Erlend Sande Bergaas

A techno-economic assessment of operating a deep-sea hydrogen-driven chemical carrier.

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
June 2021

Master's thesis

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PREFACE

This is a master thesis from the Department of Marine Technology at the Norwegian University of Science and Technology. The work was carried out during the spring semester of 2021, and written by Erlend Sande Bergaas. It is the final work of my Master Degree in Engineering with specialization in Marine Systems Design. The target group for the paper is a technical audience with interest in shipping and the potential for using hydrogen as a fuel.

The project was done in collaboration with Stolt Nielsen, LMG Marin and Norled.

I would like to thank Ivan Østvik at Norled, Giorgio Gadagna, Loek Dejong and Per Roed at Stolt Nielsen, and Frederic Collin and Stig Rau Andersen at LMG Marin, for sharing their experience and insights, guiding me throughout the project and giving valuable feedback on the final draft of the thesis.

Furthermore, I would like to thank my supervisor at NTNU professor Stein Ove Erikstad.

Trondheim, 10.06.2021

Erlend Sande Bergaas

ABSTRACT

To meet the United Nations Sustainable Development Goals (UNSDG), states and international authorities are motivating companies to reduce their emissions. An effective measure is to equate emissions to a cost for the companies by introducing CO2 taxes. It is therefore of great interest to shipping companies to find potential solutions to reduce their emissions, and thereby the cost. The root cause of the emissions is the fossil fuels the ships are sailing on today. Finding new potential fuels is an opportunity to remove completely or reduce the emissions during operation. For deep-sea shipping hydrogen is a promising candidate as batteries are not applicable.

This project is determining the feasibility of operating a liquid hydrogen driven chemical carrier sailing across the Atlantic Ocean. Both from an operational and design perspective.

All studies are based on an existing trade with an existing conventional chemical carrier as informed by Stolt Nielsen, including data such as operation profile, HFO consumption and reference ship data. This base case is used as reference for all presented results.

The project is consisting of three main studies, the creation of a route independent fuel consumption model, an operational study and a general arrangement study.

From an operational perspective the questions to be answered are the required amount of on-bord LH2 storage, the power rating of the fuel cell system, identifying potential bunkering ports and determine the break-even price of hydrogen.

Results from the operational study will serve as the basis for the design phase. A suggested tank arrangement and fuel cell system is identified to make sure that it is possible to fit enough fuel tanks and fuel cells on-board the vessel.

The project shows that there is a good potential for the application of hydrogen as fuel for deep-sea chemical shipping. Currently a hybrid option is the best solution as this would allow the vessel to sail over 60% of trans-Atlantic legs under most circumstances without reducing payload capacity. If the vessel should be run on pure hydrogen it would require at least 10 fuel tanks installed. This project shows that it is possible to store 8 tanks on the deck of the vessel without compromising on its capacity.

Furthermore, it shows that there is not a restriction related to the feasibility of installing a high enough power rating for the fuel cell system to power all the loads on-board. The limitation lays in the amount of hydrogen that can be stored on the ship.

As of today, bunkering opportunities are also a limitation for the feasibility of hydrogen driven chemical carriers. The project has identified that hydrogen bunkering infrastructure must be built in the Port of Houston and the Port of Antwerp before it is viable to operate the vessel.

To make hydrogen economically competitive compared to the conventional fuels the project has found that the current green hydrogen price would require to be reduced with approximately 65%.

SAMMENDRAG

For å møte FNs mål for bærekraftig utvikling så fokuserer stater og internasjonale organisasjoner på å gi insentiver til selskaper for å redusere utslippene sine. Et effektivt virkemiddel er å knytte utslippene opp mot selskapets kostnader ved å introdusere en skatt på CO2. Det er derfor viktig for shippingselskaper å finne nye løsninger som kan være med på å redusere utslippene deres. Rotårsaken for utslippene er fossilt drivstoff som skipene seiler med i dag. Det å finne nye drivstoffkandidater er en mulighet til å kunne kutte utslippene helt eller redusere dem betydelig. For deep-sea shipping er hydrogen en god mulighet siden batterier ikke er konkurransedyktige for dette segmentet.

I dette prosjektet undersøkes muligheten for å operere en hydrogendrevet kjemikalietanker som seiler over Atlanterhavet. Både fra et operasjonelt og design perspektiv.

Alle studiene i prosjektet er basert på en eksisterende trade med en eksisterende kjemikalietanker som informert av Stolt Nielsen, inkludert data som operasjonsprofil, HFO forbruk og skipsdata.

Prosjektet består av tre hovedstudier, lage en ruteuavhengig modell for drivstofforbruket til skipet, et operasjonsstudie, og et general arrangement studie.

Fra et operasjonelt perspektiv så er spørsmålene som skal bli besvart mengden av hydrogen som kreves ombord, power ratingen til brenselcellesystemet, indentifisere havner hvor hydrogen bunkrings infrastruktur kan bli utviklet, og bestemme break-even prisen for hydrogen for å se om det er konkurransedyktig fra et økonomisk perspektiv.

Resultatene fra operasjonsstudiet vil være grunnlaget for arrangement studiet. I prosjektet så er et forslag for tank arrangement og brenselcellesystem identifisert for a være sikker på at det er mulig å lagre nok hydrogen ombord og at det er mulig å installere nok brenselceller på skipet.

Dette prosjektet viser at hydrogen er en god kandidat for deep-sea kjemikalieshipping. En hybrid løsning er den beste muligheten i dag siden dette vil la skipet seile over 60% av en trans-Atlantisk leg under de fleste omstendigheter uten å måtte redusere lastekapasiteten. Hvis skipet skal seile på rent hydrogen så må det plasseres minst 10 tanker ombord. Dette prosjektet viser at det er mulig å plassere minst åtte tanker på dekk uten å måtte redusere kapasiteten til skipet.

Prosjektet viser også at antallet brenselceller ombord ikke er den begrensende faktoren. Det som begrenser gjennomførbarheten, er antallet drivstofftanker som kan bli plassert ombord.

I dag er også bunkringsmuligheter en begrensning for muligheten for å operere en hydrogendrevet kjemikalietanker. Prosjektet har indentifisert at hydrogen bunkringsmuligheter må bli utbygget i Port of Houston og Port of Antwerp før det er mulig å operere skipet.

For at hydrogen skal være konkurransedyktig så har dette prosjektet funnet ut at dagens pris for grønn hydrogen må reduseres med rundt 65%.

Contents

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Nomenclature

CO	Carbon Monoxide
COA	Contract of Affreightment
dwt	Deadweight Tonnage
EEDI	Energy Efficiency Design Index
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LH2	Liquid Hydrogen
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
OPEX	Operational Cost
PEM-FC	Proton Exchange Membrane Fuel Cell
SFC	Specific Fuel Consumption
SOFC	Solid Oxide Fuel Cell
SOLAS	Safety of Life at Sea
UNSG	United Nations Sustainability Goals
VCG	Vertical Center of Gravity

Chapter 1

Introduction

1.1 Background

To meet the United Nations sustainable development goals (UNSDG) authorities are focusing more and more attention on reducing greenhouse gas (GHG) emissions globally. Several policies and regulations are making emissions expensive, creating an incentive for businesses to focus on reducing their emissions. EU has indicated that it might imposed a CO2 tax for the shipping sector[3]. This can be a great opportunity for companies that are innovative and able to adapt to an environmentally friendly operation of their fleet. The companies that are able to make the transition in an effective way will have a competitive advantage over the slower adapters. Today, the shipping sector accounts for about 2.5% of the global emissions, making it an important industry to focus on to be able to transition to a green economy[4].

Several studies are being conducted to figure out possible ways to reduce the emissions in shipping. Ranging from more efficient operations, environmentally friendly designs and finding new possible fuel candidates for the vessels. Among the fuels that are being explored are biofuels, ammonia, electricity from batteries and hydrogen. For short-sea shipping and shorter sailing times, like ferries, batteries are the superior choice compared to hydrogen, as the electricity can be taken from the existing power grid, and batteries are better to handle load changes compared to fuel cells. Deep-sea shipping on the other hand is not suitable for batteries, as there can be issues installing enough batteries on-board the vessel to last the whole trip, without significantly reducing the payload capacity. This is were other options are considered, and where hydrogen can be a good candidate. However, the hydrogen supply chain is holding back the development as is not mature enough yet. Still, today there are a lot of hydrogen projects under development which shows the potential for hydrogen, even with the current hydrogen supply chain.

The conventional fuels that are used in shipping today are oil based and called heavy fuel oils (HFO), marine diesel oils (MDO) and marine gas oils (MGO). Hydrogen has a lower volumetric energy density, meaning that to have the same energy output as conventional fuels the volume of the hydrogen on-board will be increased, on the expense of cargo capacity, or that not as much energy is stored on the vessel, leading to more frequent bunkering stops.

A study conducted by Mao et al. (2020) examined the feasibility of using hydrogen for container vessels sailing between North America and Asia showed that most of the legs could be attained without reducing the payload capacity too much or including many extra stops[9]. This study led to the basis for examining the feasibility of operating a chemical carrier sailing between North America and Europe. It is of interest to figure out whether it is possible with the current technology and how it must be done, if it can be done on pure hydrogen or a hybrid option.

1.2 Objective

The goal of the project is to determine the feasibility of operating a liquid hydrogen driven chemical carrier sailing across the Atlantic Ocean. Both from an operational and design perspective.

From an operational perspective the questions to be answered are the required amount of on-bord LH2 storage, the power rating of the fuel cell system, identifying potential bunkering ports and determine the break-even price of hydrogen. Results from the operational study will serve as the basis for the design phase. A suggested tank arrangement and fuel cell system is identified to make sure that it is possible to fit enough fuel tanks and fuel cells on-board the vessel.

1. Operational
    (a) Amount of hydrogen required
    (b) Power rating of the fuel cell system
    (c) Identify ports for development of hydrogen bunkering infrastructure
    (d) Break-even price of hydrogen
2. General Arrangement
    (a) Fuel tank arrangement
    (b) Arrangement of fuel cell system

All studies are based on an existing trade with an existing conventional chemical carrier as informed by Stolt Nielsen, including data such as operation profile, HFO consumption and reference ship data. This base case is used as reference for all presented results. The case is a 33000-dwt chemical carrier sailing on a trans-Atlantic route, as this is the most relevant ship to install fuel cell system on, and it is a deep-sea route were batteries are not applicable.

1.3 Limitations

The study is only considering one and not several vessels. It is also limited by the amount of data regarding certain components on the vessel, like the boiler. Furthermore, it is focusing only on a trans-Atlantic route, and not considering other deep-sea routes.

1.4 Structure

The thesis starts out with a brief introduction to chemical shipping, chapter 2, and fuel cells, chapter 3, for readers who are unfamiliar or want a short recap on the topics. In chapter 4 the case and data that the study is built upon are presented. The first study of the project is the creation of the route independent fuel consumption model covered in chapter 5. This will be used for input in the operational study. Chapter 6 is presenting how the operational study and general arrangement study are performed, and the corresponding results are covered in chapter 7. The thesis closes out with a summary, chapter 8, an discussion, chapter 9, a conclusion, 10, and further work that can be done to continue exploring in the direction the thesis have set out, chapter 11. An appendix is attached for reference data and information for the studies performed.

Chapter 2

Chemical Shipping

Chemical shipping is the seaborne transportation of liquid chemicals. As the use of chemicals range across a wide variety of industries, a reliable transportation system of these are essential for the society as a whole. Shipping can be into deep-sea and short-sea shipping, based on the distances they service. Deep-sea shipping is the transportation over long distances, typically servicing large terminals between the continents, and short-sea shipping is the transportation over shorter distances, distributing the cargoes of the large intercontinental terminals to the smaller terminals in the region. This separation is important when considering the fuel that can substitute conventional fuels. Batteries have an advantage in short-sea shipping as there already exist an electrical supply network through the power grid. Furthermore, for short sailing durations there are more changes in loads which the fuel cells are not as good to adapt to as the batteries. For deep-sea shipping on the other hand there are far less load changes as the vessel is sailing in fairly constant speed and the batteries are not applicable for these trips.

Three important efficiency measures of chemical shipping are the vessel utilization, how much the average ships is carrying each leg compared to its maximum capacity, port congestion, the time ships spend waiting in queues for the terminals to become available, and the operational cost(OPEX) of the vessel.

2.1 Market

Chemicals transported by tankers are used in a wide range of industries, in electronics, construction, agriculture, cosmetics and more. The four main categories are, organic chemicals(methanol, xylene, ethylene, glycol), inorganic chemicals(sulfuric acid, caustic soda, phosphoric acid), vegetable and animal fats/ oils(palm oil, soybean oil, rapseed oil) and molasses(molasses cane, base oils, molasses beet sugar)[10]. Also products like lube oil, lube oil additives, alcohols, jet fuel, kerosene, gasoline and naphtha are being transported by chemical tankers.

Shipping rates are determined by the demand for transportation of chemicals and the supply of available chemical tankers. Since chemicals are used in a wide range of industries the customers are quite diverse, some examples can be chemical producers, trading companies and manufacturers. The purchase of this service can be either through spot rates or contracts of affreightment(COA). A COA is an agreement between the customer and the shipping company for transporting a set of chemicals over an agreed-upon period of time. COAs are usually entered to increase predictability and reduce risk from the cyclical nature of the shipping industry. For efficient operation management this can be beneficial as it makes it is easier to schedule vessels and allocated cargo. However, the downside of this is that the ship operator potentially can miss out on the upside of high spot rates. Spot rates have in general higher expected value than COAs. Usually shipping companies diversify their risk by having a mix between spot and COAs.

Shipping companies have to make decisions regarding the choice between spot or COA contract for the freight rate of the cargoes, and the spot or forward contract for the fuel price. The combination of the different contracts that are chosen will have great impact on the future profit of the company depending on how the market will evolve. The COAs and forward contracts are more predictable financial instruments and may give a more reliable stream of income than the spot contracts. They also serve as a buffer for declining markets, but it should be noted that they are still exposed for counterparty default risk during these times. On the other hand, in rising markets the spot contracts tend to outperform the COAs and Forwards; it has a higher expected value. This means that there is a possible opportunity cost related to going for the more predictable options, and often, to diversify their exposure to the market, companies tend to go for a combination of the two. The decision is mainly based on the balance sheet, how much cash they have as a buffer, how much debt they have to service, and their willingness to take risk.

Chemical transportation supply is determined by the number of chemical tankers available at a given time. It is easier to estimate the growth rate for the supply rather than the demand, since it is based on the number of delivered newbuildings subtracted with the number of scrappings during the time period of interest. But the location of the vessels are also affecting the local markets.

2.2 Assets

The main assets required to transport chemicals are tankers and terminals. Chemical tankers are commonly divided into five categories, parcel tankers, chemical carriers, solvent carriers, specialized chemical tankers and molten sulphur carriers[10]. The most common being parcel tankers which can carry many different chemicals at the same time. To handle different chemical properties, tanks are either stainelss steel tanks or coated tanks. Coatings determine which chemical that can be loaded in the tank. Examples of coatings can be epoxy-based(organic) paints and and zinc silicate(inorganic) paints. Tank coating combinations vary from vessel to vessel, but the fleet should in aggregate be able to handle the cargo demands. The vessels in the fleet can be catagorized into, vessels that are owned and operated and vessels that are leased on a bareboat charter.

Terminals are where ships are coming to load and/or offload the cargo. They provide chemical storage and further transportation to and from the hinterland either through trucks, pipelines or train. Furthermore, they may also provide some special services like bunkering(refueling of the ship), vessel maintenance and classification inspections. Terminal properties are number of berths, maximum draft limit, the set of tugboats and storage capacity. Terminals can be classified into pickup ports, delivery ports and bunkering ports, and most often, they are a combination of all three.

