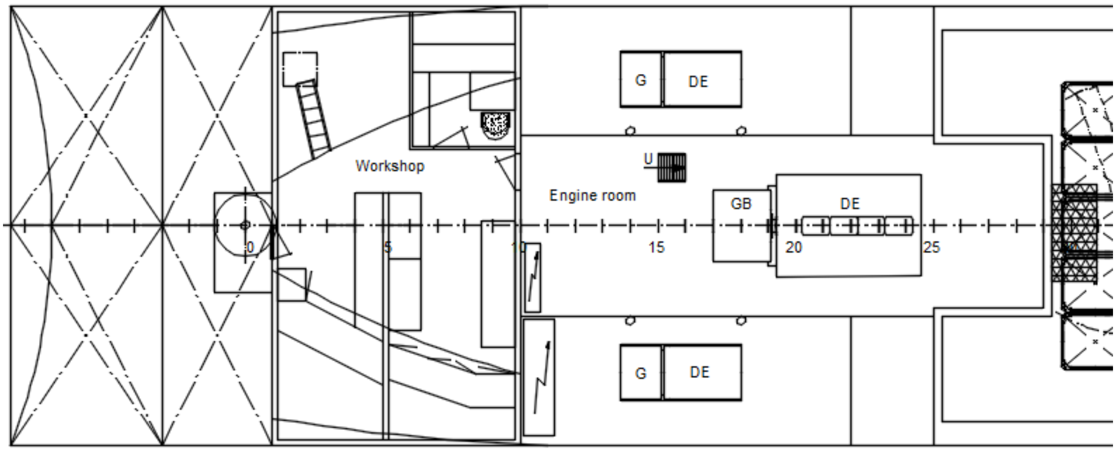


Figure 3.6 GA-plan for current design

The main engine on board Jóhanna Gisladóttir GK was manufactured by Wichmann Engines in Norway and is a two-stroke medium speed diesel engine with four cylinders, see Figure 3.7. The maximum power output of the engine is 1007 kW at 375rpm. The generating sets used during normal operation consist of two four stroke diesel engine with 6 cylinders (6D24-TC manufactured by Mitsubishi Diesel Engines). The power output of the generators are 181 kW at 1500 rpm. Only one generating set is used during normal operation, where the second is used for redundancy in case of break down or during maintenance only.

The propulsion arrangement is a single-screw type where the power from the main engine to the propeller is provided by a shaft arrangement, which includes a reduction gearbox, which results in a final propeller rpm of 275. The propeller consists of a CP-propeller with a propeller diameter of 2100 mm fixed with a nozzle. Additionally, the vessel is outfitted with two tunnel thrusters. One of the tunnel thrusters is located at the stern section of the vessel and the other is located in the forward part at the bow, see figure 3.2. The thrusters system is of hydraulic type where a hydraulic pump is connected to the main engine.

*Figure 3.7 The Wichmann engine onboard Jóhanna Gísaldóttir GK*

#### 3.3.1.2 Simulation of the baseline system

In order to perform a consistent comparison of the designed alternatives of the diesel-electric and hybrid system with the current arrangement, a baseline system was simulated. The baseline system consists of the current auxiliary engine since good fuel consumption and power output numbers where available for it. Further, a 4-stroke medium speed engine with similar power output was chosen to represent the main engine. The engine that was used is from Caterpillar and of type C32 ACERT. (CAT marine, 2009). The reason for this procedure is to make the game fairer and have engines as up to date as for the other design alternatives.

The baseline system was then simulated with the “average voyage” power profile as an input. The total bunker consumption for the “average voyage” along with the operational profile of the baseline system is then generated.

Information about the bunker bought for Jóhanna Gisladóttir GK for a time period was provided by Vísir hf and with that information, the average fuel consumption for one voyage is calculated[6]. This is done in order to compare the result of the baseline system with the current system and thereby validate the simulation. The information below considers the current system;

| | |
|---|---|
| Consumption for January and February: | 124,6 $m^3$ |
| Number of voyages during January and February. | 9 voyages |

---

[6] Andrew Wissler(e-mail from the financial manager at Visir hf)

- Average consumption for these 9 voyages 13,8 $m^3$

The simulator used to reflect the current system with use of the baseline system is explained with a schematic picture as could be seen in Figure 3.8.

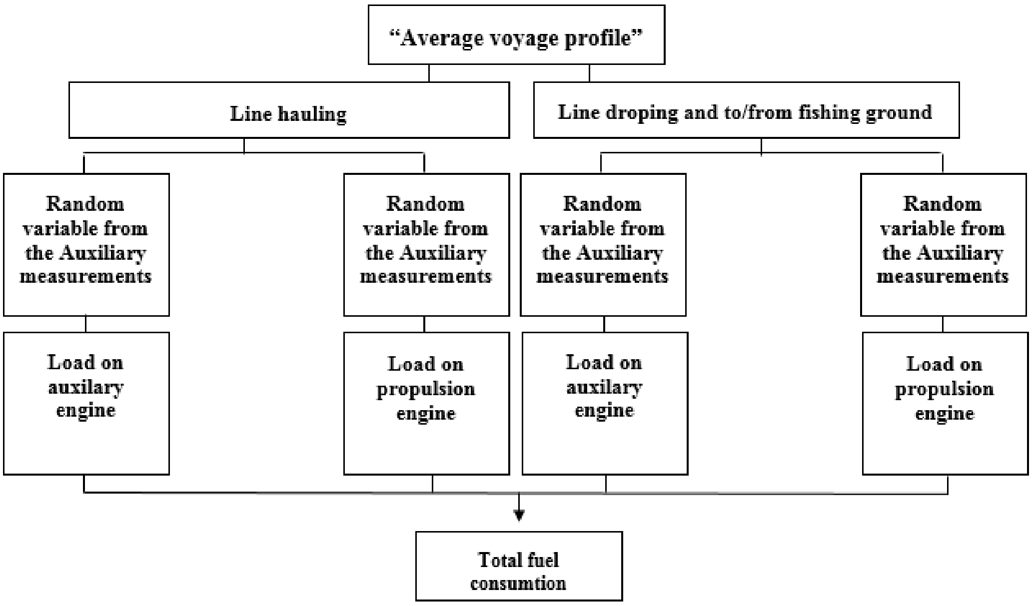


*Figure 3.8 Flow chart of the modelling procedure of the baseline system.*

A random value from the auxiliary data and from the propulsion power data are generated and from that, the load on the engines is calculated. This process is iterated until the average bunker consumption converges as can be seen in Figure 3.9. By following this procedure a load distribution, number of engines running and power demand during time could be mapped in order to generate a realistic case.

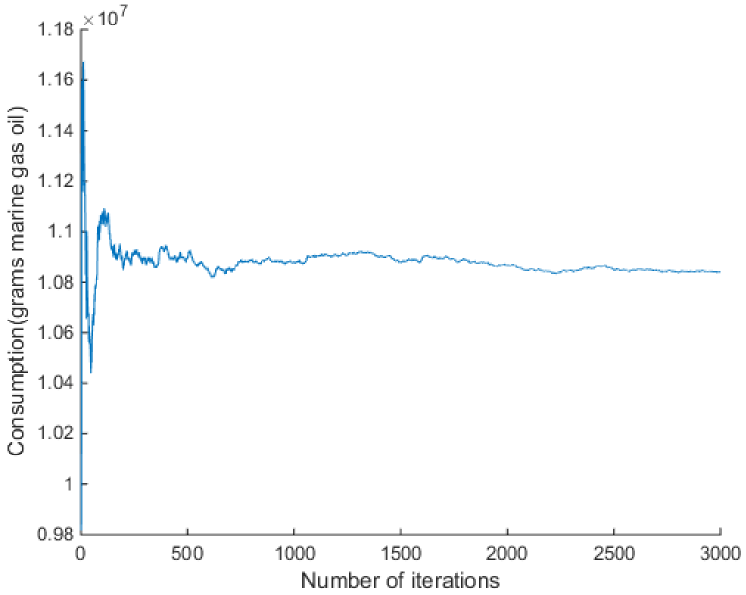


*Figure 3.9 Convergence graph of the mean value for the baseline system.*

To evaluate the modelling procedure, graphs were generated for each iteration. Two examples of these graphs can be seen in Figure 3.10 and 3.11. The required power from each engine is presented along with the power the engines are providing. The load on each engine is presented as well to see if the engine load makes sense.

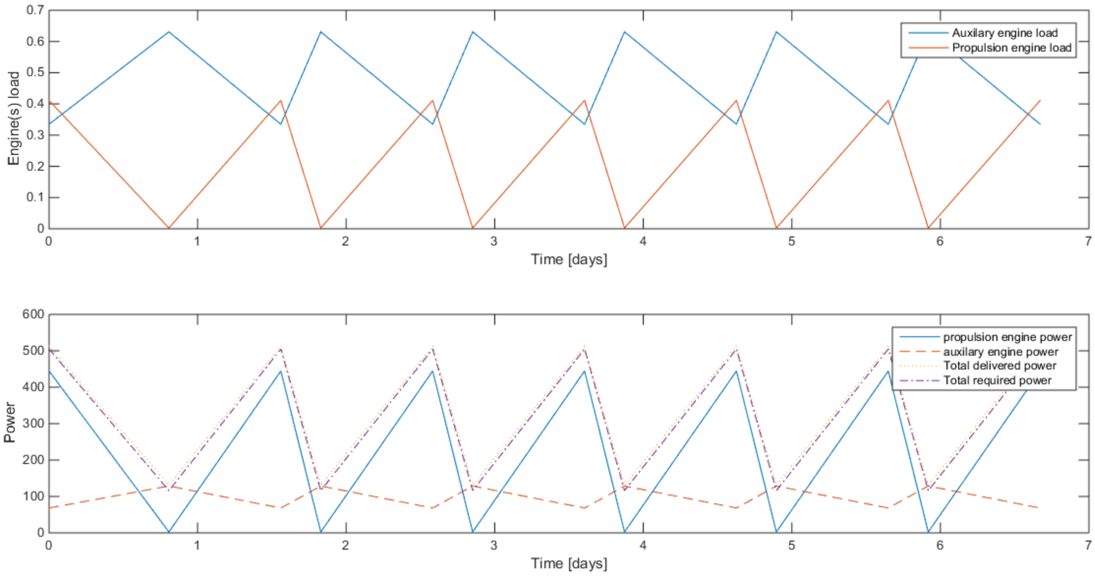


*Figure 3.10 Randomly picked evaluation graph that show one loading case for one iteration*

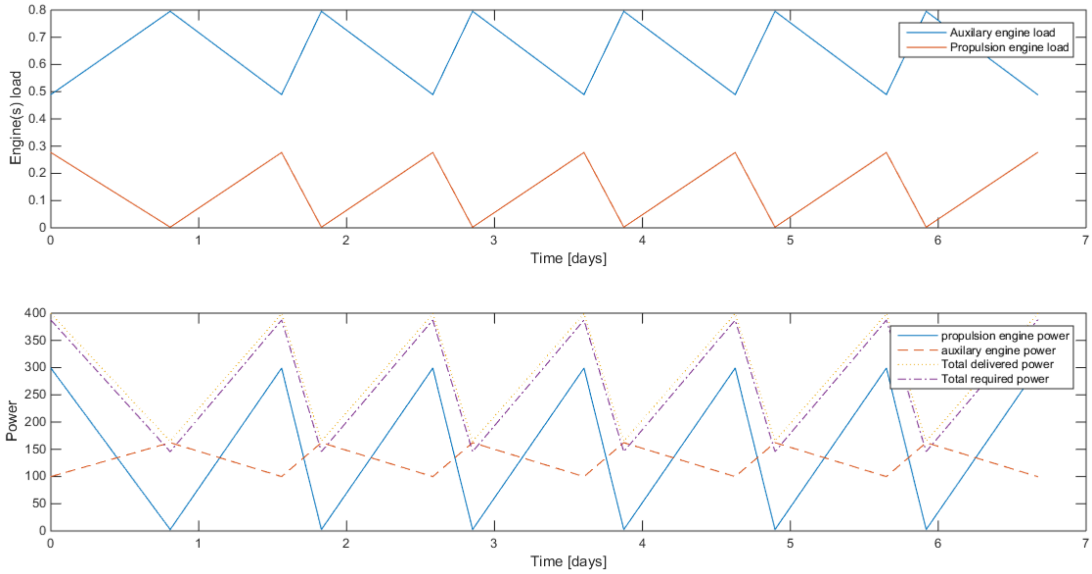


*Figure 3.11 Randomly picked evaluation graph that show one loading case for one iteration*

Figures that present equivalent values as in Figures 3.10 and 3.11 were made for each iteration. This is done to evaluate the simulation code until it is behaving as it should and is representing for a system in the real world. The results from the simulations will be presented in Chapter 4.