Time spent in a terminal is determined mainly by time spent entering and leaving the terminal and the time it takes to offload and load the tanker. These operations must be done in sequence and is therefore the lower bound for the time requirement. However, there are also other operations like tank cleaning and vessel bunkering that may affect the total time requirement. These can be done in parallel with the offloading and loading of the ship, and does not necessarily impact the time.

Chapter 3

Fuel Cells

Fuel cells are electrochemical devices which generate electricity through a red-ox reaction from fuel and air. The waste products are water and heat which are environmentally friendly compared to the CO2, SOx and NOx exhaust gases from the internal combustion engines. This waste heat can be reused through a heat exchanger, which potentially can reduce the hotel load or increase the efficiency of boilers on vessels.

With more industries being affected by the cost of CO2 and rising prices of emissions, equipping vessels with fuel cells fueled by green hydrogen can be a path for cost efficient and green shipping in the coming decade.

A fuel cell is composed of an anode and a cathode separated by an electrolyte. The components are similar to that of a battery but unlike the battery the fuel cell requires a continuous supply of fuel and don't deplete. A fuel cell generates electricity by keeping the anode and cathode separated by an electrolyte, called the membrane, which only allows ions to flow through. The anode is negatively charged with a surplus of electrons while the cathode is positively charge with a surplus of positive ions(cations) creating a voltage difference between the two electrodes. A circuit connects the anode with the cathode which creates a path for the free electrons to flow through, generating electricity, and connect with the molecules on the other side of the membrane.

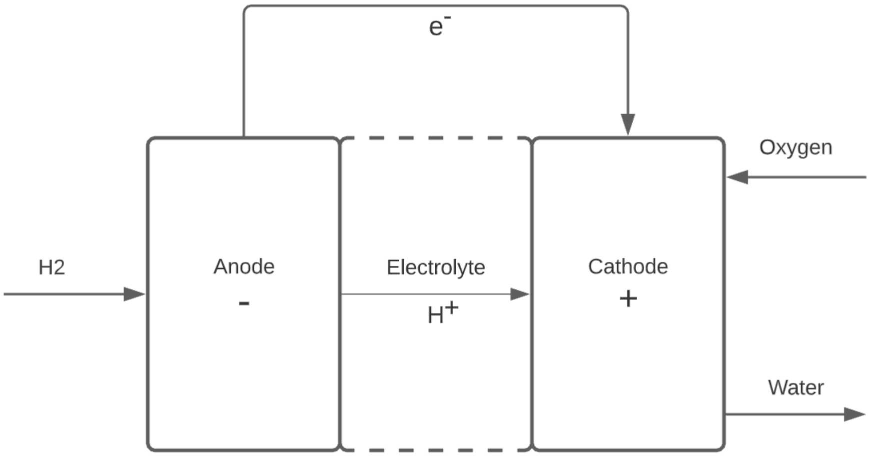

Figure 3.0.1: General Principle of a PEM Fuel Cell

Fuel cells require fuel and air to function. The fuel can be most types of hydrocarbons, but the most common fuels are hydrogen, ammonia and methane. Usually, ambient air is used as the air supply. The general fuel cells system requires fuel processing and reforming, air supply, thermal management, water management and electric power conditioning. Over time the fuel cells are degraded, and the efficiency of the fuel cells is continuously being reduced. The degradation is typically due to corrosion, but in some cases, it can be malfunctioning of the components.

There exist different types of fuel cells, usually categorized by the type of electrolyte that is used. In turn this determines the operating temperature of the fuel cells and the rest of the materials that are used in the fuel cell. The two types that are given a brief introduction in this paper is the proton exchange membrane fuel cell (PEM-FC) and the solid oxide fuel cell (SOFC).

3.1 PEM-FC

PEM-FCs are a type of fuel cells that are equipped with polymer membranes where positive hydrogen ions are able to flow through. Oxygen is arriving at the cathode reacting with the hydrogen cations and electrons from the circuit producing water and heat while ensuring that the cathode remains positively charged.

$$2H_2 \rightarrow 4H^+ + 4e^- \tag{3.1.1}$$

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \tag{3.1.2}$$

PEM-FCs operate at relatively low temperatures of around 60 – 80 degrees. However, for these low temperatures there are not many materials that can provide enough catalytic activity. Therefore, the PEM-FC often use platinum as catalyst, the downside is that this is a precious material that is driving up the cost of the fuel cell. Another aspect of using platinum as the catalyst is that the hydrogen fuel must be pure as platinum is degraded by contact with carbon monoxide (CO).

Advantages with PEM-FCs are the low operating temperatures which makes material selection flexible and quick to start up. PEM-FCs also have high power densities, making them light and compact. Which can be a good thing for maritime applications as this can counterweight some volume for increased fuel tank sizes.

3.2 SOFC

SOFCs are fuel cells that are equipped with a ceramic membrane and operate at high temperatures of up to 1000 degrees. Negatively charged oxygen ions are flowing through the membrane and reacting with the fuel at the anode. This reaction is freeing the electrons of the oxygen anion and results in water and heat.

$$O_2 + 4e^- \rightarrow 2O^= \tag{3.2.1}$$

$$H_2 + O^{=} \rightarrow H_2O + 2e^- \tag{3.2.2}$$

Due to the high operating temperatures, the SOFCs avoids the need for precious metals. Another advantage is that it requires no liquid which removes the potential for rapid material corrosion. However, disadvantages of SOFCs are the low flexibility in material selection. All the materials used in the fuel cell should have same thermal expansion coefficients to avoid mechanical failures. They are also slower to start up compared with the fuel cells with lower operation temperature such as PEM-FCs.

Chapter 4

Case

The study will be based on a case from Stolt Nielsen. The data provided were about ship characteristics, describing the machinery as well as technical documents related to the hull and cargo tanks of the vessel. Furthermore, operational data related to two different routes, the initial route of the vessel and the desired route to conduct the study on, were provided. The data used for the project are mostly based on these internal documents.

Advantages of performing the study on a real case is that the study can be performed on actual operational data which can give a more accurate picture than performing the study on a purely theoretical case. Furthermore, it can be easier to implement and apply the findings to the real world. However, disadvantages may arise from the fact that the results can be harder to interpret since the factors that are affecting the results can be harder to decouple.

4.1 Ship Characteristics

Provided were the electrical load analysis, final trim and stability booklet, general arrangement, capacity plan, final calculation of attained EEDI, machinery arrangement, and the procedure and arrangement manual for the vessel.

The vessel is an 33000-deadweight tonnage(dwt) chemical tanker installed with a main engine and three auxiliary engines running on heavy fuel oil (HFO) and/ or marine gas oil (MGO)

The machinery includes the main engine, auxiliary engines, a boiler and the fuel tanks, as well as the piping system and electrical circuits related to the engines. How the configuration of the machinery is affected when using fuel cells instead of internal combustion engines will be a central topic.

Some general data about the vessel is provided in Table 4.1.1 to give an overview of the vessel that is examined.

Table 4.1.1: Ship Characteristics

Capacity	32824.50 ton
Lightweight	11043.10 ton
LOA	185.00 m
Breadth	28.40 m
Depth	15.20 m
SMCR Main Engine	5850.0 kW x 85 r/min
Auxiliary Engine 1	1040.0 kW x 900 r/min
Auxiliary Engine 2	1240.0 kW x 900 r/min
Auxiliary Engine 3	1240.0 x 900 r/min

4.2 Operational Data

In the operational data provided are the coordinates, weather conditions, port names, average engine load, cargo load, fuel consumed and the draft for the vessel recorded once every 24 hour for the year 2020. Including the running hours of the main engine, auxiliary engines and the boiler. Two sets of operational data is provided, one relating to the initial route and one related to the trans-Atlantic route.

The vessel described in section 4.1 is sailing on the initial route. The operational data for the trans-Atlantic route is recorded by another vessel that is older and has an larger capacity. Since the initial route are not sailing the long distances where hydrogen has an advantage it is necessary to translate the vessel over to the new route. In this project this is done by creating a route independent model for the fuel consumption in chapter 5 this will be used to describe the fuel consumption of the vessel and the power required to sail on the trans-Atlantic route.

The route where the hydrogen study is being conducted are on a trans-Atlantic route. This sails mainly between two large continental ports of Houston and Rotterdam, and some smaller ports in North-East Europe. There are different operational conditions between the new route and the initial route of the vessel. While conducting the route study it is important to be aware of these differences as they affect the operation of the ship and the requirements for the fuel cells. To capture these differences in the most accurate way, a model is formulated which describes how the original fossil fueled vessel behaves when operating on the new route. The requirements for the fuel cells are then in turn drawn from this model before the conducting the main route study with the hydrogen machinery.

Some differences between these two routes that are worth noting, are the sailing distances for the new route is in general longer than the initial route, also the vessel spends more time waiting in port on the new route. Furthermore, the mean cruising speeds for the legs are different, and the weather conditions varies between the two routes since they are located in other parts of the world.

A summary of the general data for both routes are provided in appendix B which gives an overview of both the initial and the trans-Atlantic route.

Table 4.2.1: Trans-Atlantic Route

Voyage	Leg	From	To	Time at port (h)	Sailing time (h)	Waiting time (h)	Total time (h)	Distance (nm)	Mean transit speed (knots)
1	1	BEANR	USHOU	381	371	0	371	4576	12,33
2	1	USHOU	BEANR	139,48	386	0,02	386,02	5219	13,52
	2	BEANR	NLRTM	132	7,5	0	7,5	89	11,87
3	1	NLRTM	RUULU	127,5	125	0	125	1457	11,66
	2	RUULU	LVRIX	31,5	30,5	0	30,5	409	13,41
	3	LVRIX	LVVNT	107	11	0	11	127	11,55
	4	LVVNT	LTKLJ	115,52	7,5	0	7,5	99	13,20
	5	LTKLJ	PRGUY	95	315,5	0	315,5	4969	15,75
	6	PRGUY	PRSJU	8	16	0	16	192	12,00
	7	PRSJU	USHOU	267,8	149	0	149	1891	12,69
4	1	USHOU	USTXT	24,2	1,2	0	1,2	0	12,00
	2	USTXT	USBTR	133,4	26,5	0	26,5	340	12,83
	3	USBTR	BEANR	156,5	347,4	0	347,4	4803	13,83
	4	BEANR	NLRTM	244,1	43,7	0	43,7	422	9,66
	5	NLRTM	FRLEH	29,7	19,2	0	19,2	254	13,23
5	1	FRLEH	USHOU	40,9	397,8	0	397,8	5159	12,97
	2	USHOU	USHOU	40,1	36,5	0	36,5	362	9,92
	3	USHOU	USHOU	141,9	59,4	24	83,4	631	10,62
	4	USHOU	USHOU	181,7	26,8	0	26,8	294	10,97
6	1	USHOU	BEANR	168,8	419,2	0	419,2	5420	12,93
	2	BEANR	NLRTM	89,5	59,7	0	59,7	583	9,77
7	1	NLRTM	USHOU	-	349	0	349	5128	14,69
8	1	USHOU	USFPO	140,5	12	0	12	127	10,58
	2	USFPO	BEANR	-	418	0	418	5275	12,62

Chapter 5

Fuel Consumption Model

5.1 Model Introduction

In this paper the vessel that serves as a potential possibility to develop liquid hydrogen fuel cell machinery is sailing on a route around Europe and the Middle East. However, for a hydrogen driven vessel the most interesting route to examine is the trans-Atlantic route and not the initial route which it is currently sailing today, informed by Stolt Nielsen. This project sets out to determine the number of fuel tanks, the power rating of the fuel cell system, the number of fuel cells required and the feasibility of operating a hydrogen driven chemical carrier sailing across the Atlantic Ocean.

To figure out the amount of hydrogen needed, the chemical energy content of the volume of heavy fuel oils (HFO) consumed during each leg is calculated. Multiplying the total energy content by the efficiency of the engine for each leg is resulting in the energy needed to complete a given leg. Using this approach, it is necessary to determine the fuel consumption of the vessel sailing on the trans-Atlantic route.

To be able to examine how the fuel consumption and how the required power output for the vessel will behave on a new route it is necessary to create a route independent model. The downside of this approach is that parts of the operational data will be lost as they will not be translated to the new route.

A model is a simplification of the real system and will not be completely accurate, but a good model will provide valuable insights about how the vessel will operate on different routes and in different operational conditions. This section will present the model and the basis and assumptions which it is built upon.

A general model is created for the vessel which describes the fuel consumption and power output of the vessel when sailing on different routes. The model is a function that can take route specific data as input to produce a desired output. This gives the possibility to analyze the behavior of the vessel for many different routes as well as how individual operational conditions are impacting the fuel consumption. Operational conditions are all the factors that impact the vessel when sailing. Examples are the speed, cargo load and weather. The input for the model is the distance, speed, cargo load, boiler running hours and time in port for each leg. All this information is found in the operational data.

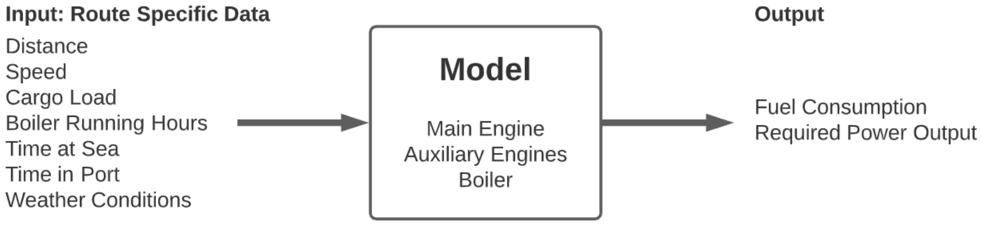

Figure 5.1.1: Model Concept

The foundation for the model is the operational and ship data, and knowledge of ship machinery, design and operational research. Internal combustion machinery consists of the main engine, auxiliary engines, boiler, fuel tanks and the circuit and piping system related to the engines. To be able to model the fuel consumption all the components that consume fuel are analyzed individually and the fuel consumption for each one are be expressed mathematically.

Components that consume fuel are the main engine, auxiliary engines and the boiler. The main engine is used for propulsion, while the auxiliary engines are used for pumps and electrical loads on-board the ship. The boiler is used for heating of cargo and bunker fuel and tank cleaning.

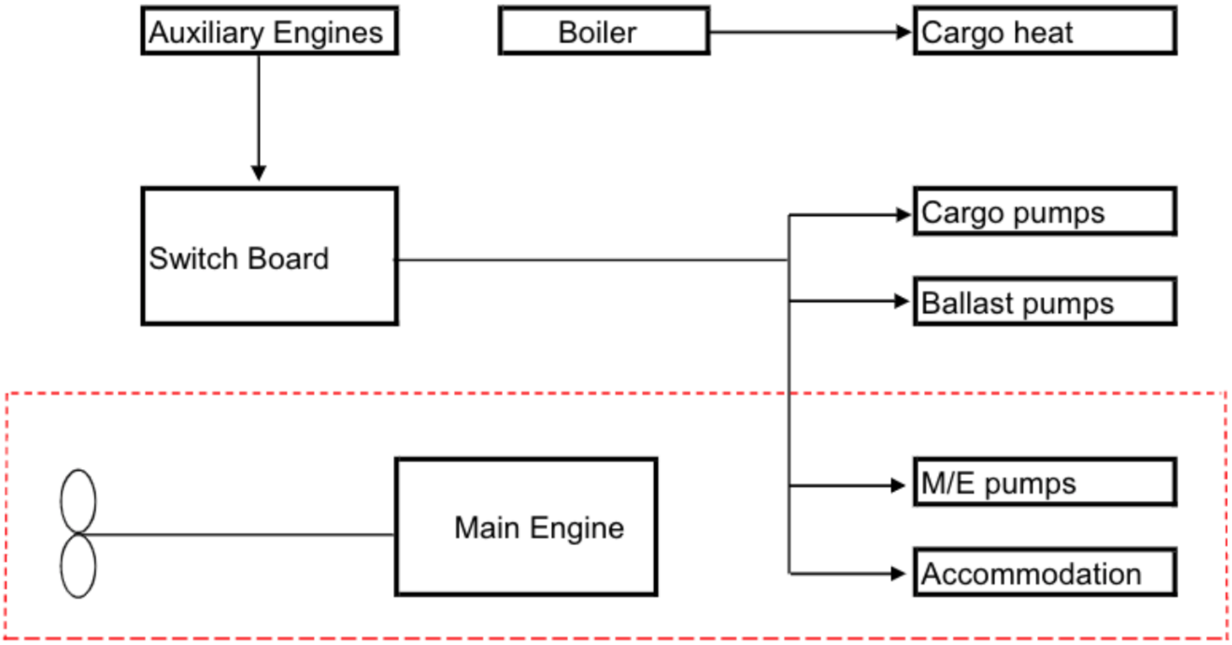

Figure 5.1.2: Schematic figure of propulsion and electric power supply system

The main properties of the engines are the efficiency to convert fuel to energy and the specific fuel consumption (SFC). SFC indicates how much fuel are consumed per unit of power output each hour and includes the efficiency of the engine. To account for small differences between individual engines of the same type, design flaws and other uncertainties the SFC is multiplied with an iso-tolerance of 5%. The value of the iso-tolerance is based on information from LMG Marin.

Table 5.1.1: Engine Properties

Component	SFC (g/kWh)	Efficiency (%)
Main Engine	165	38
Auxiliary Engine 1	216	38
Auxiliary Engine 2	216	38
Auxiliary Engine 3	216	38

To determine the accuracy of the model the fuel consumption is calculated for each leg for the initial route and compared with the actual fuel consumption from the operational data. This is a way to make sure that all relevant factors are accounted for as well as serving as a basis for further work and improvement on the model. After comparing the model with the operational data, it will be applied for the trans-Atlantic route which is the foundation for the studies regarding the fuel cells later in the project.

5.2 Main Engine

The main engine is used for propulsion when sailing, and is not used when it is moored at port. It's fuel consumption is determined by the speed profile, the weather conditions and cargo load during the given leg.

5.2.1 Power/Speed Curve

The power speed curve graphically displays the relationship between vessel speed and power output in calm weather with no wind or waves. This curve is created by running the vessel through speed trials and is provided by the ship builder. The required power output is dependent on the amount of resistance it needs to overcome. This in turn is based on the displacement of the vessel, due to the quantity of water it needs to displace in order to move. For deeper drafts, when the vessel is loaded, it will require more power than for lower drafts, i.e., when the ship is in ballast for this vessel. However, this is not always the case, for some vessels LMG Marin have worked on, the required power increase for smaller drafts.

Figure 5.2.1 shows the relationship between cargo load and draft. This is found by plotting the average draft, the mean of draft aft and draft fore, against the cargo load from the operational data for the vessel. A second order polynomial function is used to express this relationship to be able to find the draft for an arbitrarily cargo load. The reasons for different drafts for the same cargo load can be explained by differences in amount of bunker fuel, fresh water on-board, and ballast water to remove trim and list for the vessel.

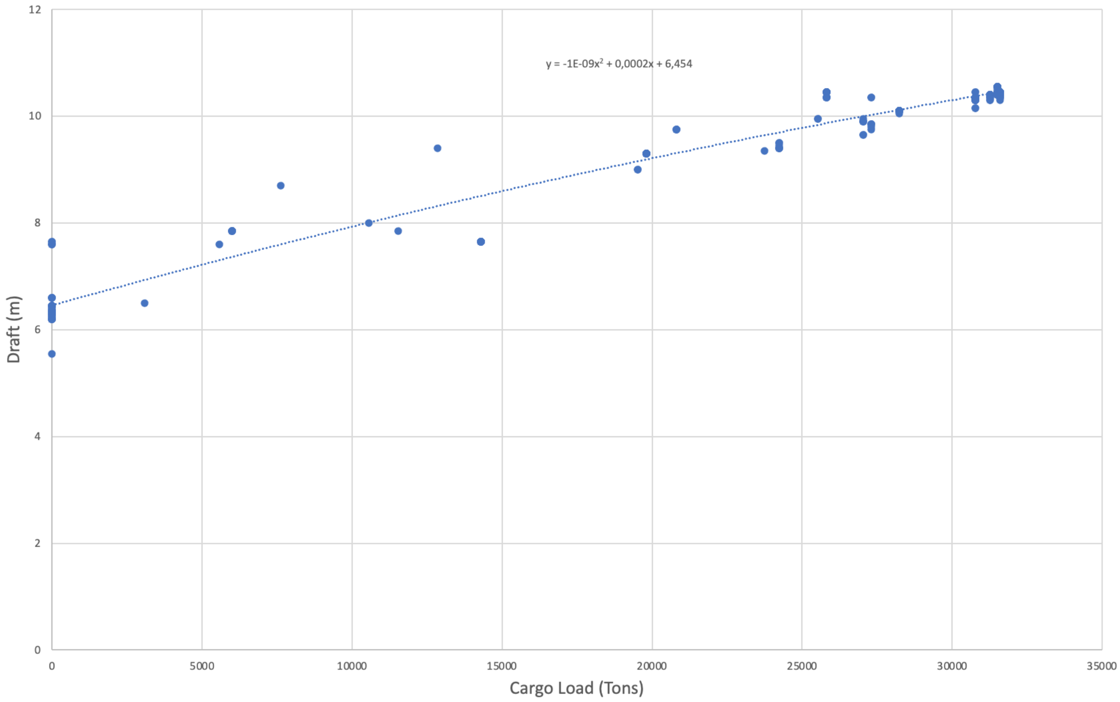

Figure 5.2.1: Draft vs Cargo Load

The power speed curves from speed trials are only given for the scantling draft and the design draft of 10.4m and 9.7m respectively. To determine the power requirement for lower drafts the power output are extrapolated from these two drafts. Extrapolations are in general more imprecise than interpolations and using this approach for lower drafts can cause some inaccuracy for the vessel when sailing in ballast and light cargo loads.

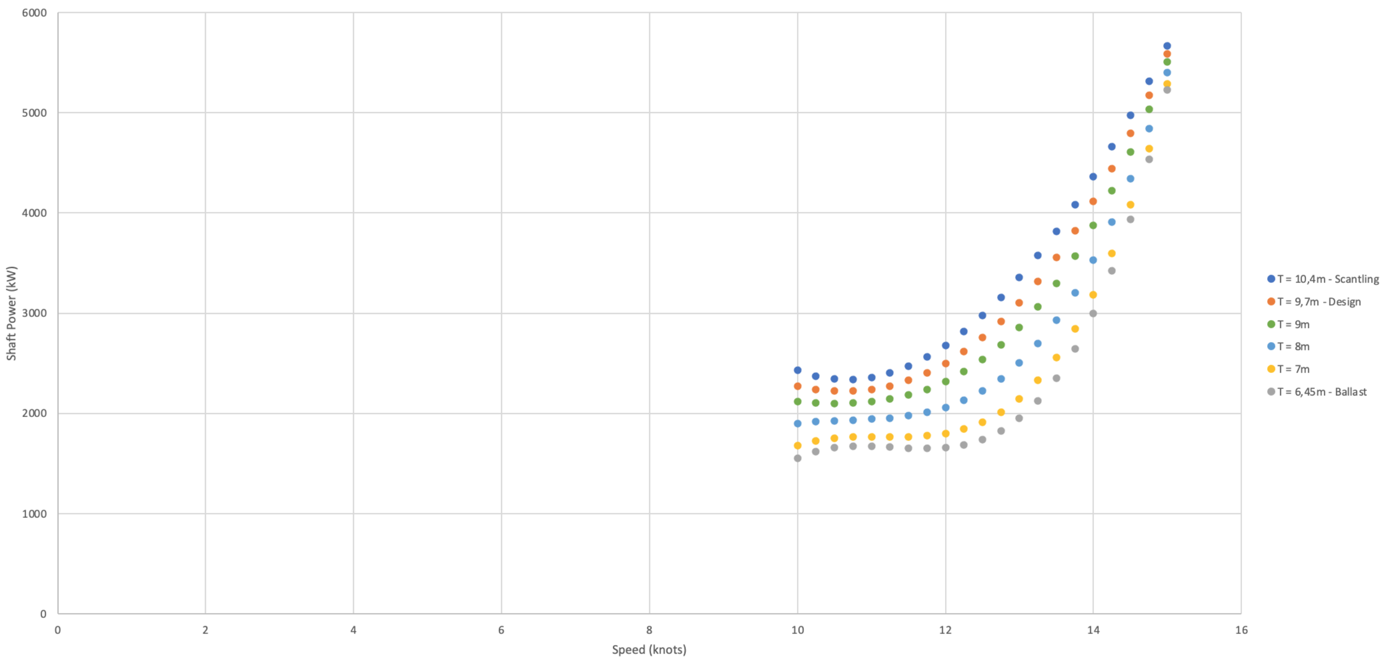

Figure 5.2.2: Power vs Speed Curves

For each leg on the initial route the cargo load is found to determine the draft of the vessel. Then the mean sailing speed is used to find the power output. This results in the required power output for each leg in calm weathers. By using the mean speed, the speed profile during a leg is neglected. Since the duration of the legs usually are over several days, it is assumed that the speed will remain fairly constant, which makes the changes in speeds during a leg negligible. However, for some of the legs with short duration this can be a source of inaccuracy for the model.

In addition speed and displacement, the power output is also affected by the hull form and propeller design. A general way to categorize the resistances caused by the form of the hull in calm weathers is into frictional resistance, residual resistance and air resistance [8]. The frictional resistance is determined by the form of the hull, the more streamlined and smoother the hull the lower the frictional resistance. This is the greatest contributor to the total resistance in calm weather. Wear and tear as well as fouling of the hull during the lifetime of the vessel will increase the frictional resistance. This means that the actual required power will be increasing over time compared to the speed power curve, as these were based on speed trails when the ship was new. The residual resistance is the energy loss to the waves and eddy current that are created when the vessel is moving through the water. Lastly, the air resistance which is determined by the speed and cross-sectional area of the vessel. However, this is not the same as wind resistance, and air resistance is not a large contributor to the total resistance in calm weathers compared to the frictional and residual resistances.

These factors are related to the hull form of the vessel. This means that when examining the same vessel running on hydrogen it is assumed that the propeller design and hull form remains the same.

5.2.2 Weather

Having determined the required power output in calm weathers for different speeds and loading conditions the added resistance from weather conditions are being examined. Forces from wind, waves, swells and currents are increasing the resistance for the vessel which in turn increases the required power output. The weather data provided is based on the observational approach to categorize the weather conditions, where the wind force is measured in the Beaufort scale while the wind waves and swell force are measured in the Douglas sea scale. The currents are not included and will be neglected in this paper.

For each of the legs the required power output for calm weather found by using the speed power curves are compared with the actual power output during each day for every leg. Each leg is divided up into several instances which are periods of 24 hours. For each instance the direction and force of the wind, waves and swells are provided, as well as the average power output during the period. The added resistance can be found as the percentage the average power output for an instance is above the power output calculated in calm weathers for the same leg. However, using this added resistances will account for more than just the weather. This will include all the other factors not accounted for, like the fouling of the hull, as well. The purpose is to find a relation between the weather conditions and the added resistance.

By sorting all the instances for all legs after wind force, wave force and swell force. There is a clear relationship between the wind force and the added resistance. Both the force of the wind and waves are dependent on each other so this relationship holds true for the wave force as well. However, for the swells there was no clear relationship with the added resistance. Therefore, the added resistance, which will be called the sea-margin, are expressed as a linear function based on the average wind force during a leg. As there is no clear relationship between the wind direction and the added resistance, illustrated in table 5.2.4, the direction will not be of importance in the model.

However, the weather conditions are dynamic and using this static approach using only the average wind force for the whole leg can lead to some inaccuracy in the model.

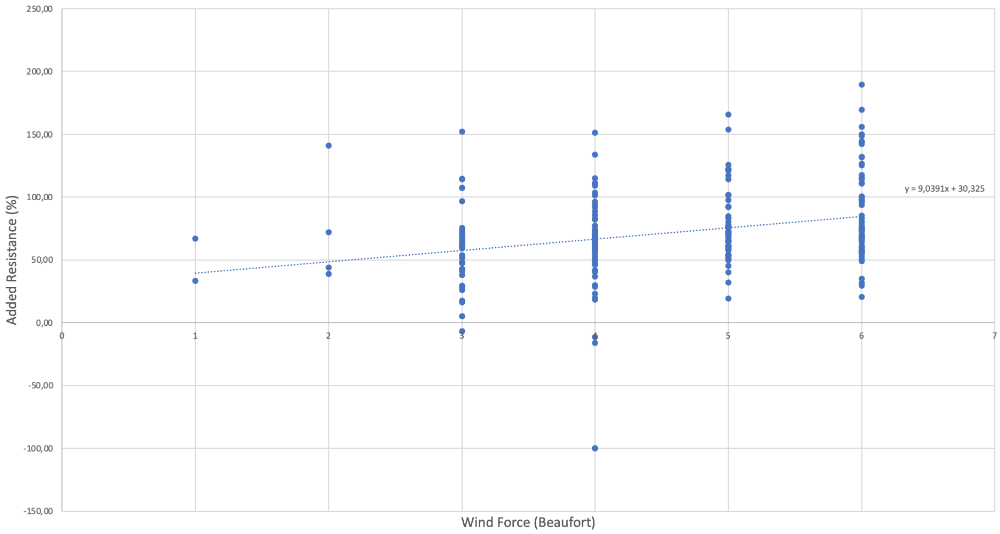

Figure 5.2.3: Added Resistance vs Wind Force

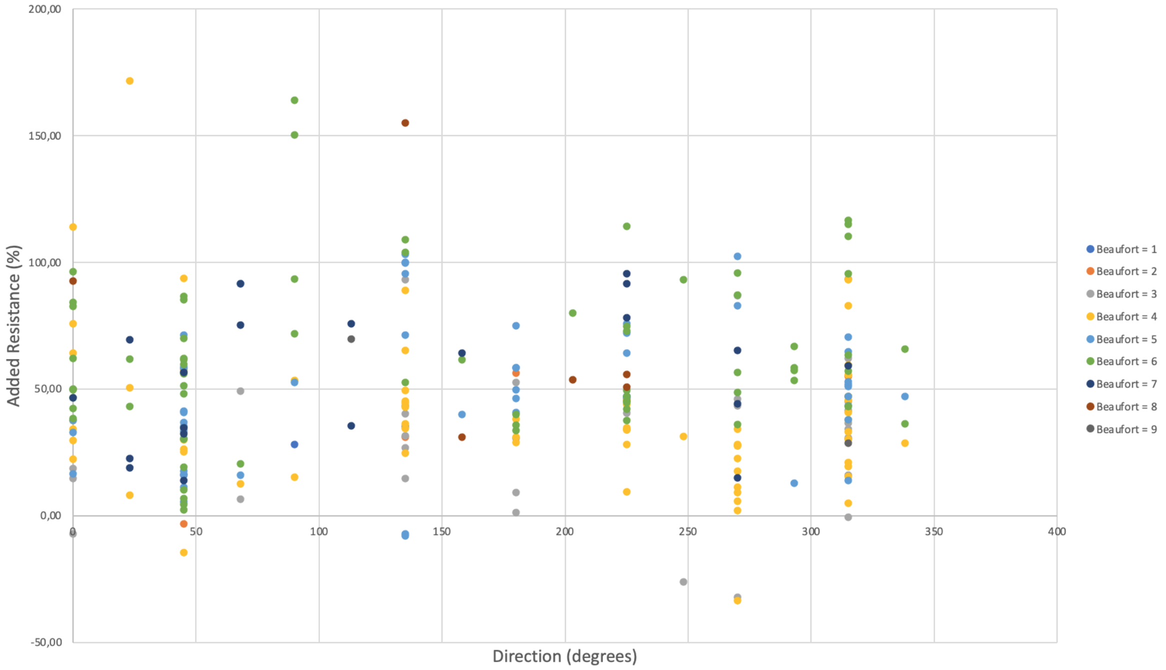

Figure 5.2.4: Added Resistance vs Wind Direction

5.2.3 Main Engine Fuel Consumption

Combining the power requirement found from the speed power curves and the sea-margins results in the actual power output of the vessel. This is then used to calculate the fuel consumed during all legs and compared with the fuel consumption for their respective legs from the operational data.