## 3.3.2 Diesel-electric system

### 3.3.2.1 Description of the diesel-electric system

For the studied long-liner vessel in this thesis, a design alternative of a diesel-electric propulsion and power plant is developed and evaluated. The diesel-electric arrangement that is proposed is based on an investigation of a similar long-liners propulsion and power plant (Scana Volda, 2015). The proposed design only includes main components and should only serve as a principle of this system type. Information about typical transmission losses within the system can be seen in Table 2.1 (Woud and Stapersma, 2002). Components are chosen from the market to get an overview of principle dimensions and weights.

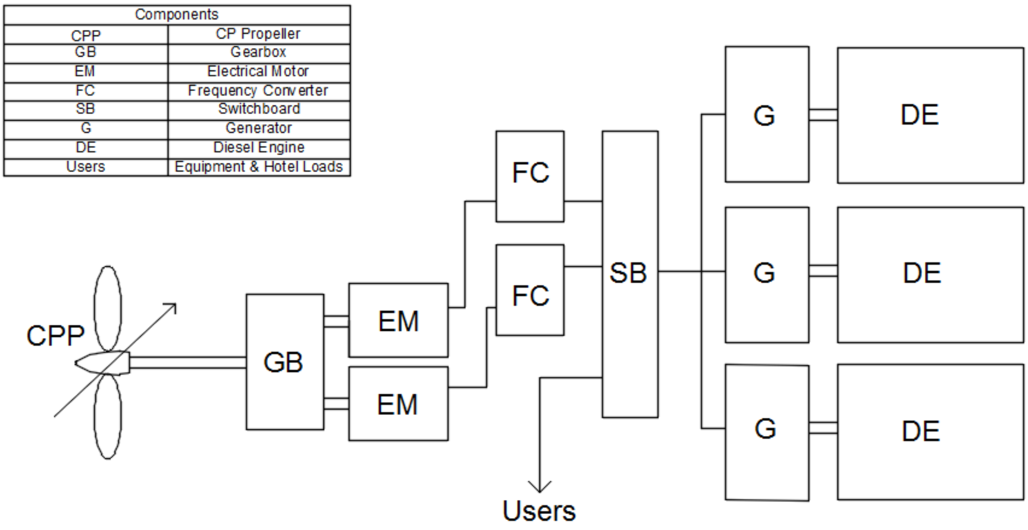


*Figure 3.12 Principle of the diesel-electric main components*

The design proposal for the propulsion and power plant of the vessel under consideration consists of three generating sets and has a maximum power output of 425 kW each (Caterpillar Marine, 2013). Three gensets are chosen in order to have the flexibility in power generation where the number of engines running is decided upon to fulfil the power demands at each time. Further, frequency converters (ABB, 2015a) are included to be able to adjust and control the two electrical motors with regards to RPM. The two electrical motors (ABB, 2015b) have a maximum power output of 500kW each, and were chosen to match the power output of the current main engine on the vessel under consideration. The two electrical motors drive the propeller, through a combined gearbox, were the shaft, propeller and rudder arrangement is based on the existing system. Two motors are needed to fulfil the DNV's rules for redundancy (DNV GL, 2010). This type of arrangement is suitable since it requires minor changes of the existing vessel and of parts such as the shafting, propeller and rudder arrangement. For dimensions of the components see Table 3.3 and for schematic figure see Figure 3.12.

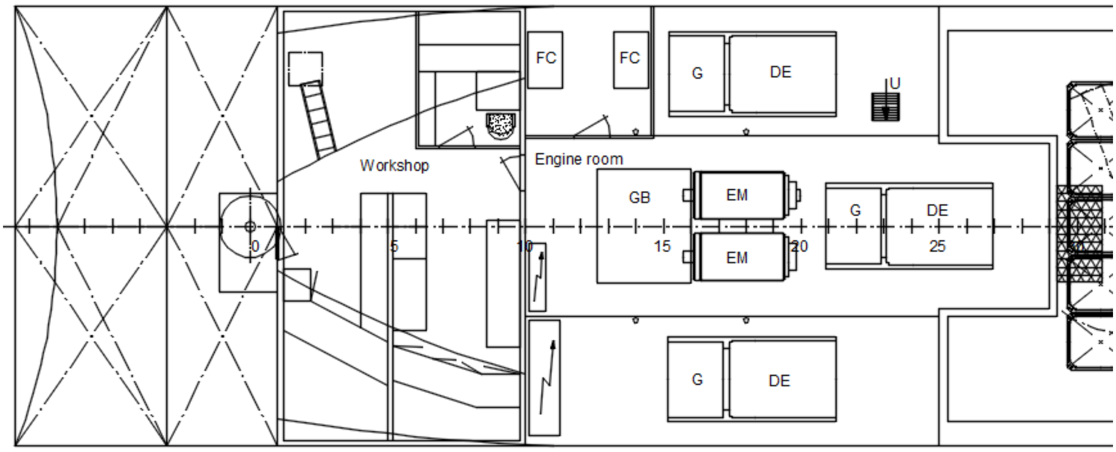


*Figure 3.13 GA-plan for the diesel electric design*

The type of generating sets and manufacturer were chosen due to its appropriate power range but also to obtain tentative information regarding fuel consumption, dimensions and weights. Further, the number of gensets is chosen in a way so it reflects the current propulsion and power plant system regarding its power output, but it is also based on studies of recent new buildings of long-liners. Space requirements with regards to Jóhanna Gisladóttir GK´s engine room was also taken under consideration. It should also be noted that the gensets are fitted in similar positions as the current main engine and generating sets, see Figure 3.6 and 3.13.

*Table 3.3 Main particulars of components*

| Generating Sets | | Electrical Motor | |
|---|---|---|---|
| Type | CAT Marine | Type | ABB |
| Number | 3 | Number | 2 |
| Output [kW] | 435 | Output [kW] | 500 |
| Length [mm] | 3040 | Length [mm] | 1600 |
| Breadth [mm] | 1547 | Breadth [mm] | 702 |
| Height [mm] | 1684 | Height [mm] | 958 |
| Weight [kg] | 4406 | Weight [kg] | 2000 |
| Frequency Converter | | Combined Gearbox | |
| Type | ABB | Type | Scana Volda |
| Number | 2 | Number | 1 |
| Length [mm] | 1030 | Length [mm] | 2010 |
| Breadth [mm] | 644 | Breadth [mm] | 2074 |

| | | | |
|---|---|---|---|
| Height [mm] | 2003 | Height [mm] | 1750 |
| Weight [kg] | 700 | Weight [kg] | 7500 |

#### 3.3.2.2 Simulation of the diesel-electric system

To see how the new system fits the operational profile of Jóhanna Gísladóttir GK, a mathematical model was developed similarly to what done for the baseline system. The modelling procedure is more complicated since the number of engines is different and more parameters need to be monitored. In Figure 3.14 below, a schematic modelling procedure is described.

Similarly to the baseline case, a random value is chosen from the auxiliary power measurements and propulsion power estimations. Since the power plant system is integrated for the diesel-electric system, i.e. for both auxiliary and propulsion systems, these random values are added together as a total value. From this total value, the system checks if one engine is enough and if not, it checks if two or three engines will be needed to fulfil the power requirements.

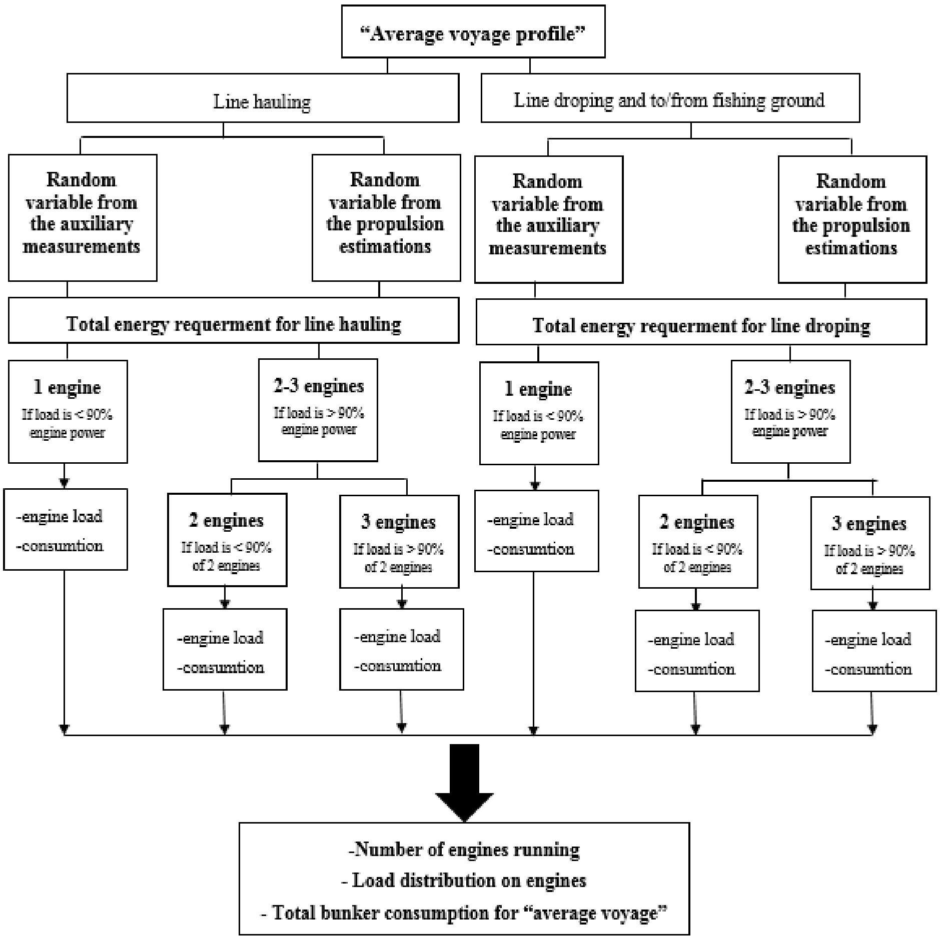


*Figure 3.14 Flow chart of the simulation procedure for the diesel electric system*

This procedure is then iterated until its consumption has converged (see Figure 3.15). It should be noted that the simulator converges before 3000 iterations but the simulation time was not long so a conservative approach was taken.

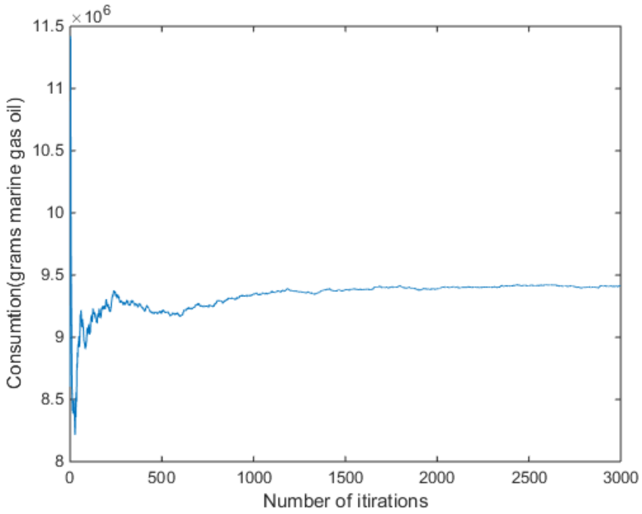


*Figure 3.15 Converging graph of the mean value for the diesel-electric system*

To monitor how the system is operating in the same manner as the baseline system, evaluation graphs are produced for each randomly picked value and the way the system responds to that randomly picked load. In Figures 3.16 and 3.17, two examples of these evaluation graphs are presented.

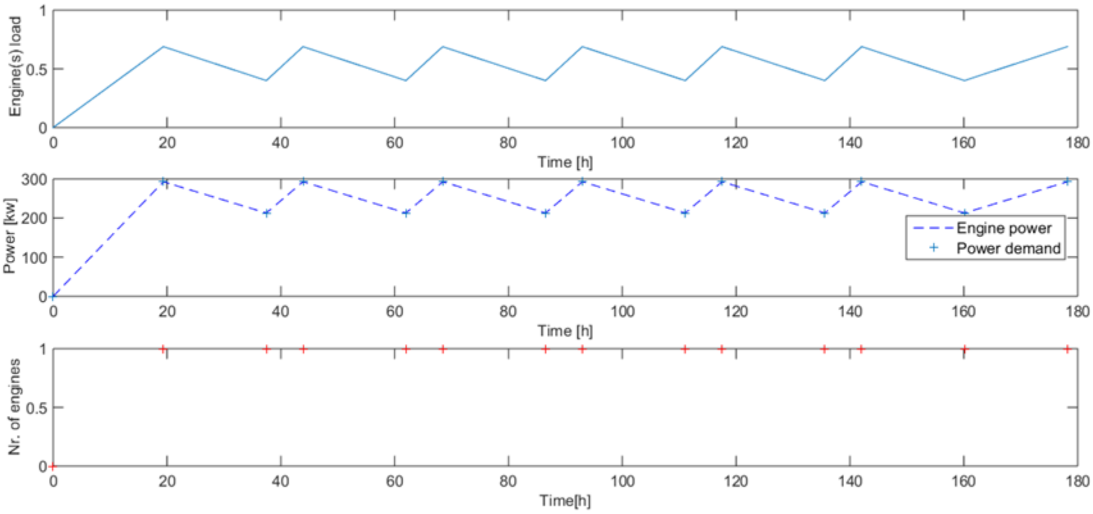


*Figure 3.16 Evaluation graph for a random loading case of the diesel-electric system*

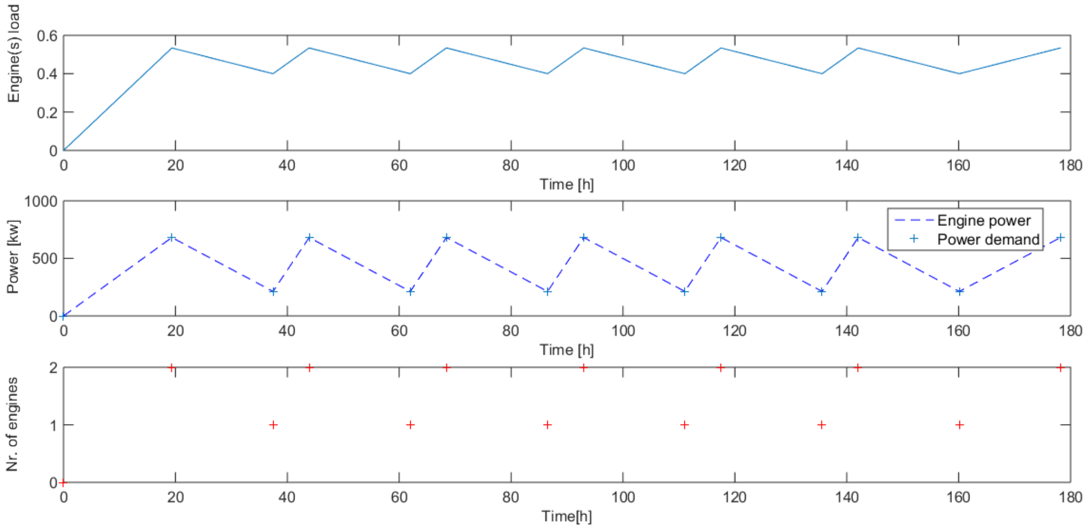


*Figure 3.17 Evaluation graph for a random loading case of the diesel-electric system*

To get a feeling of how the system is operating, the load and number of engines running during the operational time is recorded and presented as a histogram in the Chapter 4. The total bunker consumption for the "Average voyage" could then be calculated and compared to the other propulsion and power plant systems.

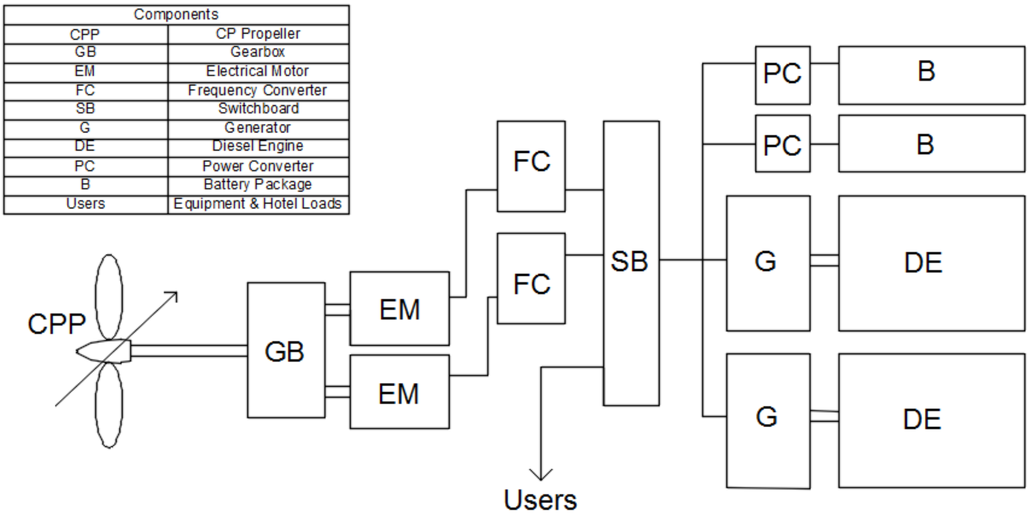
This simulator makes it possible to evaluate the system for different number and sizes of engines and is used to evaluate and decide the diesel-electric system presented in this feasibility study.

## 3.3.3 Hybrid system

### 3.3.3.1 Description of the hybrid system

For the studied long-liner vessel in this thesis, an additional propulsion and power plant arrangement is designed. The design is a proposal of a hybrid diesel-electric system, including batteries as an extra power supply. The proposed design only includes main components with an added battery package and should only serve as a principle of this system type. Components are chosen from the market to get an overview of principle dimensions and weights.

The design proposal of a hybrid diesel electric system consists of 2 generating sets for propulsion and power production, with the maximum power output of 550 kW each (Caterpillar Marine, 2013). Further, frequency converters are included to be able to adjust and control the electrical motors. The frequency converters together with the electrical motors are of the same type and size as in the diesel electric design alternative, see Table 2.5. The electrical motors are connected through a combined gearbox in the same manner as in the diesel electric design alternative, see Section 3.3.1. Additionally, 2 battery packages are installed with the capacity of 137 kWh each (Corvus, 2015). Transmission losses of the system are assumed to be the same as for the diesel electric design, Table 2.5.



| Components | |
|---|---|
| CPP | CP Propeller |
| GB | Gearbox |
| EM | Electrical Motor |
| FC | Frequency Converter |
| SB | Switchboard |
| G | Generator |
| DE | Diesel Engine |
| PC | Power Converter |
| B | Battery Package |
| Users | Equipment & Hotel Loads |

*Figure 3.18 Principle of the hybrid diesel-electric main components*

The decision to have two generating sets in this system is due to space requirements and the fact that with batteries, not as many "steps" in energy production are required. With a low power demand it is possible to either run on batteries or run an engine and charge the batteries at the same time.

The amount of batteries is decided by some major factors. Space is very limited in the engine room of the Jóhanna Gísladóttir GK. Even though this study in particular does not only consider Jóhanna Gísladóttir GK, but long-liners in general, the space constraints of Jóhanna Gísladóttir GK, are used as a design criteria. It can be assumed that for a new design, the space limitations would be similar. Since the energy is produced on board by the generating sets, the amount of energy stored does not have such a significant effect on the total fuel consumption, but rather on the lifetime and the quality of the batteries. Installing only one battery package would reduce the initial investment cost, but also reduce the lifetime of the batteries when compared to the installation of two or three battery packages, because of the different usage pattern. For principal characteristics of lithium-ion batteries, see Section 2.4.

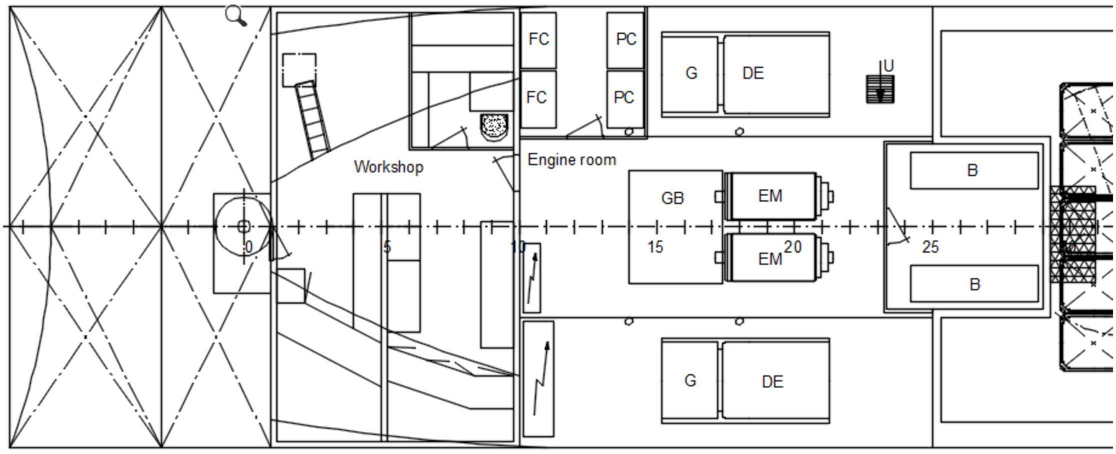


*Figure 3.19 General arrangement plan for the hybrid-propulsion system*

The reason why two battery packages are implemented in this design alternative is to provide enough power in combination with the space limitations of the engine room of Jóhanna Gísladóttir GK. The number of battery packages and the generating sets is chosen in a way so it reflects the current propulsion and power plant system with regards to its power output.

*Table 3.4 Main dimensions of generating set and battery package.*

| **Generating Sets** | |
|---|---|
| Type | CAT Marine |
| Number | 2 |
| Output [kW] | 550 |
| Length [mm] | 3040 |
| Breadth [mm] | 1547 |
| Height [mm] | 1684 |
| Weight [kg] | 4406 |
| **Battery Package** | |
| Type | Corvus |
| Output [kWh] | 137 |
| Length [mm] | 2010 |
| Breadth [mm] | 670 |
| Height [mm] | 2310 |
| Weight [kg] | 1570 |
| Min. Operating Temp. Discharge [C°] | -40 |
| Max. Operating Temp. Discharge [C°] | 50 |
| Cycle Life at 80% discharge | >5000 cycles |

#### 3.3.3.2 Simulation of the hybrid system

To compare the hybrid system with the diesel-electric and baseline system, the same foundation as for the simulator of the diesel-electric system is used, but with minor modifications for the implementations of the batteries. The simulation is performed to estimate how much bunker could be saved compared to the diesel-electric and baseline system, but also to show how the operational pattern of the engines looks like.

The simulator works in the same way as for the diesel electric system in section 3.3.2.2, where the values are picked randomly from the auxiliary power measurements and propulsion power estimations. The simulator then checks the state of the batteries and if the power required can be provided with the batteries or if an engine is needed to fulfil the power demand. If the batteries are fully charged, the system uses their energy and power first, and compliments them by using the gensets. There is a lot of research currently going on in energy management for hybrid systems, therefor this modelling procedure is used to simplify the modelling and become manageable for master thesis of this kind (Koot, 2006). If the batteries are empty or running low the power required is delivered by one or two engines and the rest of the engines power production is stored in the batteries to the batteries maximum capacity. In Figure 3.20 the simulation procedure is presented in a graphical way.

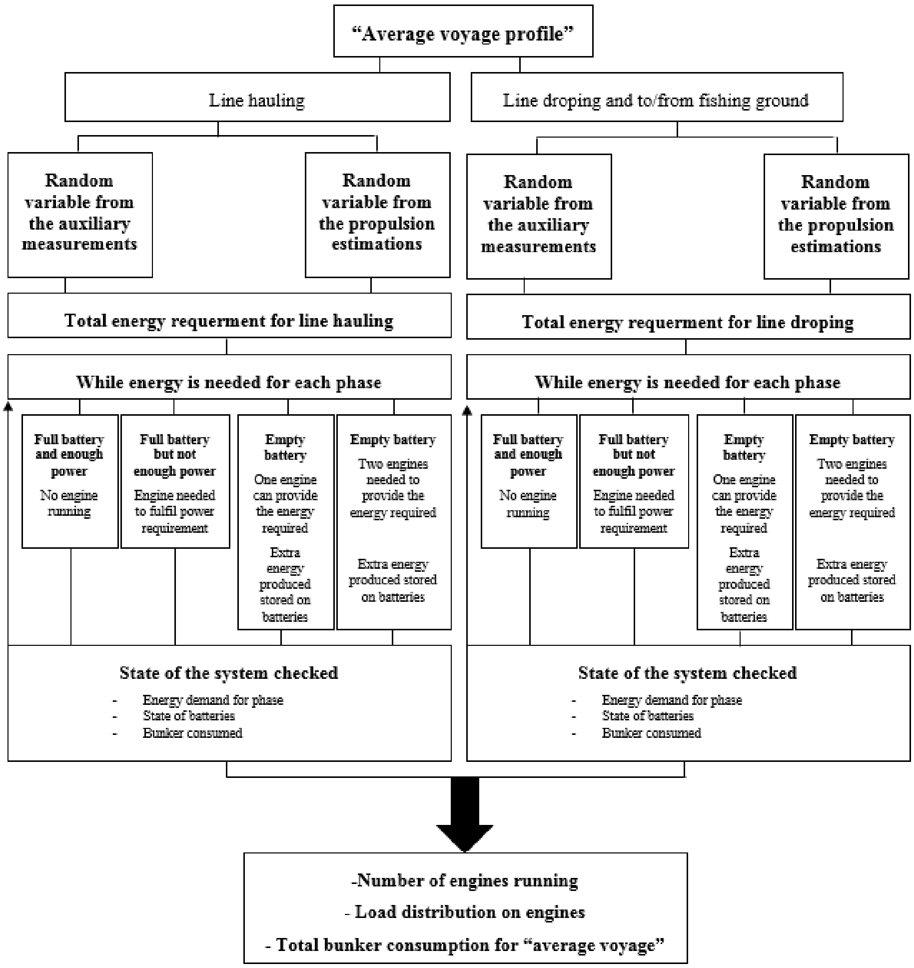


*Figure 3.20 Flowchart of the simulation procedure for the hybrid system*

This procedure is iterated 3000 times as can be seen in Figure 3.21. The simulator has converged before that number of iterations but since it was not so computationally time consuming it was iterated more times than needed for a conservative approach.