Given the power output required for each leg the fuel consumption K_{ME} were calculated.

$$K_{ME} = \frac{P \quad t^{sailing} \quad SFC_{ME}}{\rho_{HFO}} \tag{5.2.1}$$

P - Power output in kW

$t^{sailing}$ - Time spent sailing in h

SFC_{ME} - Specific fuel consumption of the main engine in kg/kWh

ρ_{HFO} - Density of HFO in kg/m3

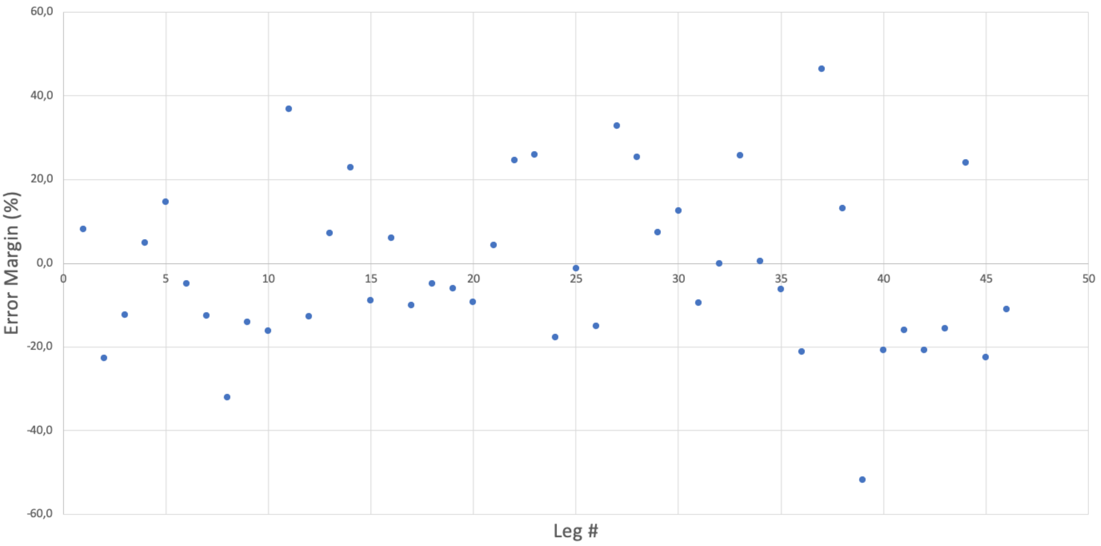

Figure 5.2.5: Main Engine, Error Margin vs Leg

$$\epsilon = \frac{K_{ME}^{A} - K_{ME}}{K_{ME}} \cdot 100\% \tag{5.2.2}$$

Where K_{ME}^{A} is the actual fuel consumption from the operational data.

For a completely accurate model the calculated fuel consumption should equal the fuel consumed from the operational data. However, this is an unrealistic requirement to meet as there are several complex factors that need to be accounted for, but the purpose is to make sure the model is accurate enough to yield valuable insights to the task at hand.

At port the fuel consumption from the main engine will be zero.

5.3 Auxiliary Engines

The auxiliary engines are providing power to the generators which supplies the vessel with electricity. There are three auxiliary engines on-board the vessel, these can be used individually or in combination with each other. Generating electricity will result in a loss of energy equal to the efficiencies of the auxiliary engines and the generators. However, the efficiency of generators are generally high. To determine the fuel consumed by the auxiliary engines all the energy requirements that are not related to propulsion on-board the ship must be measured. The collective term for these loads are referred to as the hotel load.

The electrical load table is an overview of all the non-propulsion loads on-board the ship. It gives an overview of all the components on the ship and how much energy on average each of these require for different modes of operation. This table is developed at newbuilding stage with the purpose of giving an indication of the hotel load for the vessel. However, in operation these values can be slightly different.

The loads in the table are divided into operations at port and at sea. A summary of the electrical load table is presented in Table 5.3.1. Where all the components on-board have been collectively categorized into intermittent, continuous and scrubber loads. All pieces of equipment that require power but are not continuously on, are grouped as intermittent loads. Examples of this can be pumps and fans. In the table all intermittent loads are assumed to be used 40% of the time. The continuous loads are referring to all the loads that are on all the time. Lastly, the scrubber load is the energy that is consumed by the sulphur cleaning system.

If the vessel is running on very low sulphur oil it is not required to use the scrubber. However, since the vessel that are being examined are running on heavy fuel oil (HFO) and marine gas oil (MGO) it is necessary to account for this load when determining the accuracy of the model. If it is not accounted for, the calculations in the model will be an underestimation of the real value found in the operational data. Summing the intermittent, continuous and the scrubber load results in the total load which will represent the hotel loads of the vessel.

Table 5.3.1: Electrical loads

*All numbers in kW	**Sailing**			**Maneuvering**	**Cargo handling**	**At port**
	Without TK cleaning	**N2**	**With TK cleaning**			
Intermittent load	235,8	247,2	323,3	553,5	285,7	193,7
Continuous load	560,3	559,5	810,3	1368,7	1663,8	303,8
Scrubber load	150	150	150	150	63,1	63
Hotel load without scrubber	796,1	806,7	1133,6	1922,2	1949,5	497,5
Hotel load with scrubber	946,1	956,7	1283,6	2072,2	2012,6	560,5

At sea the hotel load is divided into three different modes of operation, without tank cleaning, with nitrogen, and with hydraulic power pack. To be able to completely determine the correct distribution between these three modes, detailed cargo data and general ship data is required. Therefore, to be able to determine the mean hotel load at sea it is assumed that 80% of the time it is running without tank cleaning, and 20% with nitrogen and hydraulic power pack.

$$P^{H,S} = 0.8P^{normal} + 0.2P^{N2} \tag{5.3.1}$$

$P^{H,S}$ - Hotel load in kW

P^{normal} - Total load without tank cleaning in kW

P^{N2} - Total load with nitrogen/ hydraulic power pack in kW

The fuel consumed by the auxiliary engines at sea is then calculated by using the specific fuel consumption for the main engines and the hotel load during sailing.

$$K_{AE}^{S} = t^{sea} \quad P^{H,S} \quad \frac{SFC_{AE}}{\rho_{HFO}} \tag{5.3.2}$$

K_{AE}^{S} - Fuel consumed by auxiliary engines at sea in m3

t^{sea} - Time at sea in h

SFC_{AE} - Specific fuel consumption for auxiliary engines in g/kWh

ρ_{HFO} - Density of HFO in g/m3

When the vessel is at port the hotel load is dependent on whether cargo handling is performed or if it is waiting idly at port. Only the fuel that are consumed when the vessel is moored at port are included. Therefore, fuel consumed when maneuvering in and out of port are not included. This should be accounted for in the fuel consumed when sailing. However, since the duration of the legs usually are over several days this will be negligible as the time spent maneuvering in and out of port are around 1.5 hours to 3 hours, as informed by Stolt Nielsen. The amount of time the vessel is spent cargo handling is dependent on the quantity of cargo that is loaded or offloaded at port and the discharge rate of the pump and piping system. For this vessel the stripping system for each individual cargo tank is designed to be able to unload 330 m3/h and the maximum unloading capacity for the vessel is 1650 m3/h according to the procedures and arrangement manual. The quantity of cargo unloaded or offloaded is the difference between cargo at arrival and departure found in the operational data.

$$t^{cargo} = \frac{|Q_{arrival} - Q_{departure}|}{r} \tag{5.3.3}$$

t^{cargo} - Time spent cargo handling in h

$Q_{arrival}$ - Cargo load at arrival in m3

$Q_{departure}$ - Cargo load at departure in m3

r - Unloading rate in m3/h

For the remainder of the time in port, when the vessel is not engaged in cargo handling, it is assumed that it is waiting idly at port.

$$t^{wait} = t^{port} - t^{cargo} \tag{5.3.4}$$

t^{wait} - Time spent waiting at port

t^{port} - Total time at port

The hotel load is calculated as the weighted average load based on the amount of time spent cargo handling and waiting at port. For each port the hotel load may be different depending on the amount of cargo it is unloading or loading.

$$P^{H,P} = \frac{1}{t^{port}}(t^{cargo}P^{cargo} + t^{wait}P^{wait}) \tag{5.3.5}$$

$P^{H,P}$ - Hotel load at port in kW

P^{cargo} - Total load when cargo handling in kW

P^{wait} - Total load when waiting at port in kW

Similarly to when the vessel is at sea, the fuel consumption at port is calculated by the time in port, the specific fuel consumption and the weighted average hotel load for each individual port.

$$K^{P}_{AE} = t^{port} \quad P^{H,P} \quad \frac{SFC_{AE}}{\rho_{HFO}} \tag{5.3.6}$$

K^{P}_{AE} - Fuel consumed by auxiliary engines at port in m3

Finally the calculated values are compared with the operational data to determine the accuracy of the model.

$$\epsilon = \frac{K^{A,S}_{AE} - K^{S}_{AE}}{K^{S}_{AE}} \cdot 100\% \tag{5.3.7}$$

$$\epsilon = \frac{K^{A,P}_{AE} - K^{P}_{AE}}{K^{P}_{AE}} \cdot 100\% \tag{5.3.8}$$

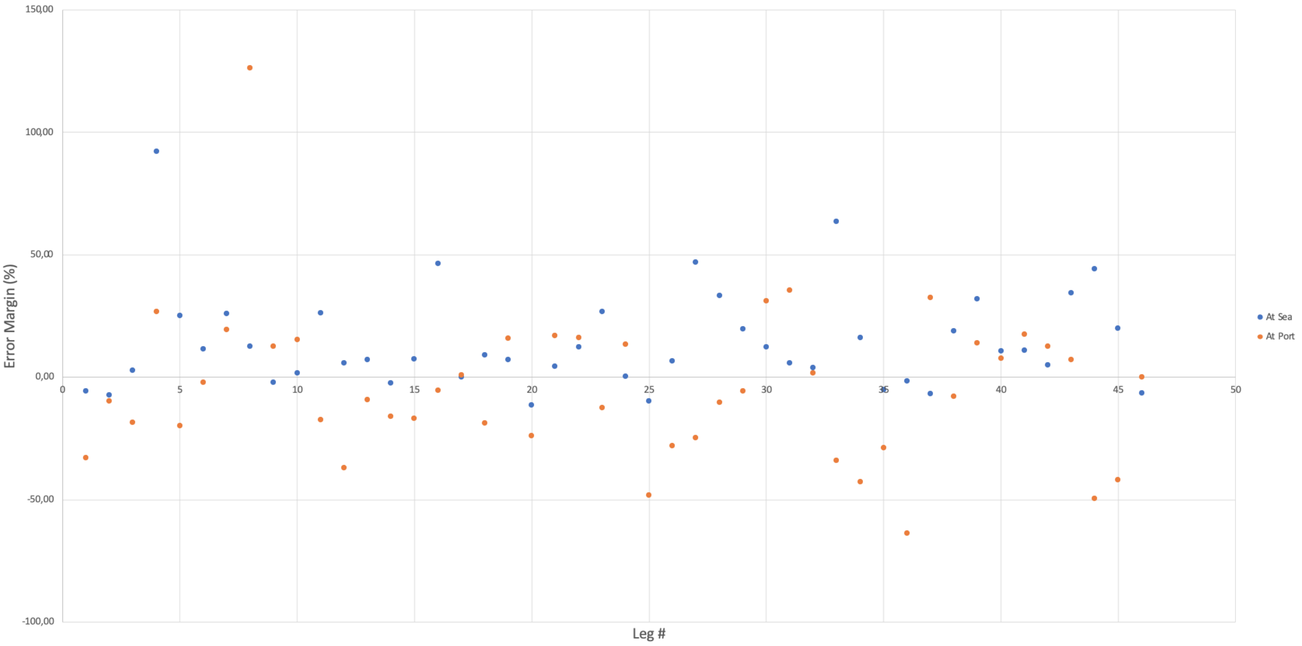

Figure 5.3.1: Auxiliary Engines, Error vs Leg

Overall the accuracy for the fuel consumption calculations for the main engine is good, both in port and at sea. There are some legs that are not accurate, that miss with over 50%. However, most of the legs are within the margin of 20% some case underestimating and in some cases overestimating, this is expected due to the complex nature of the operation of the vessel.

5.4 Boiler

The boiler is an integral part of chemical carriers. It is used to generate steam for cargo and fuel oil heating, tank cleaning and lubricant oil purification as well as some smaller tasks like heating of accommodations and it can be running both at sea and in port. The use of the boiler is very cargo dependent, for some legs it is used all the time and for other legs it is not used at all. This makes the accurate modeling of the fuel consumption a challenge. This requires specific data about the types of cargo it is transporting as well as decisions regarding when to perform tank cleaning and other tasks. Due to a lack of this data and general data about the boiler, makes this component quite difficult to model accurately.

Therefore, assessing the quantity of fuel consumed by the boiler will be simplified using the operational data about the average fuel consumption and running hours at sea as well as assuming that the boiler is running 15% of the time in port. These assumptions are made on the basis of the operational data but using this sample might not be an accurate representation over longer time periods.

However, based on observations using the overall average fuel consumption for the boiler, results in overestimations for long running hours. Therefore, instead of using the overall average the average fuel consumption will be a function of running hours. Where the average consumption is decreasing the longer the boiler is running, up until 87 hours when a linear average of 0.21 m3/h will be used for longer running hours. This simplification will result in noisy results but the boiler is the smallest contributor to the overall fuel consumption of the vessel therefore the model will still yield valuable results.

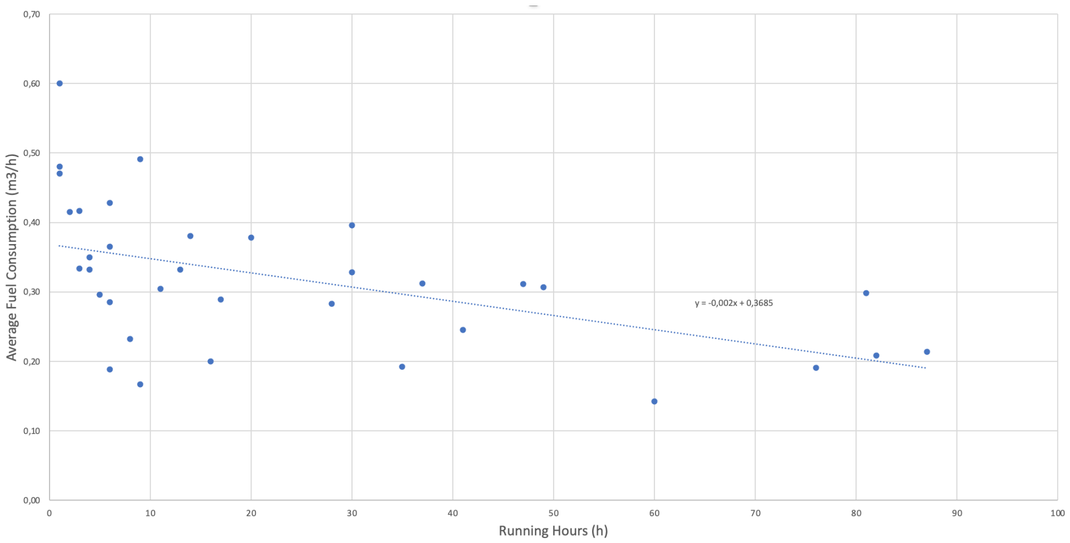

Figure 5.4.1: Average Fuel Consumption vs Running Hours

To calculate the fuel consumption of the boiler K_B^{avg} the average fuel consumption per hour from the operational data is taken and for this design it assumes that the boiler is running 20% of the time. Then the fuel consumption in port and sailing can be calculated.