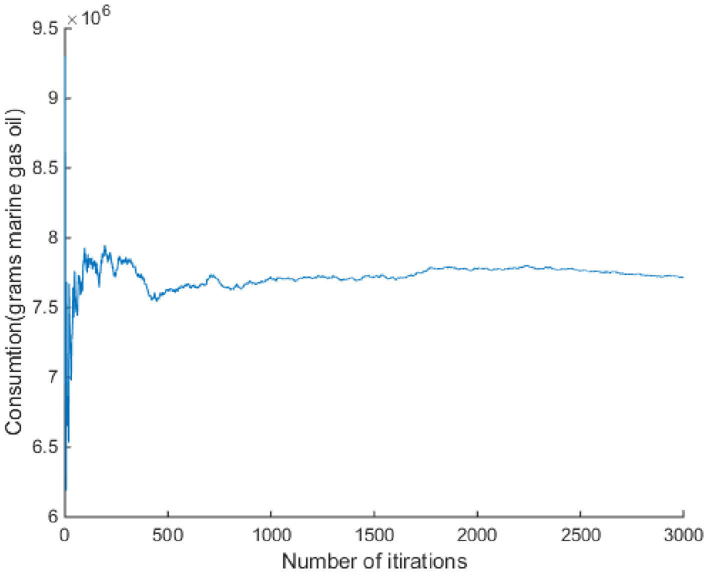


*Figure 3.21 Convergence graph for the mean consumption value of the hybrid system*

To monitor how the system is operating, evaluation graphs are produced in the same manner as for the previous two systems, for each randomly picked values and the way the system responds to that randomly picket load.

For the hybrid system are displayed more graphs than the previous two systems, due to additional complexity and increased sensitivity when modelling the hybrid system. In Figures 3.22 and 3.23, two examples of these evaluation graphs are presented.

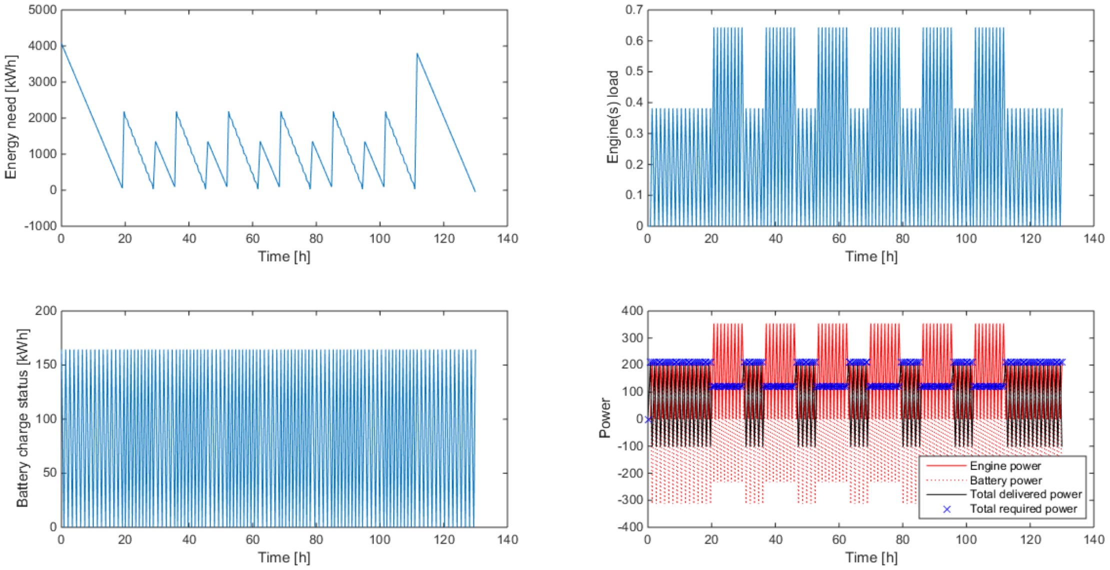


*Figure 3.22 Evaluation graphs for a random case of the simulation of the hybrid system*

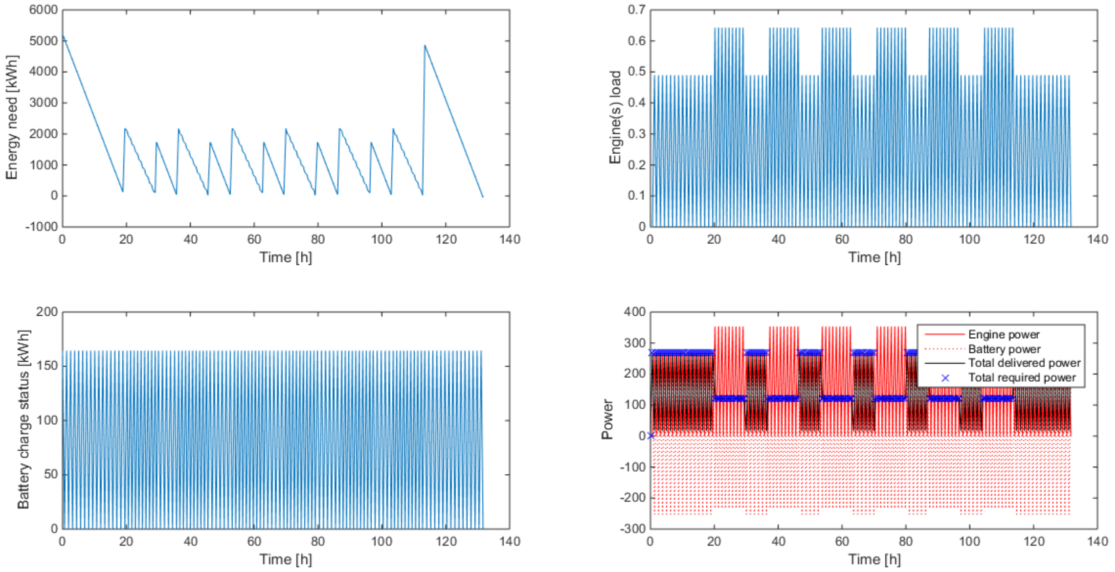


*Figure 3.23 Evaluation graphs for a random case of the simulation of the hybrid system*

The graphs in Figure 3.22 and 3.23 make it possible to evaluate the behaviour of the simulator and adjust it until it was working as it should. These graphs where generated for each iterations to see if the system works for all kinds of lading cases.

The reason for the fluctuation in the load in the upper right figure is the control strategy. The engines are running for a period of time until they have fully charged the batteries. When the engine power is larger than the energy demand is the fact that it is charging the batteries and therefore the engines need to produce more power than the vessel is demanding.

### 3.3.4 Economical evaluation

To be able to compare the current and alternative designs regarding their feasibility with an economical point of view, an investment evaluation is performed. The investment evaluation should only be seen as tentative since several parameters are excluded, such as additional investment cost of auxiliary systems, commissioning costs and maintenance requirements. The costs presented are not related to the manufacturers used as examples in the different propulsion and power plant systems.

As a starting point and foundation for the current vessels propulsion and power plant, which includes the main engine and two auxiliary engines, the installed power is simply added together as a total installed power. The total installed power is then multiplied with a cost factor in Euro/kW, which supposedly assumes the cost of the baseline.

For the diesel-electric system, the installed power of the three gensets is added as a total power installed, and is multiplied with a cost factor in Euro/kW in the same way as for the baseline. Further, additional costs are added to account for the power electronics, i.e. for frequency converters and electrical motors.

For the hybrid diesel-electric system, the total installed power for the two gensets is multiplied with a cost factor in the same manner as for previous designs. Further, power electronics are added in the same manner as for the diesel electric design. Finally, the battery cost is calculated by using the total installed power of the battery package multiplied with a cost factor in Euro/kWh.

$$Investment\ Cost = CF_{PE} * P_{PE} + CF_{PB} * P_{PB} + C_{PE} \qquad (3.12)$$

Where;

$CF_{PE}$ - Cost factor installed power engines

$CF_{PB}$ - Cost factor installed power batteries

$C_{PE}$ - Cost power electronics

$P_{PE}$ - Installed power engines

$P_{PB}$ - Installed power batteries

The following values included in the cost comparison are presented as follows;

- For the total cost of installed power, the cost factor of 330 Euro/kW is used, and accounts for medium speed diesel engines (Woud and Stapersma, 2002). This cost factor is used for all designs, both when considering the main engine of the current design as well as for the generating sets.
- For the cost of power electronics, including frequency converter and electrical motors, a similar project setup was studied. The cost for the similar system was approximately 754.000 Euro[7]. It should be noted that the cost of the power electronics presented is used for both the diesel-electric and the hybrid diesel-electric design alternative.
- The cost of the battery package is obtained by using a cost factor of 1000 USD/kWh presented in (DNV GL, 2014b). In order to maintain consistency in the pricing of the cost factors, the price of the battery package is converted to 900 Euro/kWh[8]. The cost is assumed to cover all essential components accompanying the battery system.

The total investment cost for the respective systems is then evaluated with the Net Present Value method, which is commonly used when performing investment assessments. The principle of the NPV method is basically to compare future income and expenses by re-calculating them to present day value and comparing it with the initial investment cost, by using the estimated lifetime of the investment and the discount rate stated from the investors. The discount rate should consider parameters such as required rate of return, alternative investments, cost of the capital and risks. The investment may be profitable if the criteria NPV > 0 is fulfilled, where the NPV is calculated accordingly to the general formula in Equations (3.12-3.13).

$$NPV = -I + \sum_{i=1}^{N} \frac{a}{(1+r)^i} - \sum_{i=1}^{N} \frac{U}{(1+r)^i} \qquad (3.12)$$

If r > 0, the Equation (3.12) above could be rewritten as follows:

$$\mathrm{NPV} = -\mathrm{I} + \mathrm{a} * \left(\frac{1-(1+\mathrm{r})^{-\mathrm{N}}}{\mathrm{r}}\right) - \sum_{\mathrm{i}=1}^{\mathrm{N}} \frac{\mathrm{U}}{(1+\mathrm{r})^{\mathrm{i}}} \qquad (3.13)$$

---

[7] Einar Kristinsson(Naval Architect at Navis ehf, discussion about price based on recent projects)

[8] The currency rate 4. May 2015, taken from Dagens Industry

Where the parameters included in this thesis refer to the following;

I - Initial investment cost

U - Battery package Upgrade cost

a – Annual cost reduction due to fuel savings

N - Expected lifetime of the investment

r - Discount rate

It should be noted that the discount rate and fuel savings are assumed to be fixed values throughout the lifetime of the investment. The annual fuel savings will be obtained by comparing the fuel consumption of the design alternatives with the baseline system. Further, the initial investment cost is the difference between the alternative propulsion and power plant systems investment cost compared to the investment cost of the baseline system. The initial investment cost can be seen as an additional cost when comparing the different design alternatives.

For the case under consideration, the discount rate is assumed to be 10%. The discount rate is often considered to be between 10-20% (Luenberger, 1998). The lifetime of the investment is stated for 20 years, where the calculation for the Hybrid diesel electric system is done once considering upgrade cost for the battery after ten years and then three times every five years (Stopford, 2009). This is done in order to consider different lifetimes of the batteries and how it affects the investment.

# 4 Results

In this chapter, the results of the estimated propulsion power requirement followed by the auxiliary power requirements is presented for Jóhanna Gísladóttir GK. Further, a comparison is shown for the different design alternatives in terms of bunker consumption. Finally, the result of the economical evaluation is presented.

## 4.1 Power requirement analyses

The power production by the auxiliary engine onboard Jóhanna Gísladóttir GK is based on data measured during the whole month of January 2015. For the main engine, power requirements have been estimated by using AIS data of the vessel, which includes speed data of the vessel. The AIS data consist of speed information for the whole year of 2014.

The vessel operates in general with an average voyage of one week, where catch levels and weather conditions decide whether the trip will be longer or shorter. By using the AIS data, the area where the vessel operates within can be obtained, as can be seen in Figure 4.1. The location of Grindavík, the homeport of Jóhanna Gísladóttir GK, can also be seen in Figure 4.1.

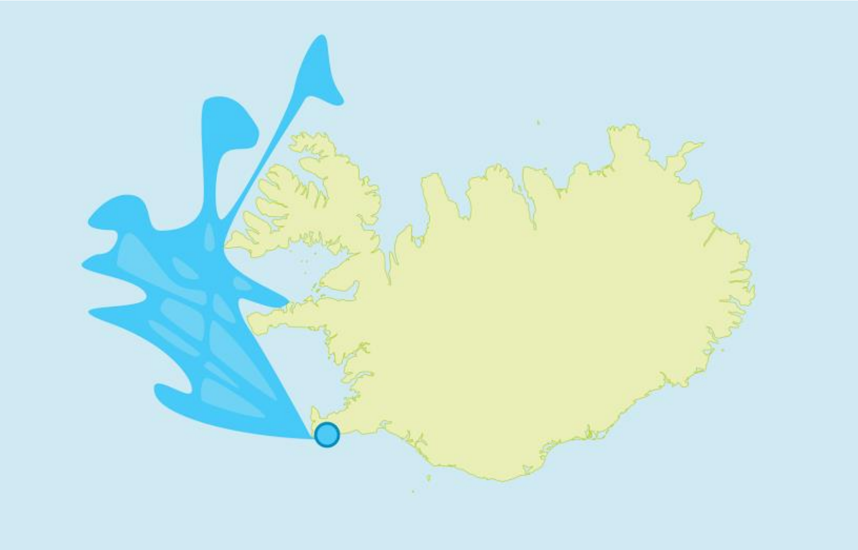


*Figure 4.1 Fishing grounds during January 2015*

### 4.1.1 Propulsion power requirements

As described in Section 3.2.1 the propulsion power for the vessel has been estimated by using empirical formulas together with the speed data from 2014. This approach was used to get an overview of how the vessel is operated throughout the year. AIS speed data for 2014 is used to analyse the operational profile of the vessel and predict the propulsion power required during the operational time. From the speed data, the average voyage time has been calculated to 7 days and 3.5 hours and the average port time has been calculated to be14.5 hours.

In Figure 4.2, the speed data is represented as a histogram with an interval of 2 knots from 0 to 12. The histogram illustrates the speed distribution very well which implies that the information is also suitable when deciding different operational modes of the vessel. It shows how the vessel is operating from 0-3 knots for most of its operational time and that is explained by the fishing method employed. It should be noted that this speed distribution is the main drive for this feasibility study.

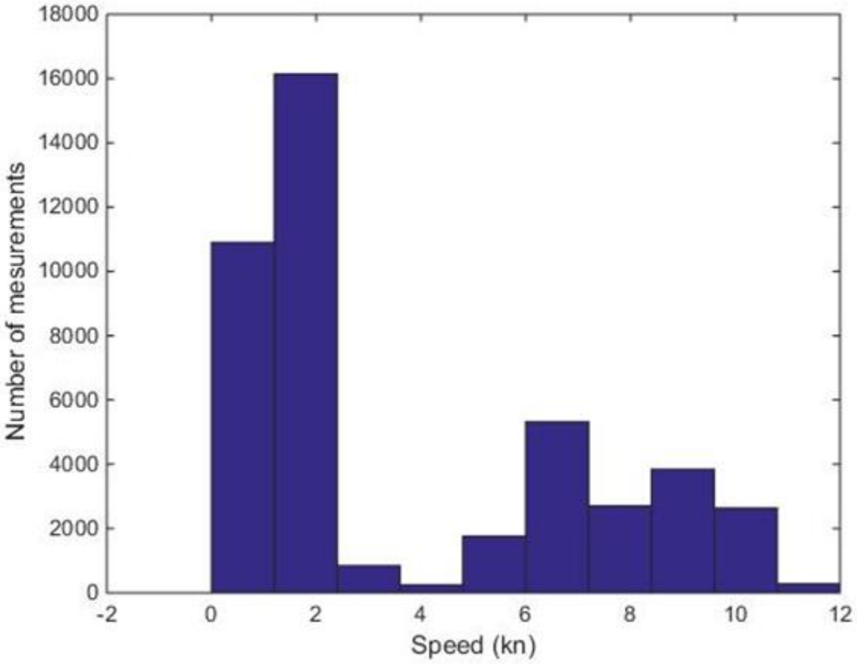


*Figure 4.2 Histogram of the speed distribution for the year 2014*

The speed data that is presented in Figure 4.2 for January month was then used to model the operational profile of the vessel since the auxiliary power requirement was only measured for January. Empirical formulas where then used to estimate the propulsive power requirements, see Section 3.2.1. The estimated propulsion data is presented in Figure 4.3 and from that figure, the operational modes can clearly be seen, where the power requirement is low during line hauling and high during line drop and back and forth from the fishing grounds.

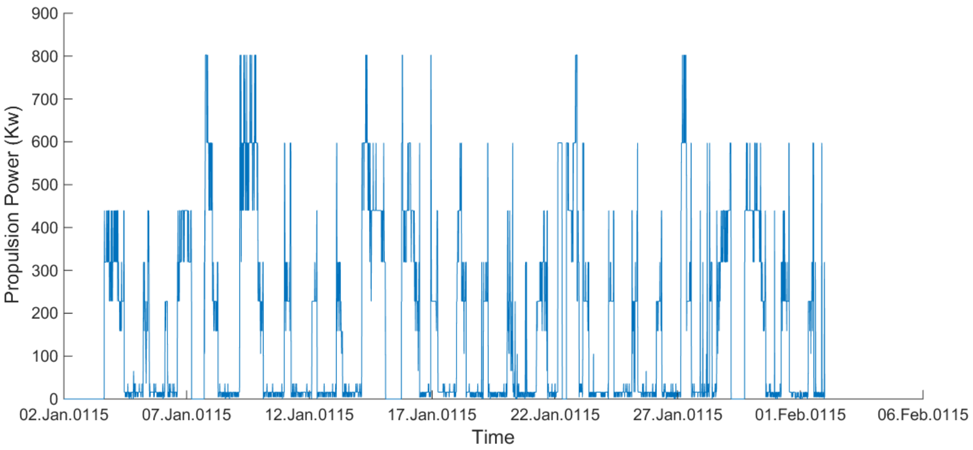


*Figure 4.3 Estimated propulsion power for 2014.*

### 4.1.2 Auxiliary Power requirements

In Figure 4.4 the data for auxiliary power demand is presented for January 2014. As can be seen, the power requirements show very strong characteristics.

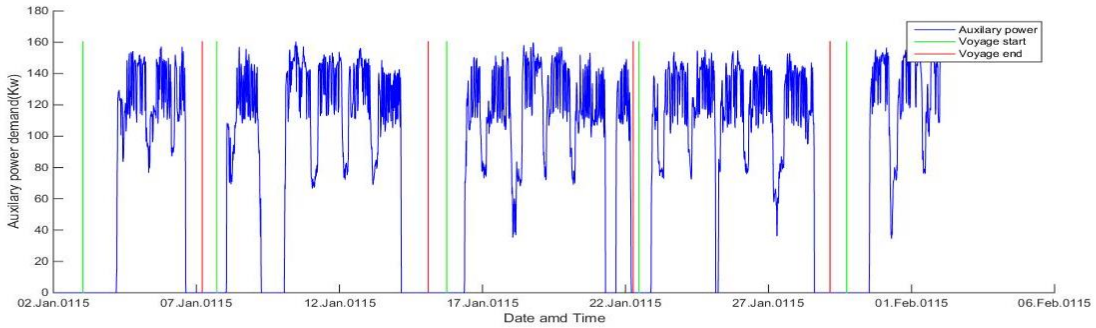


*Figure 4.4 Auxiliary power demand for January 2015*

Since each operational mode has such strong characteristics, they will be presented separately. The different operational modes consist in general of putting out the line, hauling in the line and transit back and forth from the fishing ground. Since the auxiliary power requirements are very similar for the modes when putting out the line and transit to and from the fishing ground, it is assumed that the information for putting out the line can represent both.

#### 4.1.2.1 Line hauling

The power distribution for hauling the line is plotted separately as kW versus time and can be seen in Figure 4.5. This operational mode has a mean value of 130.7 kW with a standard deviation of 15.9 kW. The mean value can be seen as the red line and the standard deviation as the green line in Figure 4.5. Due to the overall measurements of the auxiliary power requirement, this operational mode stands for approximately 82% of the time during each voyage. Since each phase is measured separately the maximum power demand for the last 15 minutes is more than the engine can provide the system with. That is because the peaks are in different time of these 15 minutes and add up to a number exceeding the produced power.

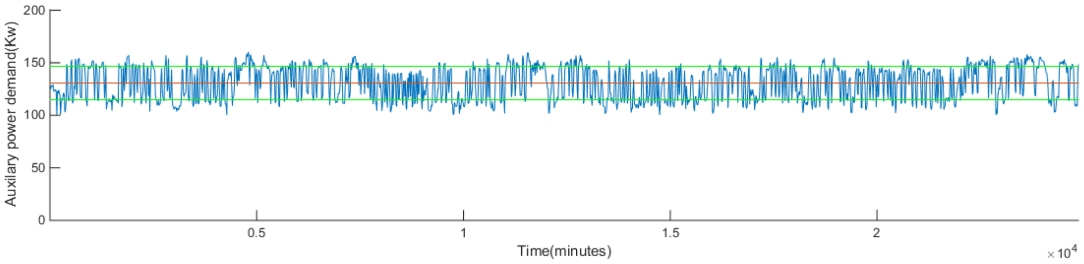


*Figure 4.5 Auxiliary power demand during line hauling.*

#### 4.1.2.2 Line dropping

The power distribution for dropping the line is plotted separately as kW versus time and can be seen in Figure 4.6. This operational mode has a mean value of 79 kW with a standard deviation of 10.4 kW. The mean value can be seen as the red line and the standard deviation as the green line in Figure 4.6. Due to the overall measurements of the auxiliary power requirement, this mode stands for approximately 18 % of the time during each voyage.

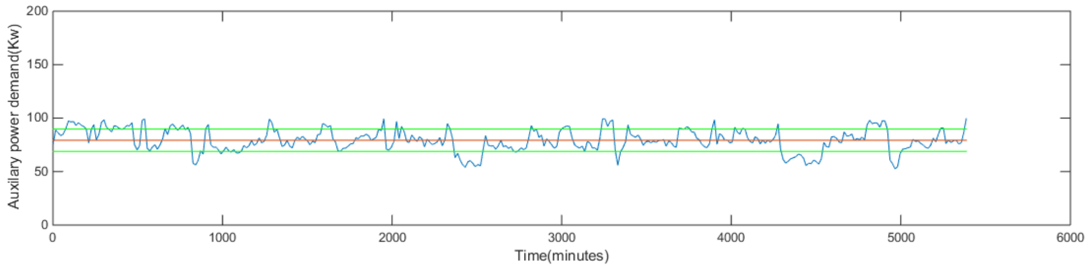


*Figure 4.6 Auxiliary power demand during line dropping*

### 4.1.3 Total power demand

The power demand is presented in Figure 4.7 for the auxiliary power and the estimated propulsive power, where the auxiliary is presented as the blue lines and the propulsive power as the red lines. The reason why they are plotted together is to be able to see the trends connected to the different operational modes.

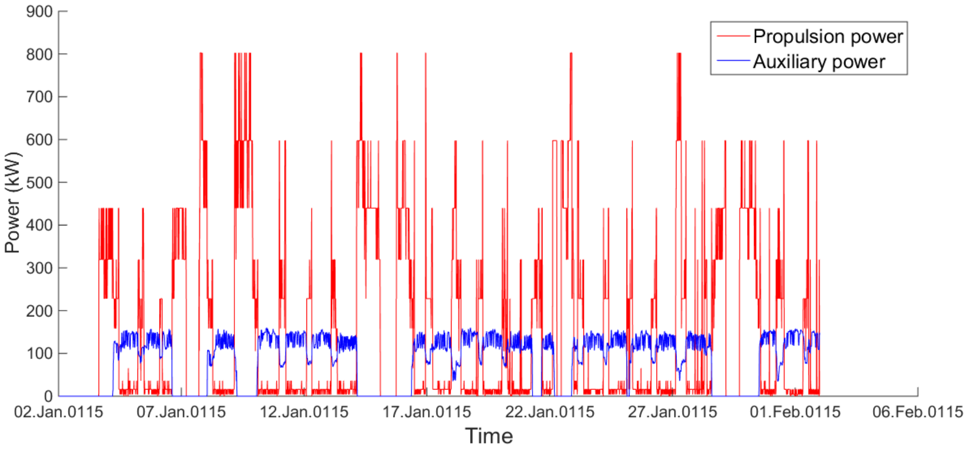


Figure 4.7 *The required auxiliary and propulsion power*

To simplify all this amount of data the "average voyage" was made to use as a reference during the design of the new propulsion systems. Average length voyage with an average power demand during each phase and average length of each phase. Since this is only the average of the data this can only give the total consumption but not the peaks that the system has to be able to supply.