Fuel consumption while sailing.

$$K_B^S = K_B^{avg} \cdot t^{sea} \cdot t^{running} \tag{5.4.1}$$

Fuel consumption at port.

$$K_B^P = K_B^{avg} \cdot t^{port} \cdot 0,15 \tag{5.4.2}$$

K_B^{avg} - Average fuel consumption boiler, in $\frac{m^3}{h}$

t^{sea} - Time at sea in h

t^{port} - Time at port in h

$t^{running}$ - Boiler running hours

$$\epsilon = \frac{K_B^{A,S} - K_B^S}{K_B^S} \cdot 100\% \tag{5.4.3}$$

$$\epsilon = \frac{K_B^{A,P} - K_B^P}{K_B^P} \cdot 100\% \tag{5.4.4}$$

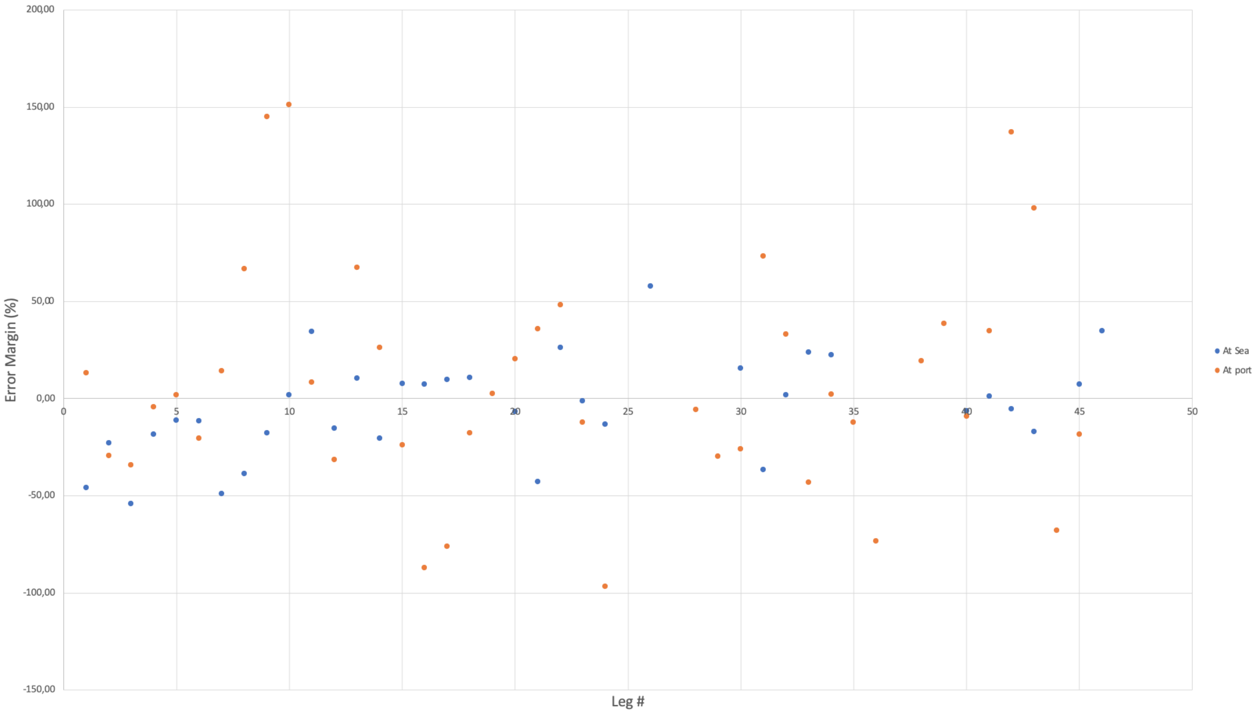

Figure 5.4.2: Boiler, Error vs Leg

The accuracy for the fuel consumption for the boiler is not as good as it is for the main engine and auxiliary engines. This is because of the lack of data regarding the boiler. However, for this project it will be an alright assumption for the fuel consumption.

5.5 Total Fuel Consumption

Combining the fuel consumption by the main engine, auxiliary engines and boiler the total fuel consumption for the vessel is found. This model will not examine additional sources power consumption which may arise for the storing and fuel treatmeant of LH2 on-board. Again this is compared to the operational data to display its accuracy.

$$K^S = K_{ME} + K^S_{AE} + K^S_B \tag{5.5.1}$$

$$K^P = K^P_{AE} + C^P_B \tag{5.5.2}$$

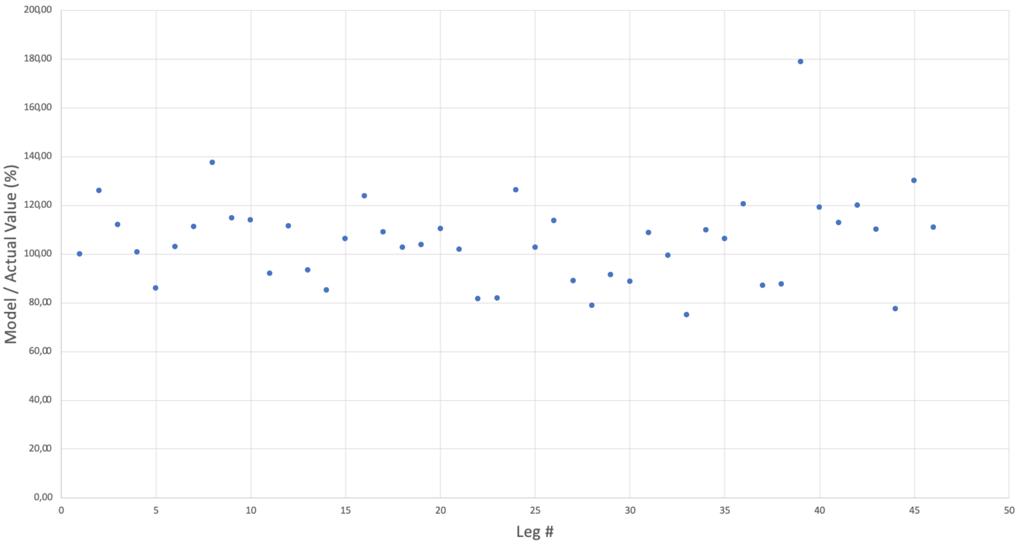

Figure 5.5.1: Accuracy of Model at Sea

The overall accuracy of the model at sea is good as most legs are within the 20% margin of under- or overestimating. For the average of all the legs the model is overestimating the fuel consumption by 5%.

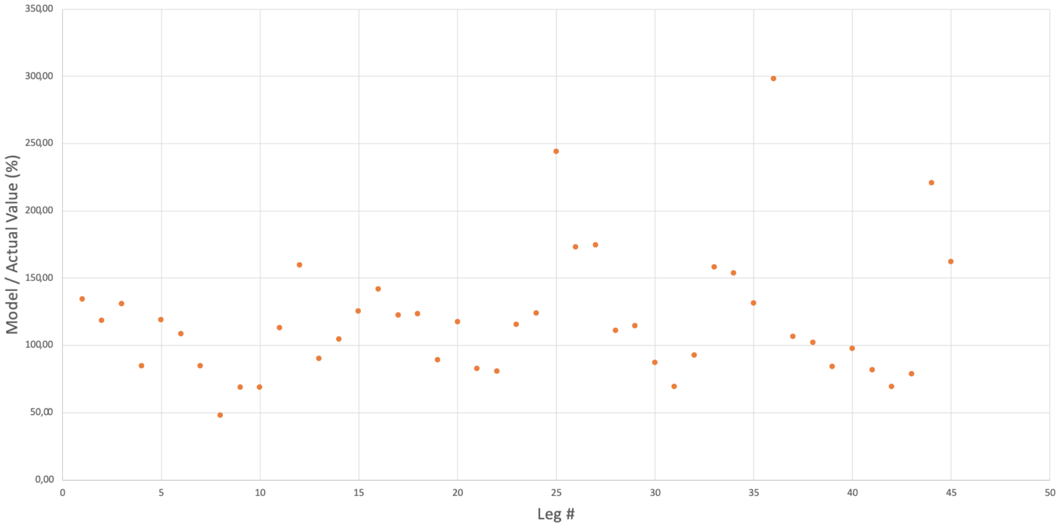

Figure 5.5.2: Accuracy of Model at Port

For the model's accuracy at port the model is more imprecise, so it should be taken caution when working with the fuel consumption at port. However, for the purpose of this project it is acceptable.

Chapter 6

Method

The method is presenting two studies, the operational study 6.1 and the general arrangment study 6.2. This chapter introduces the method and approach of the studies while the results are presented in chapter 7.

6.1 Operational Study

This section investigates the operational aspects for the chemical carrier sailing between North America and Europe. In general, the approach of an operational study is to decouple all the operational conditions to be able to study each one of them individually to determine their effect on the vessel. The basis for the study will be the model for the fuel consumption outlined in chapter 5.

Exploring the operational implications of operating the vessel is important in order to identify the required amount of hydrogen and the power output the vessel needs to sail the trans-Atlantic route. Furthermore, for the vessel to be feasible it requires hydrogen bunkering infrastructure along the route, and it must be economically competitive compared to vessels running on conventional fuels. If it is not competitive it will be difficult to justify the investment in building such a vessel.

The operational study is going to answer the following questions. How many LH2 fuel tanks does the vessel require to be able to operate under different conditions? What is the required power for the vessel? Which ports are the best candidates to develop hydrogen infrastructure? What is the break-even price of hydrogen which makes the vessel economically competitive?

To answer these questions the operational study will be divided into four parts.

1. Power Required 6.1.1
2. Number of LH2 Fuel Tanks 6.1.2
3. Bunkering 6.1.3
4. Break-Even Price for Hydrogen 6.1.4

The operational study is performed by grouping route specific data and operational conditions and create a set of different scenarios to see how the vessel is performing under different circumstances and how each of the individual operational conditions are impacting the performance.

In all part some general operational conditions are identified, and the operational study will focus primary on the trans-Atlantic legs, where the sailing distances are found in the operational data. The expected sailing speed for the vessel will be in between 11 knots and 14 knots. Therefore, to look at the impact from the speed, all speeds between 11 and 14 knots, with a step of 0.1 knots, will be examined in this study.

The vessel is going to be fully loaded, as the minimum requirement should be for the vessel to be able to utilize all of its available capacity if needed. It is evident that if the LH2 vessel is able to sail the distance when fully loaded, it will be feasible for lighter cargo loads as well.

To account for the weather, it will be assumed that the weather conditions is constant during the trip and the weather conditions are divided into good, moderate and bad weather. The average wind force for each category is found in the operational data for the trans-Atlantic route. Good weather is the lowest wind force among the legs from the data, moderate is the average of all the wind forces for all of the legs, and bad weather is the largest average wind force.

According to LMG Marin a sea-margin of 15% in good weather is common practice. However, the sea-margin that are used in this project is accounting for more than only the weather, it is also accounting for the wear and tear and fouling of the hull as well as other resistance that are not captured by the power/speed curve. This increases the resistance, and thus the sea-margin.

Table 6.1.1: Weather Conditions

Weather Conditions	**Average Wind Force**	**Sea-margin (%)**
Good	1	39,36
Moderate	3,7	63,77
Bad	7	93,60

Furthermore, different load conditions are examined. These are categorized into what the engine is providing power to, only propulsion, both propulsion and hotel load, or to propulsion, hotel load and the boiler. As this gives an overview of whether the LH2 can be used for everything, or if some of the loads must be powered by another source.

An overview of the operational conditions are listed.

- Distance
- Speed
- Cargo Load
- Weather Condition
- Load Condition

The number power required will be the input for the design of the vessel in chapter 6.2.

6.1.1 Power Required

It is important to determine the amount of installed power the vessel require to be able to power all loads on-board. This will have impact on the size of the fuel cell system. The more installed power it requires the more expensive the machinery would be. Therefore, the vessel would be designed to meet the power requirements for all the loads that it is supposed to serve. In this part of the operational study the required power will be analyzed for the different load conditions as well as for different speeds sailing in different weather.

For the fuel cell system arrangement, the goal is to determine whether it is possible to arrange enough fuel cell units to meet the power requirement. The maximum power required is when it is supplying power to all loads on-board. Therefore, the required power is found for when it is providing power to propulsion, hotel load and the boiler. It ensures that if it is feasible to install enough power to everything, it is also able to install power for when the fuel cell system is only providing power to propulsion or both propulsion and hotel load.

The required power is determined by demanding that the vessel should be able to minimum maintain an operating speed of 12 knots in all weathers when providing power supply to propulsion, hotel and the boiler. At sea the power requirements are significantly higher than at port. By using the power output at sea as the requirement for the arrangement for the fuel cell system, the required power at port is met as well.

When calculating the power requirement, the calculation for the shaft power from the model is used. For the hotel load it will be assumed that the vessel will be run in normal condition 80% of the time and 20% on nitrogen and hydraulic power pack. The scrubber is not used when sailing on LH2 so this load will not be included. This gives a hotel load of 500 kW, not accounting for the boiler.

The fuel cell system is going to provide power in the form of electricity and the current installed boiler is running on HFO and MGO. Therefore, the boiler must be changed to an electrical boiler to be able to be powered by the new system. Due to lack of supplier data for the electrical boiler the electrical load will be assumed to be 200 kW. This results in a total hotel load of 700 kW for the vessel.

Using the model to calculate the power required for different speeds, load conditions and weather conditions results in the power requirement table in Appendix I.

The results for the power required are presented in 7.1

In this project a supplier of low temperature PEM-FCs are examined. These have an operating temperature between 60 - 80°C [1]. The waste heat can be utilized to reduce the hotel load or increase the efficiency of the boiler by using a heat exchanger. The hotel load can be further decreased by introducing spinning reserves, frequency control equipment and low energy equipment to further decrease the hotel load for the vessel. However, this is not examined further in this project, but is an important aspect to be aware of, as this would reduce the required power as well as the hydrogen consumption for the fuel cells leading to increased competitiveness of fuel cells.

6.1.2 Number of LH2 Fuel Tanks

This part will examine how much hydrogen the vessel requires when operating under the different conditions. Sailing between North America and Europe is a long journey, and it is expected that it will require a lot of hydrogen to be able to complete this trip. Compared to short-sea shipping the on-board storage of hydrogen is not as big as a limitation as it is for deep-sea shipping.

The aim of this part is to determine the number of LH2 fuel tanks the vessel needs to be able to operate on the trans-Atlantic route. This is determined by examining a set of different number of fuel tanks on-board without taking into account the feasibility of arranging these on the ship, Figure 6.1.2. Data regarding LH2 fuel tanks are provided by Norled to the author. The tanks used in this project have a capacity of 8 tons of useable LH2.

Table 6.1.2: Number of Fuel Tanks

Fuel Tanks	**Capacity (tons)**
8	64
10	80
12	96
14	112
16	128

The number of tanks that can be installed on the vessel will determine how far it can sail. In this project the maximum distance the ship can sail using up all available hydrogen is called the range of the vessel.

To calculate the range, the model for the fuel consumption is used to find the hydrogen required to sail various distances for a set of speeds. The longest leg on the trans-Atlantic route is 5420 nm, and the vessel is expected to operate in the range between 11 and 14 knots. Therefore, the fuel consumption for the main engine, auxiliary engines (hotel load) and the boiler is found for a set of combinations of distances between 1000 nm and 7000 nm and speeds between 11 and 14 knots.

A matrix is constructed for the main engine for each of the three weather conditions, and one matrix for the auxiliary engine and one for the boiler. For each scenario in the matrices the required energy is calculated by the quantity of fuel, the energy content and the efficiencies of the components. The required quantities of hydrogen for each of the scenarios are then found by the energy density of LH2 and the efficiency of the fuel cell. Resulting in nine matrices that give an overview of the required quantity of hydrogen for distances between 1000 and 7000 nm and speeds between 11 and 14 knots, for each combination of the weather conditions and load conditions. Equations and matrices are located in Appendix G.

The range for different number of LH2 tanks on-board the vessel is interpolated from these matrices. The ranges for different scenarios are illustrated graphically by the range curves. Table 6.1.1 for propulsion, hotel load and boiler in moderate weather, all graphs are located in Appendix H. Two lines are drawn in these curves, one for the longest and one for the shortest trans-Atlantic leg of 5420 nm and 4576 nm respectively. The longest leg are labeled as "all" in the graph, meaning that above this line all trans-Atlantic legs can be completed. The shortest leg is labeled as "none", meaning that below this line no trans-Atlantic legs can be completed. Since the ranges have only been calculated up to 7000 nm, as this is a good margin to complete all legs, there is also a line labeled as ”no data” meaning that values above this line have not been calculated.

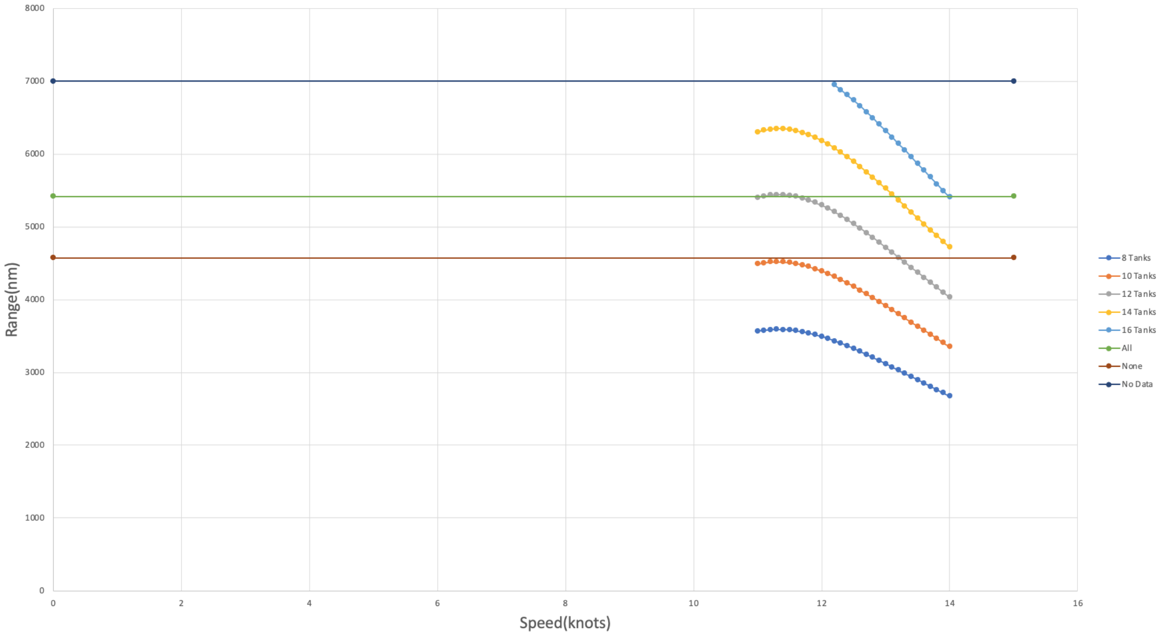

Figure 6.1.1: Propulsion + Hotel Load + Boiler, Moderate Weather

Analyzing these graphs, the LH2 storage capacities were categorized into three groups, green, blue and grey. The ones that can complete all legs between North America and Europe(green), the ones that can complete some of the legs(blue), and the ones that cannot complete any of the legs(grey). The results are presented in 7.2

For storage capacities that cannot complete any of the legs, then hybrid solutions should be considered. While for the two other groups there is a possibility to sail on pure LH2, and the maximum sailing speeds for these if they should be able to complete the legs can be found at the intersection with the lines in the range curves.

6.1.3 Bunkering

Bunkering is the refueling of the vessel. Without any bunkering possibilities there is not possible to operate on the route. As there are currently no full-scale hydrogen bunkering infrastructure along the route, it is of interest to investigate which of the ports that are the most ideal candidates for developing such infrastructure. The bunkering opportunities are determining the flexibility of the routes. If there exist several bunkering ports the routes can be altered to a greater extent than when there are only a couple of opportunities.

The lack of hydrogen bunkering opportunities is one of the greatest barriers for the use of hydrogen in shipping. It will take some time before this is developed to the degree where it gives sufficient flexibility to have a whole fleet running on hydrogen. Furthermore, the storage of LH2 at the terminals are requiring more energy compared to the storage of other potential green fuels like ammonia.

This part of the operational study is performed on the trans-Atlantic operational data. Unlike the two other parts, it examines every leg on the route and calculate the energy required to complete each leg and the energy required at port. The aim is to determine which ports are the best candidates to develop bunkering infrastructure based on the current route.

Using the fuel consumption model, the energy required to complete each leg and the energy required waiting in port are calculated and illustrated graphically. This gives an overview of the most energy intensive legs.

The results are presented in 7.3

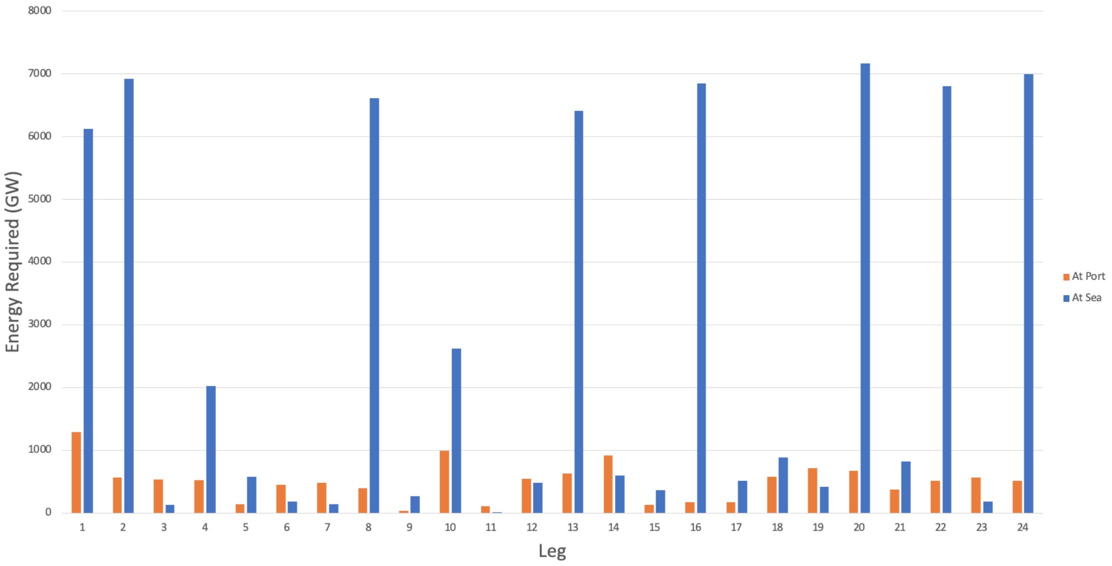

Figure 6.1.2: Energy Required

From the graph it is evident that the vessel would require to refuel both before departure and when arriving after having crossed the Atlantic Ocean. The vessel would not be designed to have a large excess of fuel after completing such a trip. Furthermore, when the vessel is sailing around ports in Europe and North America it would not require any refueling, as the sum of energy required for these shorter legs are far less than the required energy for the trans-Atlantic legs.

6.1.4 Hydrogen Break-Even Price

To determine the competitiveness for hydrogen compared to conventional fuels the break-even price is calculated. This gives a benchmark for the economic feasibility to transition over to hydrogen. For hydrogen market prices above the break-even price the fuel cost of operating the vessel would be higher, and for market prices below then it is cheaper the conventional fuels.

When calculating the break-even price, the tax on emission will be accounted for. The Norwegian government has suggested a CO2 tax of 200 EUR/mt [12]. This value will be used in the calculations.

The total CO2 emissions are found by using the amount of CO2 that is being emitted per ton of heavy fuel oil. Winnes, H. & Fridell, E. (2009) performed a study for a marine diesel engine of 4.5 MW where they estimated that heavy fuel oil is emitting 57 g-CO2/kg-fuel [14]. The engine in this project has a higher power rating that the one that they examined so the value is not going to be exactly the same, but it will serve as a fair estimation.

The calculation will be performed on the longest leg in the operational data sailing in 12.5 knots in moderate weather. From matrices F.2.2 and G.2.2 the total quantity of HFO consumed and hydrogen required to complete the leg are interpolated.

HFO price is found to be 504 \$/mt based on real time data from Ship & Bunker [13].

$$C_{HFO} = K^S \mu_{HFO} + G\tau \tag{6.1.1}$$

$$\mu_{H2} = \frac{C_{HFO}}{K^S_{H2}} \tag{6.1.2}$$

$$G = K^S\ g \tag{6.1.3}$$

K^S - HFO consumed during the leg in mt

K^S_{H2} - LH2 required to complete the leg in mt

μ_{HFO} - Price of HFO in \$/mt

g - CO2 emission per unit fuel in g-CO2/kg

τ - CO2 tax in EUR/ton-CO2

G - Total amount of CO2 emitted during the leg in mt

C_{HFO} - Total cost of HFO to complete the leg in \$

μ_{H2} - Break-Even Price of Hydrogen in \$/mt

Table 6.1.3: Values Used to Calculate the Break-Even Price

K^S	436,25	mt
K^S_{H2}	109	mt
μ_{HFO}	504	\$/mt
g	57	g-CO2/kg
τ	200	EUR/mt-CO2

To compare the break-even price Norled have provided current green hydrogen prices in Norway of 6 \$/kg. These prices are not official prices but indications. Furthermore, NEL has recently outlined a strategy with a goal to produce green hydrogen at 1.5 \$/kg by 2025 [11].

The result is presented in 7.4

6.2 General Arrangement

This section will explore the feasibility of storing enough hydrogen on-board the vessel and if it is possible to install a fuel cell system with high enough power rating. The basis for the study is the general arrangement for the vessel provided by Stolt Nielsen. For the new components related to hydrogen, like fuel tanks, evaporators, fuel cells and batteries, the dimension and data was given to the author by Norled.

The required power from section 6.1 will be used for input for the fuel cell system and the suggested tank arrangement is compared with the number of LH2 tanks analysis from the operational study.

The arrangement of LH2 fuel tanks and the fuel cell machinery is drawn in AutoCAD to determine whether there is possible to install enough power and store sufficient amount on hydrogen on-board. It is assumed that the vessel is a newbuilding and not a retrofit, as this gives more flexibility in rearranging other equipment and installations on-board the ship.

The study will be performed on the existing design and will not consider design options that are radically different than the current one. Furthermore, the piping system from the LH2 fuel tanks to the fuel cells will not be explored but is an important aspect to consider determining the practicability of the arrangement.

The goal of the general arrangement study is to determine if it is possible to install enough tanks and fuel cells to be able to operate on the trans-Atlantic route. Resulting in a suggested arrangement for the fuel tanks and the fuel cell system. The performance of the suggested solution for the vessel will be examined at the end. This is to determine whether a hybrid solution could be an option and give an indication about the vessel's optimal operational speed.

To be able to answer the questions the chapter is divided into three parts.

1. Components 6.2.1
2. Fuel Tank Arrangement 6.2.2
3. Fuel Cell System 6.2.3

The first part provides an overview of all the components that is required for the hydrogen driven vessel, their dimensions and purpose.

6.2.1 Components

The data and dimensions for the components were provided by Norled based on current technology ready suppliers.

For this study the hydrogen fuel tanks have a diameter of 4.5m and length of 14m. These have a storage capacity of 8 tons of hydrogen and does not require energy from the engine.

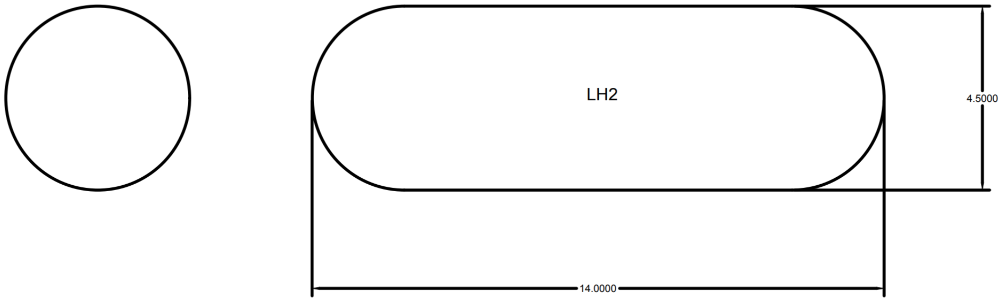

Figure 6.2.1: LH2 Fuel Tank

For each fuel tank there must be installed an evaporator close by. These have a height of 3m and a diameter of 0.7m.

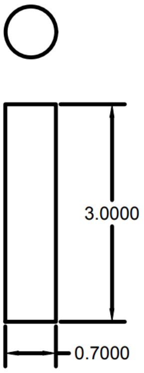

Figure 6.2.2: Evaporator

The fuel cells that are being examined are PEM-FCs as this type is currently the best alternative for maritime applications. Dimension of one fuel cell unit is 1.208m x 0.760m x 2.127m (l x w x h) and it weights 875 kg. They have a power rating of 200kW and an average efficiency of 55%.

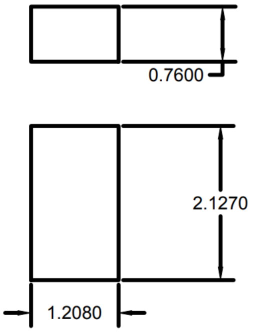

Figure 6.2.3: Fuel Cell Unit

Batteries must be installed to assist the fuel cells with peak shaving as these are more capable than the fuel cells to deal with changing loads. For this project a battery rack composed of 20 battery modules are used. These have the following dimensions, 0.84m x 0.59m x 2.256m (l x w x h) and are installed with 113 kWh and a weight of 1.18 tons.

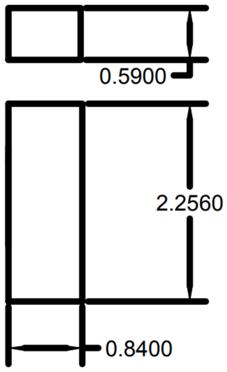

Figure 6.2.4: Battery Rack

6.2.2 Fuel Tank Arrangement

The number of LH2 fuel tanks that can be installed are subjected to a number of constraints, most defined by rules and regulations, which limits the physical amount of hydrogen this vessel can store. These can be summarized into stability, strength, location and visibility constraints.