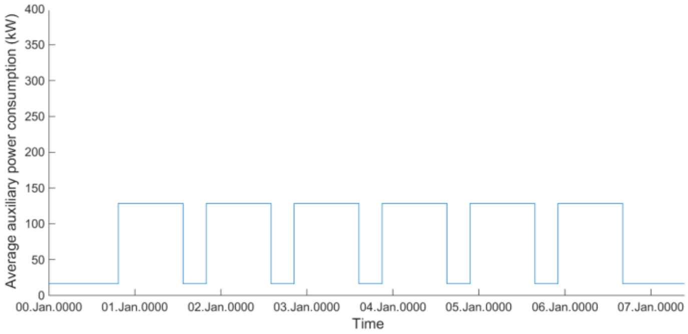


*Figure 4.8 Average auxiliary power profile for one voyage*

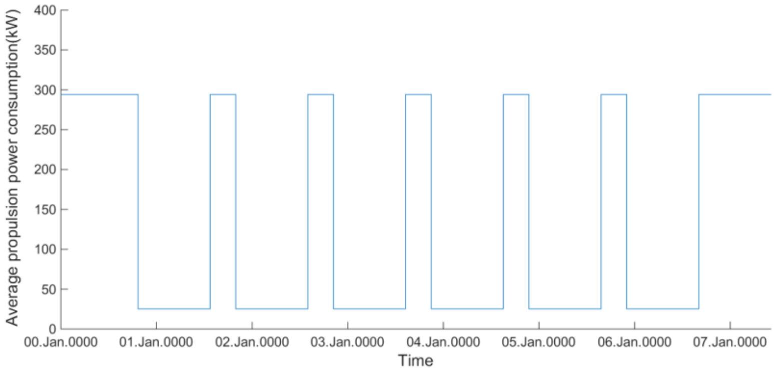


*Figure 4.9 Average propulsion power profile for one voyage*

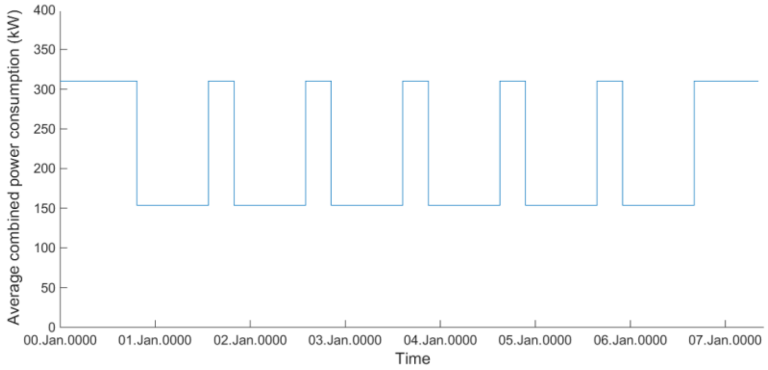


*Figure 4.10 Average total power profile for one voyage*

When the measured and estimated data are analysed, the operational pattern provides evidence of a significant potential for improvement of the existing propulsion system based on the power variations. For example, 82% of the operational time is during line hauling, which is performed at low speeds around 0-3 knots. This implies that the system is not fully utilized since the propulsion plant is not operating at its most efficient point and doesn't offer any flexibility.

## 4.2 Propulsion systems comparison

The simulator that was described in section 3 gives an overview of how the system runs. In this section, the results from the simulations along with the economical analysis are presented.

### 4.2.1 Operational comparison

In this sub-section the load pattern, number of engines running during the operational time and the total bunker consumption for each system will be presented.

#### 4.2.1.1 Baseline system

For the baseline simulation, which was the simplest, there is no reason to present the number of engines running since both the auxiliary engine and propulsion engine need to be in constant operation.

In Figure 4.11 the load distribution on the auxiliary engine for the baseline system is presented.

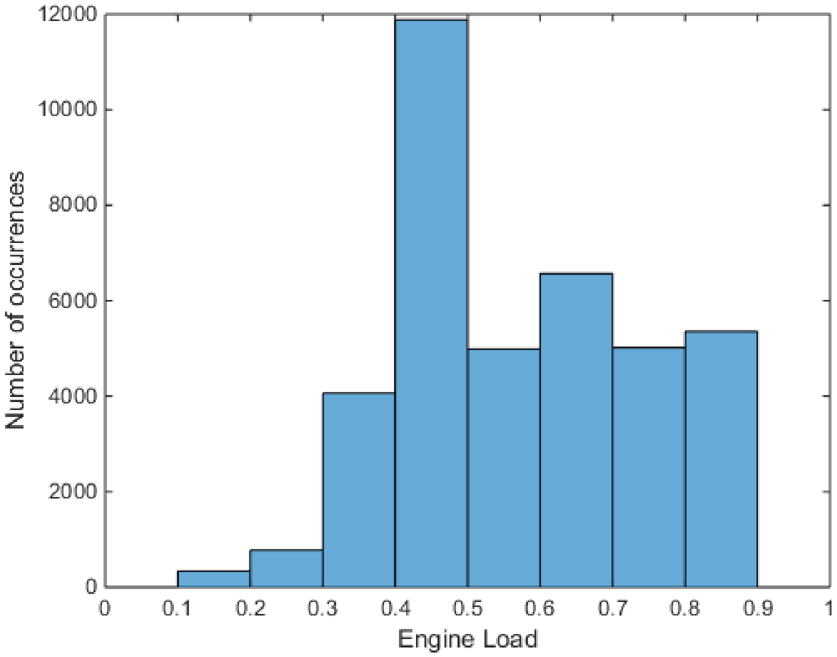


*Figure 4.11 Load distribution for the auxiliary engine*

In Figure 4.12, the load distribution for the baseline system can be seen, which should reflect the current main engine onboard Jóhanna Gísladóttir GK.

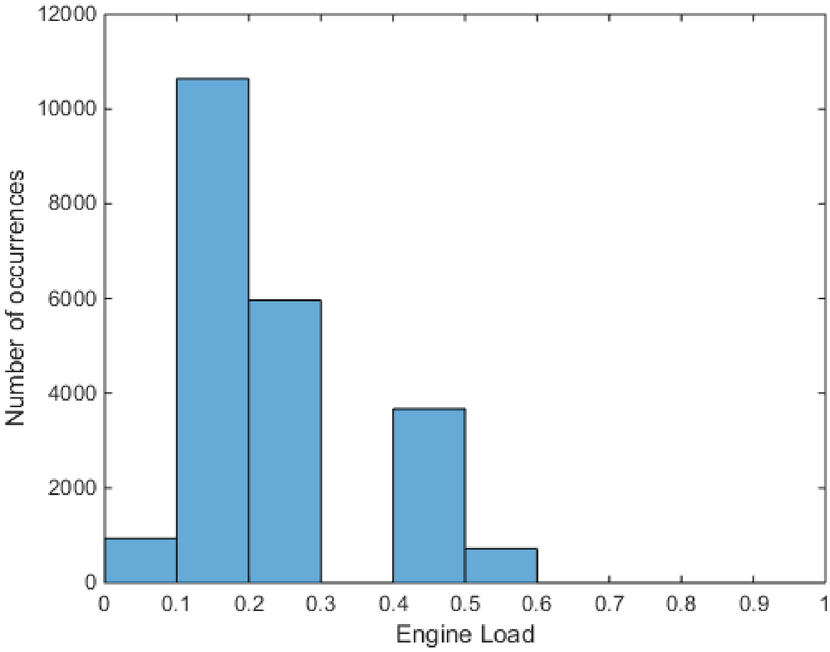


*Figure 4.12 Load distribution for the main engine*

With this simulation for the baseline system, the total bunker consumption is obtained for the “average profile” and is stated to 13.45 $m^3$

### 4.2.1.2 Diesel-electric

In Figure 4.13 the load distribution on the engines can be seen.

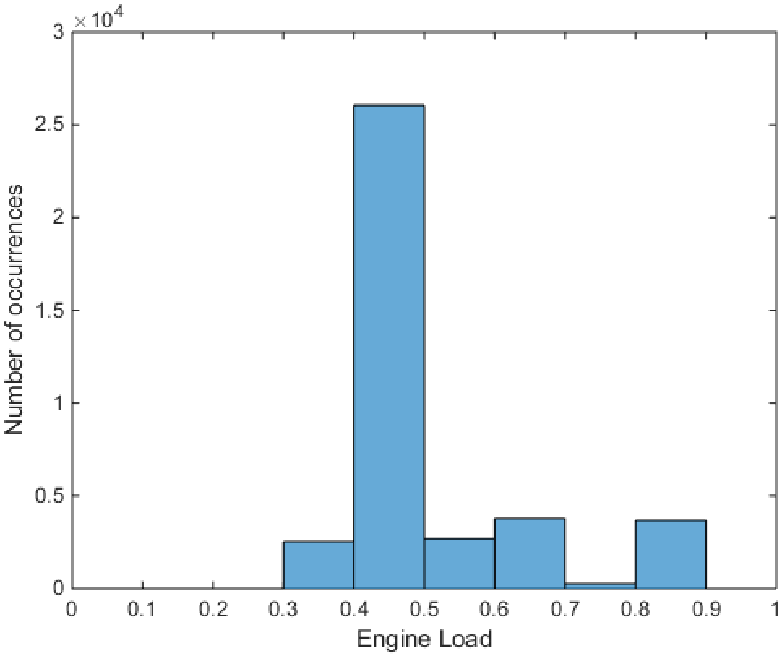


*Figure 4.13 The load distribution for the engines in the diesel-electric system*

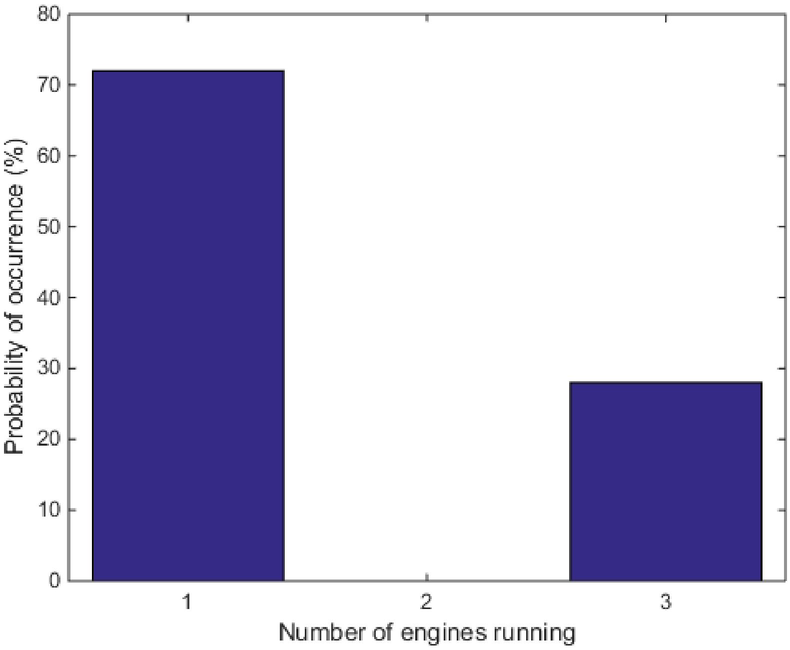


*Figure 4.14 Probability of occurrences of number of running engines*

In Figure 4.14 the probability of occurrence for each engine load is presented and will be discussed further in Section 5.1.5.2. The simulation of the diesel-electric propulsion and power plant system results in a total bunker consumption of 10.5 $m^3$ when accounting for the “average load profile”.

#### 4.2.1.3 Hybrid system

In Figure 4.15 and 4.16 the behaviour of the hybrid system is presented. In Figure 4.15 the load is presented and in Figure 4.15 the probability of number of running engines is presented. The low loads are because when the batteries cannot fulfil the power requirement, the battery power is taken first and then engine power supplemented on top. It is simulated in this way to simplify the modelling and can also be considered as conservative approach.