As of today LH2 tanks requires open deck location due as per day risk assessment informed by LMG Marin. Therefore in this project the LH2 tanks must be located on the main deck and will not be integrated in the hull like current HFO fuel tanks. This also ensures that the capacity of the vessel will not be reduced when installing the new LH2 fuel tanks. For each LH2 tank there must be an evaporator installed close by, around three to five meters away. Ideally, the path between the LH2 tank and evaporator should be kept free of any obstructions as there will be some piping between them.

The main deck must be capable to support the weight of the tanks, therefore it is subjected to strength requirements. Furthermore, when equipping the vessel with the LH2 tanks the ship's vertical center of gravity (VCG) is increasing, which is negatively affecting the stability of the ship.

To ensure that the tanks are located an acceptable distance from the deck, the minimum distance above deck will be at least 500 mm. However, on the vessel there are deck structures, like longitudinal and transverse beams, that can be up to 900mm and 1200mm above the deck. For tanks located above these structures then they will be located 500 mm above the deck structure. The deck tank foundations are welded on the main deck structures increasing the tank's distance from the deck. If the tanks are located above some cargo tank outfitting, this can be tank radars and tank cleaning machines, then these must be easily accessible from the deck, and the distance for the tank above deck must be very high. Therefore, it is in general preferable to not install the tanks above such equipment.

Furthermore, there are visibility requirements, specified in SOLAS chapter V regulation 22, that must be met [6]. This sets a limit on the total height of the tank structures at various point on the deck. The closer the tanks are to the accommodations the higher the total tank structure can be. This is important especially when examining the stacking of the LH2 tanks, as this can easily obstruct the view from the bridge.

Lastly, the IMO IGF code sets a limit of the location of the tanks from the shell plating as one fifth of the breadth at the waterline[7]. This impacts the available space on the main deck the tanks can be installed. The evaporators on the other hand are not subjected to this restriction and can be placed further to the outer sides of the vessel than the tanks.

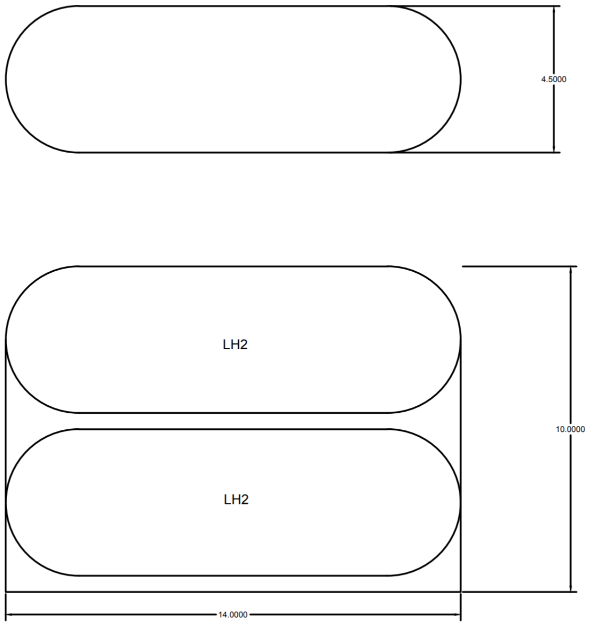

Figure 6.2.5: LH2 Storage Tank Rack

The suggested arrangement is presented in 7.5

6.2.3 Fuel Cell System

The fuel cell system is composed of the fuel cell units, an electrical motor, batteries and redundant diesel gensets.

From the results for the power required from the operational study, located in section 7.1, the vessel should be installed with an engine capable of having a power output of 6000 kW. Each fuel cell unit have an output of 200 kW which leads to a requirement that the vessel must be equipped with 30 units. An electrical motor is installed to convert the electricity from the fuel cells to mechanical energy to the propeller. The dimension of the electrical motor is assumed to be 4x4x4 m in this project but will not be drawn in the arrangement. For further specification of the dimensions a supplier must be contacted. However, this is not done in this project as the assumption is going to provide enough information to arrange the fuel cell units.

Furthermore, batteries must be installed to assist the fuel cells in the form of peak shaving as batteries are more flexible to changes in loads than the fuel cells. For the purpose of this project a capacity of 1000 kWh from the batteries is sufficient, as informed by Norled.

The battery racks are composed of 20 lithium-ion battery modules with a total capacity of 113 kWh per rack. This leads to a requirement of nine battery racks in the machinery.

Often the ship owner requires to have backup diesel gensets in case of malfunctioning of the fuel cells. The gensets used for redundancy will be similar to the current auxiliary engines that the vessel is equipped with. Therefore, the engine room for the auxiliary engines will not be used as a location for the fuel cell system, giving the flexibility to choose the number of gensets that will be needed. It should be noted if a higher power output is required this is a potential room to install additional fuel cell units.

Different from the tank arrangement, the placement of fuel cells and batteries are not constrained by the same rules and regulations. However, stability must be ensured, so heavy components should be placed low in the vessel. Inspection of the fuel cells and batteries should be possible as well, imposing a constraint of not stacking several units on top of each other. This constraint can be relaxed if the stacking is done in a proper manner, but it will not be explored in this project.

The current engine is removed and adjacent HFO tanks are removed. Freeing up potential space for installment of fuel cells and batteries. The final arrangement is presented in section 7.6.

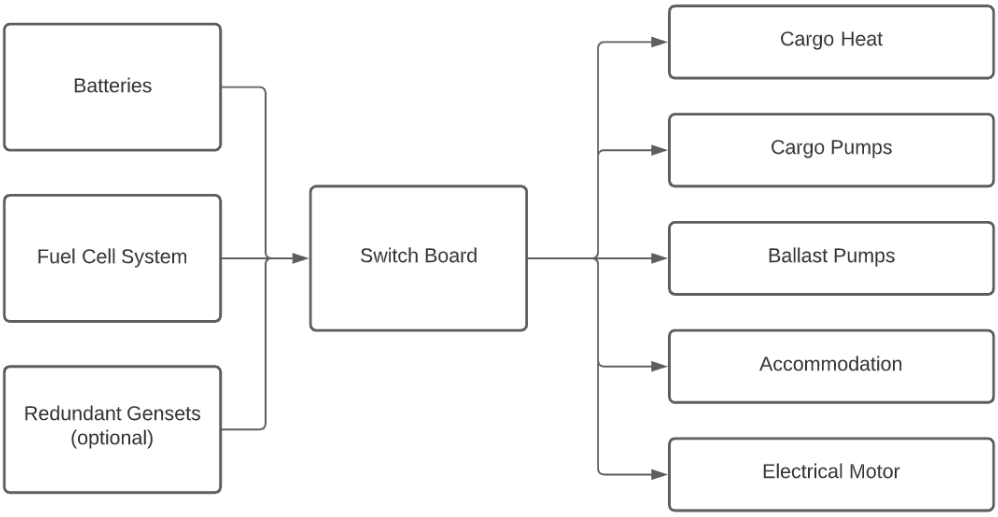

Figure 6.2.6: Schematic Figure over Fuel Cell System

Chapter 7

Results

7.1 Required Power

The power output for the vessel is based on the requirement that it is going to power all loads on-board and must be able to sail in 12 knots in all weathers.

The requirement found for this vessel is one of many possibilities. Depending on what loads the fuel cell system is going to serve and the minimum operational speed for the vessel the required power can be found from the full power requirement table in Appendix I.

For this case a graph is drawn for the vessel when the fuel cell system is supplying power to all loads. The power outputs for the different weather conditions are represented by one curve each. The required power is found at the intersection between the power output curve in bad weather at 12 knots. Resulting in a required power of 5937 kW. This is rounded up to a requirement of 6000 kW installed power for the fuel cell system. Serving as the basis for the number of installed fuel cells in the fuel cell system.

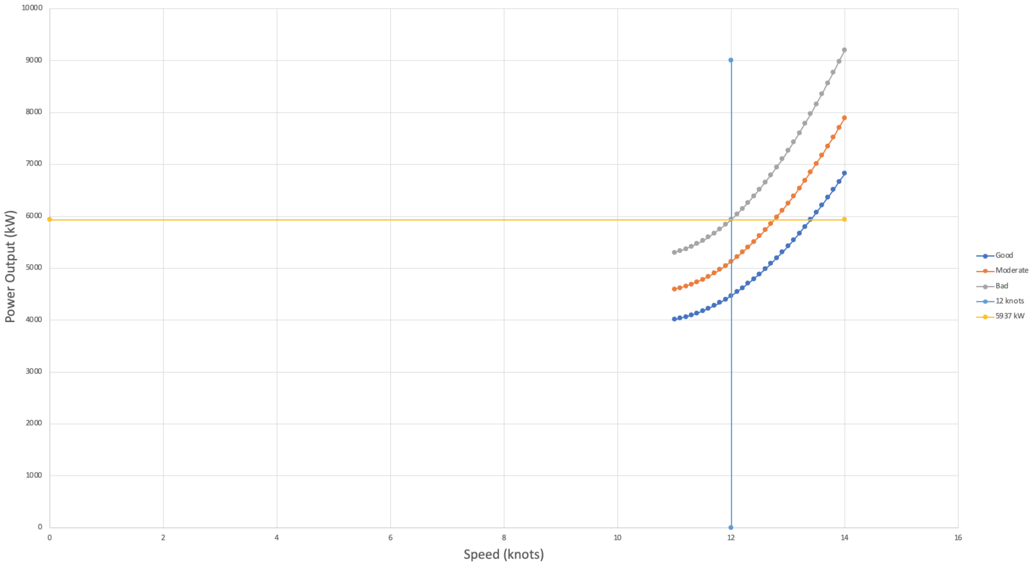

Figure 7.1.1: Required Power

A sensitivity analysis for the required power output for different operational conditions are given in Table 7.1.1

Table 7.1.1: Required Power for Different Operational Conditions

Speed	**Propulsion**			**Propulsion + Hotel**			**Propulsion + Hotel + Boiler**		
	Good	**Moderate**	**Bad**	**Good**	**Moderate**	**Bad**	**Good**	**Moderate**	**Bad**
11,5	3476	4085	4829	3976	4585	5329	4176	4785	5529
12	3770	4430	5237	4270	4930	5737	4470	5130	**5937**
12,5	4189	4922	5819	4689	5422	6319	4889	5622	6519
13	4725	5553	6564	5225	6053	7064	5425	6253	7264
13,5	5373	6314	7464	5873	6814	7964	6073	7014	8164

7.2 Number of LH2 Tanks

A table of the result matrix is presented for the different number of LH2 fuel tanks onboard the ship. Red means it cannot complete any trans-Atlantic legs. Yellow means it can complete some of the trans-Atlantic legs. Green means it can complete all trans-Atlantic legs.

This shows that to be able to sail on pure hydrogen and powering all loads, the vessel should be equipped with minimum 12 tanks. If a vessel can store a maximum of 10 tanks the vessel could sail on pure hydrogen if it is providing power for propulsion and hotel load. However, the boiler should be run on HFO or there should be installed batteries to serve the electrical boiler. For a vessel that is equipped with 8 tanks only a hybrid solution would make the vessel able to serve a trans-Atlantic route.

Table 7.2.1: Fuel Tank Sensitivity Analysis

Number of Tanks	Propulsion			Propulsion + Hotel			Propulsion + Hotel + Boiler		
	Good	Moderate	Bad	Good	Moderate	Bad	Good	Moderate	Bad
8 Tanks	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
10 Tanks	🟩	🟩	🟨	🟩	🟨	🟥	🟨	🟥	🟥
12 Tanks	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟨
14 Tanks	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
16 Tanks	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Red = None
Yellow = Some
Green = All

For eight and ten tanks not all trans-Atlantic legs can be completed. To assess the hybrid potential the leg attainment for the shortest and longest trans-Atlantic legs are presented in Table 7.2.2 and Table 7.2.3, for eight and ten tanks respectively.

Table 7.2.2 displays how much of the longest and shortest leg a vessel equipped with eight tanks are able to complete. For eight tanks under most circumstances it is able to complete over 60% of the longest trans-Atlantic leg. This means that if a vessel is equipped with only eight tanks a hybrid solution should be considered as a viable option.

The optimal operational speed that yields the longest range of the vessel is 11.3 knots. It is found in the range curves, Appendix H. It differs slightly under different weather conditions and load conditions. However, this is negligible as it is only by 0.1 knots.

Table 7.2.2: Leg Attainment, 8 Tanks

Load Condition	**Weather**	**Speed (knots)**	**Range (nm)**	**Shortest Leg (nm)**	**Longest Leg (nm)**	**Leg Attained**	
						Shortest Leg (%)	**Longest Leg (%)**
P	Good	11,5	5177	4576	5420	113%	96%
		12,5	4670	4576	5420	102%	86%
		13,5	3932	4576	5420	86%	73%
	Moderate	11,5	4405	4576	5420	96%	81%
		12,5	3974	4576	5420	87%	73%
		13,5	3346	4576	5420	73%	62%
	Bad	11,5	3727	4576	5420	81%	69%
		12,5	3362	4576	5420	73%	62%
		13,5	2830	4576	5420	62%	52%
P + H	Good	11,5	4357	4576	5420	95%	80%
		12,5	4031	4576	5420	88%	74%
		13,5	3505	4576	5420	77%	65%
	Moderate	11,5	3797	4576	5420	83%	70%
		12,5	3508	4576	5420	77%	65%
		13,5	3032	4576	5420	66%	56%
	Bad	11,5	3282	4576	5420	72%	61%
		12,5	3022	4576	5420	66%	56%
		13,5	2602	4576	5420	57%	48%
P + H + B	Good	11,5	4095	4576	5420	89%	76%
		12,5	3814	4576	5420	83%	70%
		13,5	3333	4576	5420	73%	61%
	Moderate	11,5	3583	4576	5420	78%	66%
		12,5	3327	4576	5420	73%	61%
		13,5	2896	4576	5420	63%	53%
	Bad	11,5	3111	4576	5420	68%	57%
		12,5	2880	4576	5420	63%	53%
		13,5	2498	4576	5420	55%	46%

Table 7.2.3: Leg Attainment, 10 Tanks

Load Condition	**Weather**	**Speed (knots)**	**Range (nm)**	**Shortest Leg (nm)**	**Longest Leg (nm)**	**Leg Attained**	
						Shortest Leg (%)	**Longest Leg (%)**
P	Good	11,5	6471	4576	5420	141%	119%
		12,5	5838	4576	5420	128%	108%
		13,5	4915	4576	5420	107%	91%
	Moderate	11,5	5507	4576	5420	120%	102%
		12,5	4968	4576	5420	109%	92%
		13,5	4183	4576	5420	91%	77%
	Bad	11,5	4658	4576	5420	102%	86%
		12,5	4202	4576	5420	92%	78%
		13,5	3538	4576	5420	77%	65%
P + H	Good	11,5	5446	4576	5420	119%	100%
		12,5	5049	4576	5420	110%	93%
		13,5	4381	4576	5420	96%	81%
	Moderate	11,5	4746	4576	5420	104%	88%
		12,5	4385	4576	5420	96%	81%
		13,5	3790	4576	5420	83%	70%
	Bad	11,5	4102	4576	5420	90%	76%
		12,5	3777	4576	5420	83%	70%
		13,5	3253	4576	5420	71%	60%
P + H + B	Good	11,5	5158	4576	5420	113%	95%
		12,5	4794	4576	5420	105%	88%
		13,5	4184	4576	5420	91%	77%
	Moderate	11,5	4509	4576	5420	99%	83%
		12,5	4180	4576	5420	91%	77%
		13,5	3632	4576	5420	79%	67%
	Bad	11,5	3909	4576	5420	85%	72%
		12,5	3614	4576	5420	79%	67%
		13,5	3130	4576	5420	68%	58%

7.3 Bunkering Ports

Bunkering infrastructure must be developed in the most common ports for departure and arrival for trans-Atlantic trips.