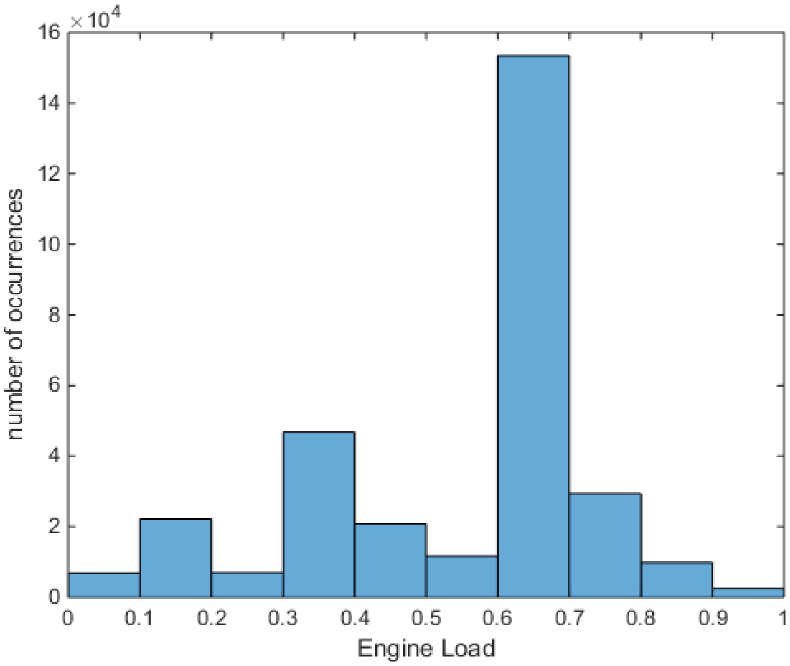


*Figure 4.15 Load distribution on engines in the hybrid system*

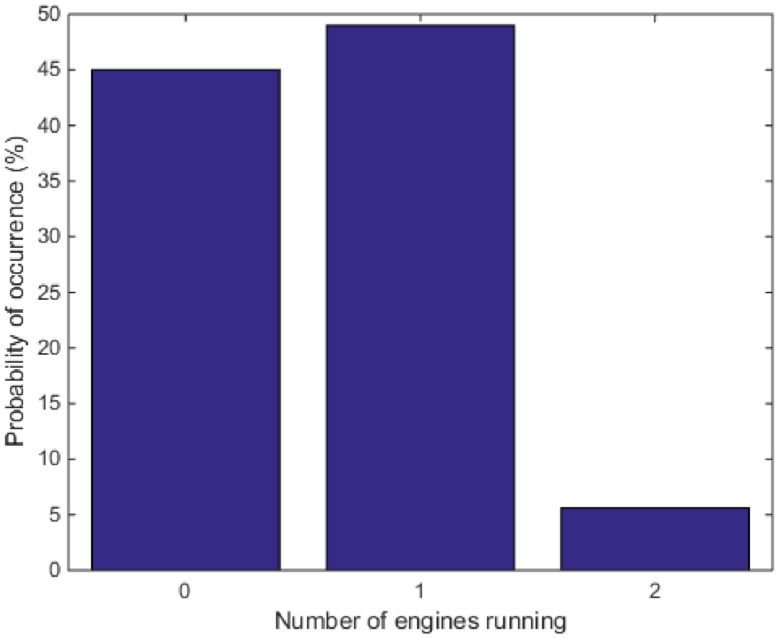


*Figure 4.16 Probability of the number of engines running*

In Figure 4.16 above, the number of engines running is presented. The simulation of the hybrid propulsion and power plant system results in a total bunker consumption of 8.5 m³ when accounting for the “average load profile”.

### 4.2.2 Consumption comparison

To see if the simulation is making some sense a fuel bill from Visir hf is used to estimate the consumption for the average voyage. This is done to compare the baseline and the current system to get a feeling for if the results are making some sense. It should be noted that the results from the simulation of the baseline system is comparable with the fuel bill from Visir hf within the range of 3% and therefore it can be assumed that the simulation is representing the system in a good way

In table 4.1 the total fuel consumption calculated with the simulators above are presented. There it can be seen that a diesel-electric system should be saving 22% compared to the baseline system and a hybrid system will be saving about 37% compared to the baseline system and about 19% with regards to the diesel electric system..

*Table 4.1 Total bunker consumption for all three propulsion and power plant systems*

| Propulsion system | Bunker consumption (average trip) | Bunker consumption (relative to baseline) |
|---|---|---|
| Baseline system | 13.45 $m^3$ | 100% |
| Diesel-electric system | 10.5 $m^3$ | 78% |
| Hybrid system | 8.5 $m^3$ | 63% |

### 4.2.3 Economical comparison

When implementing data from the method chapter, the following initial investment cost is estimated, see Table 4.2, where baseline is representing current design but still with the investment in a new propulsion system of the same kind. Alt. 1 is representing the diesel-electric system and Alt. 2 is representing the hybrid diesel-electric system.

*Table 4.2 Estimated investment cost for all three systems*

| Components [Euro] | Baseline | Alt. 1 | Alt. 2 |
|---|---|---|---|
| Installed Power | 451770 | 430650 | 363000 |
| Power Electronics |  | 754000 | 754000 |
| Battery Package |  |  | 246600 |
| Investment Cost | 451770 | 1184650 | 1363600 |

As can be seen in Figure 4.17, the NPV value is plotted versus the fuel price. Considering the estimated lifetime and discount rate from data, the break even average fuel price is obtained. When considering the Hybrid-Alternative in Figure 4.17, it is based on an upgrade cost of the battery package after 10 years. Both Figure 4.17 and 4.18 show when it is feasible to make the additional investment to the baseline system.

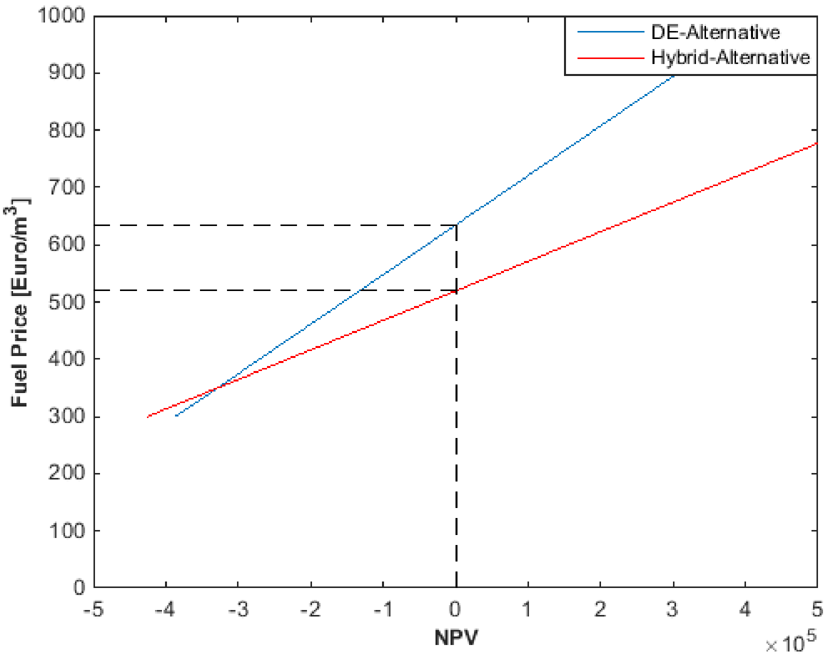


*Figure 4.17 Breakeven for additional investment cost compared to baseline with batteries renewed every 10 years*

When considering the Hybrid-Alternative in Figure 4.18, it is based on an upgrade cost of the battery package every fifth year, totally three times during a lifetime of 20 years.

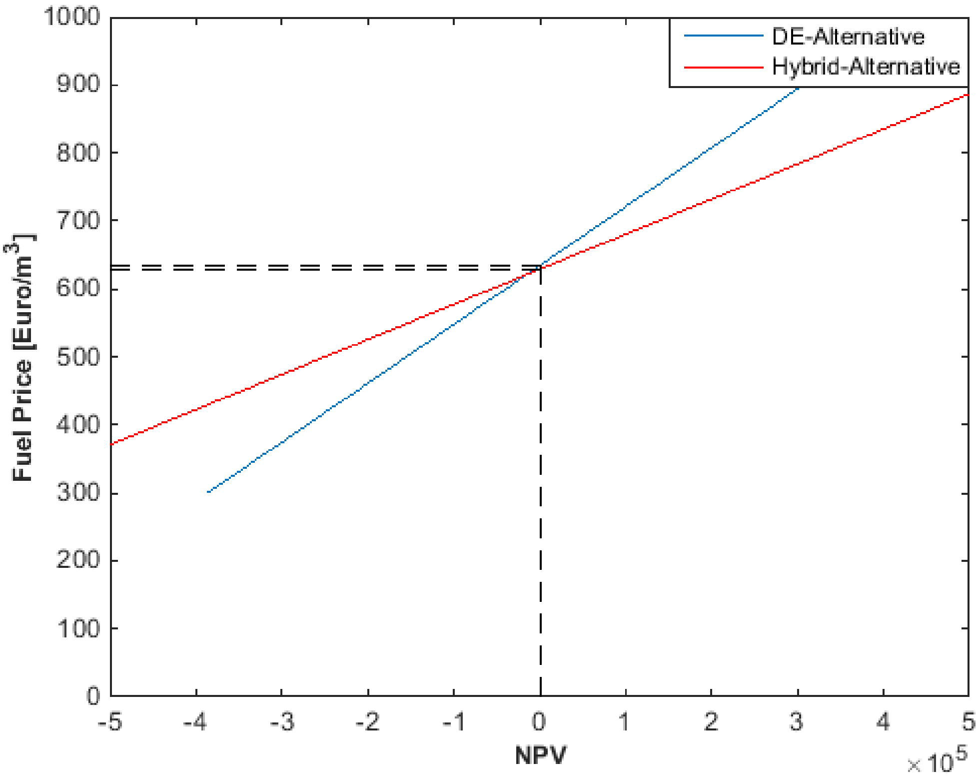


*Figure 4.18 Breakeven for additional investment cost compared to baseline with batteries renewed every 5 years*

As can be seen, renewing the batteries has a huge impact on the NPV parameters, but also the cost of power electronics. It should be noted that the fuel price is presented as an average fuel price throughout the lifetime of the investment.

# 5 Discussion

In this section, the methods and the results will be discussed. This discussion will then provide a foundation for the final conclusion.

## 5.1 Method discussions

The methods will be evaluated and discussed step by step, where every part of the way will be covered. First the reference model Jóhanna Gísladóttir GK is discussed followed by the included parts in the empirical formulation to model the vessel. Further, the current system represented by the baseline system is discussed in combination with the design alternatives. Finally, the simulation of each design alternative is discussed followed by the economical evaluation.

### 5.1.1 Case study

The main reason why Jóhanna Gísladóttir GK is used as a reference model is due to the recent upgrade of the processing line onboard and therefore it can be assumed that the auxiliary power consumption is close to what would be on a new long-liner vessel. It should be noted that this long-liner catches fish with minimum processing on board which affects the total power demand compared to vessel that performs more processing or maybe all of the processing of the catch on-board. It´s should also be noted that the catch is not frozen, only iced, which may affect the auxiliary power demands. It seems to be the trend in the industry to bring as little processed and as fresh fish as possible to the markets[9].

The operational pattern of Jóhanna Gísladóttir GK could be assumed to be the same as for other similar long-liner fishing vessels in the Icelandic fleet. As can be seen in Figure 4.7, the distance to the fishing ground differs, but can be assumed to be a short and quite similar voyage to voyage. It should also be noted that the trends for new built long-liners in general seems to have a larger beam and draft which of course have an impact of the overall hull shape when compared to the reference model, Jóhanna Gísladóttir GK. Also, the installed power seems in general to be higher for new built long-liners when comparing to the reference model, which may be due to differences of the hull shape, but also due to different fishing patterns and processing on board.

### 5.1.2 Auxiliary power measurement

For the auxiliary power requirements, real time measurements were performed during the whole month of January 2015. This data was assumed to be representative for the general auxiliary demand during the operation of the vessel independent of time which includes the following assumptions;

In this work, the auxiliary power demand is assumed to be constant over the year, independent of seasons. Preferably, the auxiliary measurements should have been based on a longer time span, including various seasons of the year to be able to see potential differences in the power requirements and the magnitude in order to increase the accuracy, or exclude potential modelling errors. Further, the measurements are based on a mean value every 15 minutes, which also can hide and mislead eventual trends when evaluating the auxiliary power distribution.

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[9] Kjartan Viðarsson(Fleet manager at Visir hf)

As can be seen above, these approximations may introduce errors, both for the highest and lowest demands in the system as well as for seasonal variations in power consumption. However, it can be assumed that they still give a good picture of the energy demand over time.

### 5.1.3 Estimation propulsion power

The propulsion power requirement was estimated in several steps and the aim was to include all essential parameters that affected the vessel under consideration during operation. The first step was performed by using the empirical method proposed by Holtrop and Mennen. This method has general applicability and is proper when considering estimations of effective power at an initial stage, but the ideal case would have been to combine CFD modelling or on-site measurements of the vessel for comparison and to be able to investigate its accuracy.

The first plan was to do on-site measurements with a strain gauge on the shaft. By doing that it would have been possible to measure the delivered power in a much more accurate way. However, as a consequence of practical reasons the required measuring instrument became available only too late in the development of the work, and it was therefore decided not to use it.

It should be kept in mind, that the maximum installed power of the current propulsion system is used as the maximum required power demand when designing the baseline and alternative propulsion systems.

#### 5.1.3.1 Propeller efficiency and transmission losses

Due to lack of information on the propeller of the vessel under consideration, the Wageningen B-series was used as seen in section 3.2.1.3. The method is based on FP-propellers, which implies an uncertainty for the result when modelling the CP-propeller for the case under consideration with regards to the efficiency of the propeller. This uncertainty was however assumed to be acceptable since realistic characteristics of the propeller during operation of the vessel were obtained.

The operational pitch of the vessel is not known and is only controlled by gut feeling of the master. Therefore the Wageningen series was used to simulate the gut feeling of the master and the best operational pitch calculated for each pitch. This procedure was decided upon to come as close to the real world as possible but this can lead to significantly large uncertainties. The same accounts for the transmission losses in the system, where the figures used are based on general values for components which specifications were not considered in depth.

#### 5.1.3.2 Wind and Wave added resistance

To account for parameters connecting to the environment such as weather and hull fouling, a service allowance factor was implemented in the method. The value chosen was decided in a conservative approach which as well will affect the results of power requirement. How the results are affected and their accuracy when comparing to the reality case is difficult to decide, which implies further uncertainties of the overall propulsion power requirements. It should be noted that added resistance from parameters such as wind and waves are very difficult to predict, since it shows very different characteristics and irregularities.

#### 5.1.3.3 Total power requirement

To combine these two different sets of data gathered an “average profile” was made. This average profile consisted of the average time and fuel consumption for each phase of the voyage.

In the simulation process a random value was then picked as discussed in section 3.3. This was done to come closer to the peak loads and low loads of the operations since the mean power demand would not represent the required maximum and minimum power demand and therefor give unrealistic results.

### 5.1.4 Design alternatives

The setup of the design alternatives, i.e. number of gensets and battery package are crucial when considering the fuel consumption in theory. This is because the flexibility and thereby the possibility to run the system as efficient as possible is entirely based on how the system can be combined. In practice, this flexibility needs to be considered in conjunction with parameters such as space, initial investment and maintenance, not only to make it feasible but profitable. When these decisions were made they were more built on recent new buildings of similar size and a feeling about how it would be done on this vessel.

The optimisation of the system is not our main concern but more to see how these different systems compare. To decide upon the designs both our simulations and recent new builds were used to decide upon systems to compare.

#### 5.1.4.1 The baseline system

To get more realistic representation of the current propulsion system on-board Jóhanna Gísladóttir a baseline case was generated. A similar new engine was selected and that makes the case more “fair” since simulations on the other systems are also based on manufacturers consumption numbers. This was done by looking at similar recent vessels with mechanical propulsion system on board. This was done to have an operational pattern and fuel consumption generated by similar methods as for the other propulsion systems.

#### 5.1.4.2 Diesel-electric system

When the diesel-electric system is designed the “average voyage” power profile is the first design criteria and the fact that the current design is using its full power and therefore an alternative system should be able to deliver the same power.

Recent new buildings where studied and tried out on the simulator that had been generated to evaluate the diesel electric systems.

#### 5.1.4.3 Hybrid system

When the hybrid system is designed the same components as for the diesel-electric system are used. Then number of engines and amount of batteries are decided. It is mostly the lifetime of batteries and amount of space that set the lines, but also the capital cost of the system.

Over the lifetime of the batteries they can only sustain a certain number of charge/discharge cycles as discussed in section 3.3.3. If more batteries are installed fewer cycles would be needed from each battery package and therefore it would endure over a longer timespan, but will result in added requirements for space, weight and capital cost.

### 5.1.5 Simulations of systems

The simulations are briefly described in Sections 3.3.1.1, 3.3.2.1 and 3.3.3.1. When the simulations were done the values were picked randomly. This was done so the total power demand would be more representative for the maximum and minimum load on the engines. If the mean value for propulsion and auxiliary power demand was used, instead, that would have resulted in a more even power profile and, consequently, a less reliable comparison of the different propulsion systems.

By iterating this random samples until the mean fuel consumption converges is considered to give a better representation of the data than just calculating the mean power demand over the mean time of each phase within each voyage. This gives the operational pattern on the engines that would not be acquired by using the mean value since the load would always be the same. The procedure was iterated 3000 times but as can be seen in Figures 3.8, 3.14 and 3.18 the consumption for all the systems converged quite a bit before that but since the difference in calculation time did not change much it was decided to be on the save site.

#### 5.1.5.1 Simulation of the baseline system

When the baseline system is modelled the required power is used to calculate the consumption for a random value both for the auxiliary engine and the main engine. The procedure is simple in comparison to the other systems and the consumption for both engines is just added together for a total number to compare with the other systems.

#### 5.1.5.2 Simulation of the diesel-electric system

Here it was decided from discussions with experienced naval architects and resources from recent new buildings that the power demand would be met in three steps or with three gensets of the same size. This can affect the total consumption value. The engine operational profile shows that the engines are only running one or three at a time. Two engines running, never occurs but that was considered to be because of the nature of the data that was used. Still the first step or one genset was working on quite high loads so this should not affect the consumption too much.

#### 5.1.5.3 Simulation of the hybrid system

This simulation of the hybrid system is the one that presented the hardest challenges. The approach was taken to keep the modelling as conservative as possible while keeping the code manageable at the same time (Koot, 2006). The approach was taken to fully charge the batteries and when they are full the engines are turned off if the batteries can provide the required power. It should be noted that there is further potential for improvements if more complex control strategies were used. This current approach gives a very high cycle count on the batteries which can affect their lifetime. Another approach would have been to keep one genset always on and use the batteries only to even out the power production. Still both methods keep the gensets at as even loads as possible and should therefore result in similar bunker savings but still the difference in cycle time could be quite big.

#### 5.1.5.4 Economical method

A preliminary economical evaluation was made in order to investigate the feasibility of alternative propulsion and power plant designs from an economical point of view. A lot of assumptions were needed to be made; in particular, the discount rate and the lifetime of the investment are essential for the outcome in combination with the average fuel price. While keeping a simple formulation, the economic overview highlights the price of fuel and lifetime of the system in an interesting way and puts it into context.

The additional cost stated for the diesel electric and hybrid propulsion and power plant compared to current design only consider electrical motor and a frequency converter and an addition cost for battery packages on the hybrid system. This implies that extra additional cost due to additional components such as generator for the gensets etc. is not included which creates a certain uncertainty regarding the cost. This is also the case for the main engine since the price is assumed to be the same in Euro/kW, both for the main engine and the gensets in the alternative designs. This will affect the result since it affects the additional cost for the design alternatives, and thereby the additional investment cost. It should also be noted that the price used is based on literature from 2002 which can be seen as outdated, even though it is used for all design alternatives.

## 5.2 Result discussions

In this section the results will be discussed and what they bring to the conclusion.

### 5.2.1 Power requirement analyses

When the power requirement analyses are looked at the first impression gives a strong hint about the potentials in some kind of energy storage system. The voyage can more or less be separated into two phases, line hauling and line dropping. This made it easier to combine the data and use it for system modelling and simulations.

The mean value of the fast phase or line dropping is about 320 kW for the propulsion and auxiliary power demands combined, that is quite far from the max power of the current system. Therefore the simulations are built from random values of that data. The line hauling then has a mean value of 160 kW for the total energy consumption. It should be noted that with this approach it is not taken into account when the master puts full throttle to push the vessel to desired speed.

### 5.2.2 Propulsion system comparison

In this section different parameters regarding the operational pattern will be discussed and evaluated.

#### 5.2.2.1 Operational comparison

If the loading pattern on the auxiliary engine is considered it can be seen it has a quite even load pattern. If the load on the propulsion engine is considered it can be seen that the load distributes over very low load. These zero loads would not occur in the real world but since empirical methods are used it will result in zero loads if the speed is zero.

When the diesel-electric system is analysed it can be seen that the loads distribute with much higher loads and since the auxiliary power and propulsion power demand are combined the required power is never zero. It is interesting to notice that, although it was decided to propose a design with three genset, the simulations never resulted in the operations on two engines. It was decided to keep it as it is since the power demand for the auxiliary power is 15 minute mean and therefore the peaks will be lower than in the real world. It could though be argued to have a system with one small genset and another twice as big.

When the hybrid system is considered the load distributes over the whole operational pattern. The system starts getting zero loads again but that is when all the engines are turned off and the batteries are providing the power. The low loads occur the batteries can deliver only part of the required power and the engines are used to provide the remaining power.

The control strategy for the use of batteries was decided in the beginning of this study. A worthwhile alternative would have been running one genset all the time and only use the batteries to even out the work for that engine. But the procedure still shows in a conservative way how much energy production can be saved.

#### 5.2.2.2 Consumption comparison

The baseline was modelled to have a consumption and operational pattern that had been calculated in the same manner as the alternative systems. When the calculated value and the modelled baseline system are compared it shows that the simulation done is making sense. When cubic meters of bunker are mentioned it is marine gasoil.

| | |
|---|---|
| • Average bought fuel for January and February | 13,8 $m^3$ |
| • Baseline simulation | 13.45 $m^3$ |
| • % difference | 2.5% |

When the diesel-electric system is investigated a 22% saving can be seen from the baseline system. Then with the hybrid system a 37% saving can be seen compared with the baseline system and 20% from the diesel electric system.

These simulations and the numbers presented in Section 2 from DNV show similar results but are bit more optimistic. The DNV figures are not assigned to one type of a vessel and fuel saving potential is very dependent on the operational pattern.

It is clear that in terms of bunker consumption there are great saving potentials for both the diesel electric and hybrid systems. In Section 4.2.3 this bunker saving numbers are analysed in relation with the additional investment cost for each design alternative.

#### 5.2.2.3 Economical comparison

The economical evaluation required a lot of assumption, which influence the results. The evaluation for the hybrid propulsion system is done in two different approaches where the first consider battery upgrades after 10 years, see Figure 4.17 and the second every 5 years, see Figure 4.18.

When the diesel-electric is compared to the hybrid system, the price of batteries does not add too much to the investment cost, since the installation of power electronics is the most expensive part. On the other hand, installing batteries has a very significant impact on the potential for fuel efficiency. This makes a strong case for hybrid propulsion systems

DNV prediction of 30-50% increase of fuel prices due to new rules and regulations, should motivate investment in more fuel-efficient solutions. The possible price reduction of the batteries is not taken into consideration even though this probably will be the case. Further, the scrapping value of the system is not included in the economical comparison. In addition the lifetime of the battery should be discussed in relative to the warranty.

# 6 Conclusion

The first aspect that was looked into was if a long-liner fishing vessel in the Icelandic fleet would fall into the category of having a suitable operation profile to be fitted with hybrid propulsion system. A total energy profile was drawn for one “average voyage”. The results from that showed large fluctuations in the power demands. Therefore it can be noted that steps in the power production or some kind of energy storage systems could save some bunker by even out the energy production profile.

The literature study that has been carried out in this thesis shows that the market trend and technical development is close to be or is feasible today which implies an interesting future for hybrid propulsion.

The results from the simulation models shows that both the diesel electric and the hybrid propulsion systems can significantly reduce fuel consumption compared to the baseline system that represents traditional mechanical shaft line propulsion, see Table 4.1. Both the simulation models and reports from DNV show similar bunker saving potentials.

When the economical evaluation is considered it can be seen that today with the current battery and bunker prices both investment in diesel-electric and hybrid systems would be feasible. Future trends can change the game very fast but, as industry experts as DNV are mentioning, there are high expectations for batteries to become cheaper and bunker fuel price to increase. Both of these changes would make it more feasible to take the additional investments. Since the lifetime of the batteries is hard to assess the economical evaluation is done for both five year lifetime and a ten year lifetime. Since bunker contract prices generally are unknown, it is hard to make a yes or no decision, but for those holding that information it can be further evaluated.

When this is all taken into consideration it can be said that there is a great potential in investing in a battery hybrid power plant system. At the same time there are still a lot of questions to be answered regarding the future trends of the market and not much experience of the components used in the marine industry. So decisions should not be rushed into but should still be tried out.

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