The number of bunkering stops, if the vessel is running on hydrogen, for each port is counted and illustrated, Figure 7.3.1. This shows the name of the port on the x-axis and the number of bunkering stops the vessel would require if its running on hydrogen on the y-axis.

From the figure it can be seen that the two best candidates to develop LH2 bunkering infrastructure are the Port of Houston and Port of Antwerp, one for each continent. Naturally, if there is available LH2 bunkering in these ports the other routes would be altered to always sail from Antwerp to Houston when crossing the Atlantic Ocean until the other ports are developed.

From Figure 6.1.2 it can be concluded that the vessel would not require to bunker when it is sailing within a continent, only before and after a trans-Atlantic trip. This is because the energy required for trans-Atlantic legs are larger than the sum of all the smaller trips in between ports.

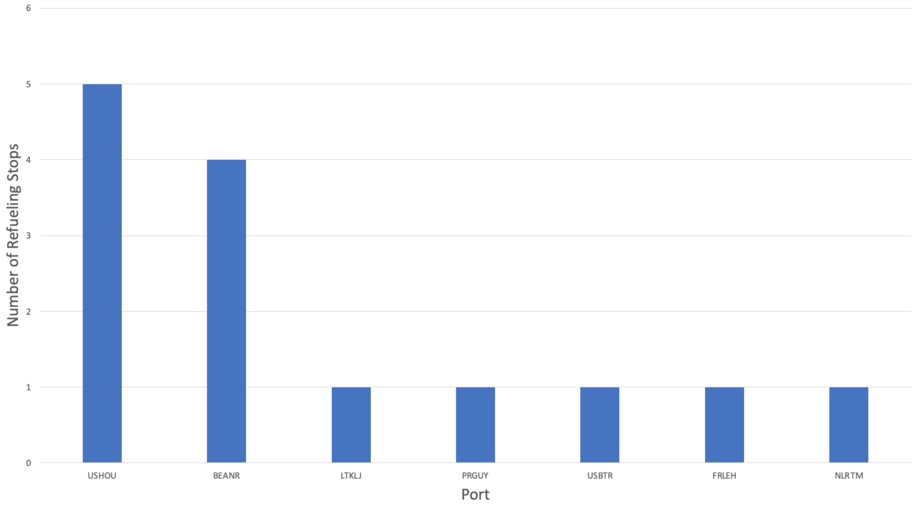

Figure 7.3.1: Bunkering Stops

7.4 Break-Even Price

The break-even price to operate the longest trans-Atlantic leg in moderate weather sailing at 12.5 knots is estimated to be 2073 \$/mt or 2.073 \$/kg. According to data provided by Norled the current green hydrogen price is 6 \$ / kg. This means that the price of green hydrogen would require to reduce by 65% to make hydrogen competitive.

According to NEL ASA's strategy to produce green hydrogen for 1.5 \$/kg by 2025, this would make hydrogen driven vessels more economically competitive than the current conventional fuels [11]. However, this is only considering the fuel cost, not maintenance, fuel cell replacements, and newbuilding of the vessel.

7.5 Tank Arrangement

Six possible placements for fuel tanks are identified that is complying with the rules and regulations. Four in front of the manifold and two behind. The arrangement is presented in Figure 7.5.1.

For the tanks located behind the manifold the maximum height of the tank structure is 13.25 meters which gives the opportunity to stack two tanks in the height. For the tanks forward of the manifold the maximum allowable height is 6.8 meters, leaving a margin of 2.3 meter the tanks can be located above deck. Therefore, the tanks in front of the manifold cannot be stacked.

Tank foundations must be welded on the deck to locate the tanks in the positions, and steel reinforcement must be installed under the tank foundations to ensure the strength requirements.

In total this shows that the vessel can be equipped with eight fuel tanks without having to reduce the capacity of the vessel or impose major changes to the design. The leg attainment for the longest and shortest leg for this vessel can then be found in the leg attainment Table 7.2.2 for eight tanks.

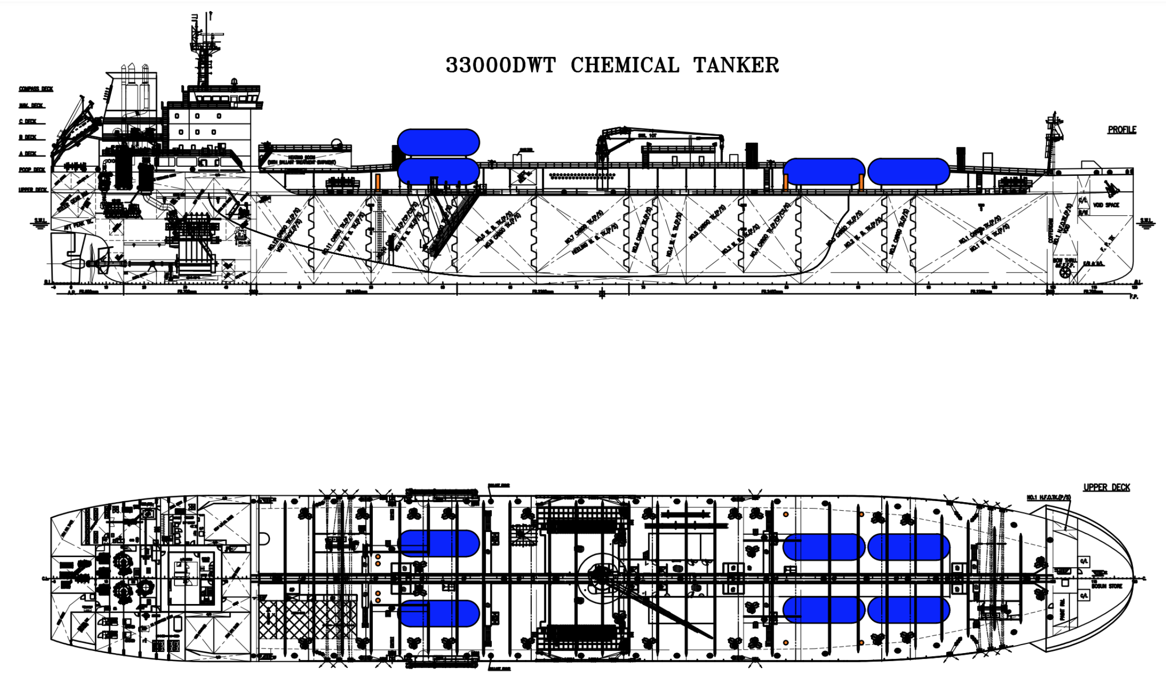

Figure 7.5.1: LH2 Tank Arrangement

7.6 Fuel Cell System

A suggested arrangement for the fuel cell system is presented in Figure 7.6.1, 7.6.2 and 7.6.3. Fuel cell units are marked in blue and battery racks are marked in orange. This arrangement places the fuel cells and batteries in the spaces where the previous HFO tanks where located. These are safe rooms protected by cofferdams which makes them an ideal place to locate the fuel cell system.

The batteries are placed in a separate room from the fuel cells and are located on the third deck. There are also 12 units of fuel cells located on the third deck. The remaining 18 fuel cells are distributed over two rooms at the second deck. To ensure easy accessibility for inspection the front part of the fuel cell units have a distance of 1 meter of open space.

The suggested arrangement is based on the current general arrangement of the vessel, in reality if this is going to be a newbuilding then the whole arrangement would be altered to optimize for the new fuel cell system.

The former main engine room is left open to make space for the electrical motor or other potential uses for the space. Furthermore, the auxiliary engines are still in place to show that there is possibility to install redundant diesel gensets if the owner requires it. However, these could be used to install additional fuel cell units if more power is required.

This shows that there is no issue of installing the required amount of power output and it is easy to increase it if more power is required. Therefore, the feasibility is not constrained by power requirements.

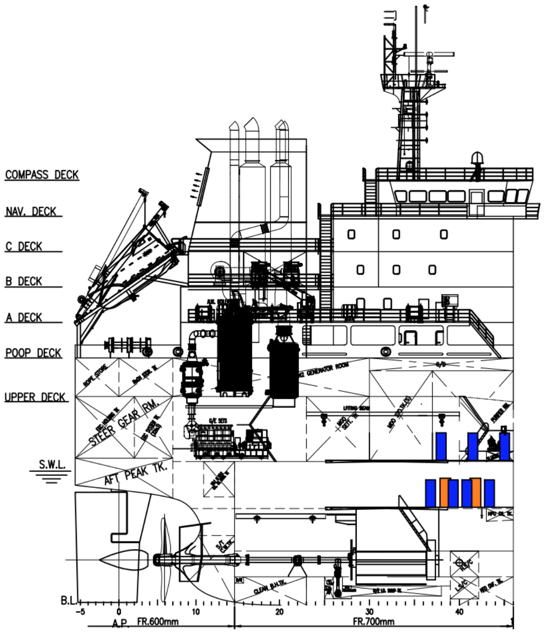

Figure 7.6.1: Fuel Cell System Overview

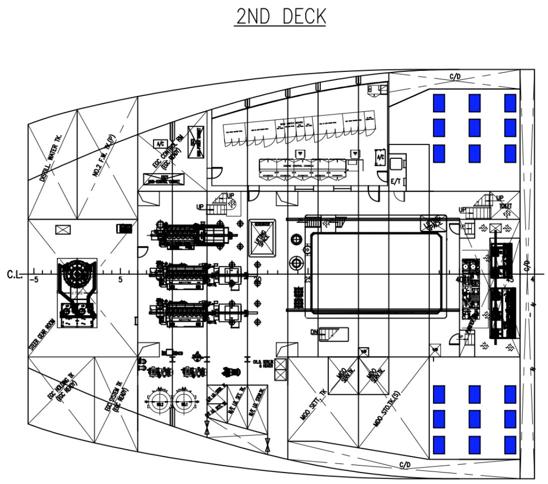

Figure 7.6.2: Fuel Cell System 2 Deck

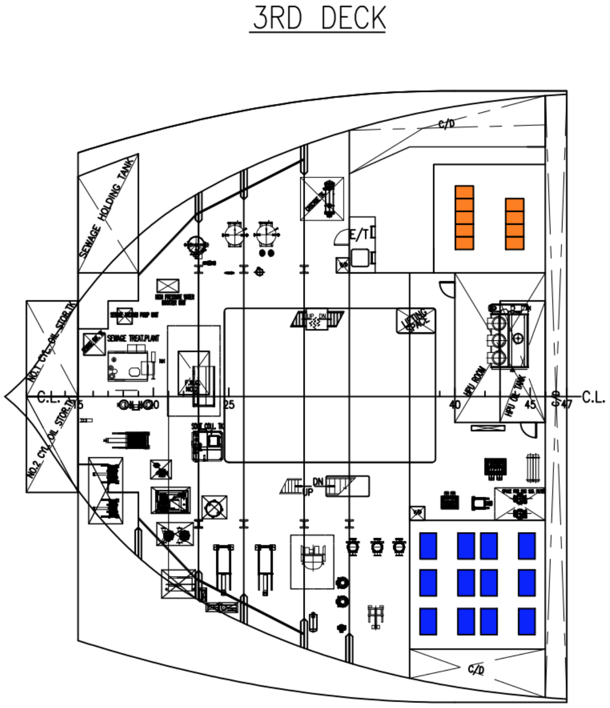

Figure 7.6.3: Fuel Cell System 3 Deck

Chapter 8

Summary

This project has shown that hydrogen is a good fuel candidate for deep-sea chemical carriers. With current technology there is possible to significantly reduce the emissions by utilizing an hybrid solution.

The project started out with the development of a route independent fuel consumption model in order to translate the desired vessel to the desired route. This was modelled by analyzing the three components that consume fuel, the main engine, the auxiliary engines and the boiler.

The fuel consumption from the main engine was developed by using the relation between draft and cargo load, the power/speed curves for the scantling and design draft and analyzing the added resistance for all weather conditions during each day for the year of 2020. Modelling the fuel consumption from the auxiliary engines was based on analyzing the electrical loads on-board the vessel, determining their contribution when sailing. The fuel consumption from the boiler was modelled empirically by analyzing the relation between the running hours and the fuel consumption.

An operational study was conducted using the fuel consumption model as input to determine the required amount of hydrogen that is required, the required power output, bunkering opportunities and the economic competitiveness of the vessel.

The required power was calculated directly from the model, with alterations to the hotel load, accounting for the difference on sailing on hydrogen compared to HFO. A discussion about the potential to reduce the hotel load by introducing energy saving measures were provided, but not explored.

For the required amount of hydrogen stored on-board the energy content of HFO and the efficiencies of the engines and boiler were used to determine the energy output for the vessel. The required energy output was used to determine the amount of hydrogen that is required to provide the same energy output for different operational conditions. Then the range were calculated based on how far the vessel would be able to sail if it is equipped with different number of LH2 fuel tanks. The range were used to determine if the vessel would be able to complete the trans-Atlantic legs.

The potential bunkering ports were identified based on the existing trans-Atlantic trade and where and how many times the vessel would require to refuel if it was running on LH2.

The economically competitiveness of hydrogen for this trade was assessed by calculating the LH2 break-even price and comparing it to the current price and the projected price in 2025. Including the suggested CO2-tax from the Norwegian government.

Lastly, a tank arrangement and fuel cell system arrangement were drawn in Autocad to show how much hydrogen that can be stored on-board and if it is possible to install enough power for the fuel cell system to serve all loads. The arrangements were made sure to comply with the relevant rules and regulations that ships and low flashpoint fuels are subjected to.

Chapter 9

Discussion

The study has presented an overview of requirements that are necessary to operate a 33000-dwt chemical carry sailing between Europe and North America. The required power and number of LH2 tanks that is required, as well as presenting bunkering ports and break-even hydrogen price. The study has also presented suggested fuel tank and fuel cell system arrangement and tested the performance of this solution. It shows that there is possibility to reduce the emissions from sailing this route with over 60% under most operational conditions.

It implies that a hybrid solution for the chemical carrier would be a good alternative, where it will sail 60% of the leg on hydrogen and final last part of the leg on HFO. Furthermore, it is interesting to further investigate a more flexible tank arrangement that are more different from the initial general arrangement, than the one presented in this project.

The piping system from the fuel tanks to the fuel cell system is not explored in this project. However, this is an important aspect to consider for the feasibility of the arrangement. Chemical carriers have initially a complicated piping system so there will be more constraints related to installing the piping system between the fuel tanks and fuel cell system than for other types of vessels.

For the suggested arrangements presented, they are created to determine whether it is possible store enough fuel on-board and enough power. These arrangements are not deviating much from the original general arrangement. In reality if a hydrogen driven vessel like this is going to be developed the whole general arrangement would be optimized to meet the requirements in the best possible way. Therefore, the number of storage tanks and fuel cells that have been installed on the vessel in the suggested arrangements will serve as a lower bound for the actual possibility.

This study has only examined one supplier of fuel cells and one supplier for LH2 fuel tanks. Examining other supplier can be a potential interesting aspect to look at to compare the performance of different fuel cells. A fuel tank with different dimensions and capacity could also be a possibility to increase the storage capacity of hydrogen for the vessel. Smaller tanks are more flexible when arranging them on the deck. However, the more tanks the vessel is equipped with the more extensive piping system from the fuel tank to the fuel cells would be required.

It should be noted that this study has been based the operational data and is susceptible for potential errors in the data set. Furthermore, the study is specifically tailored to the chemical carrier in question. So, it should be taken caution to apply the same model for a new vessel without properly examining the assumptions made and the properties of the engines and the vessel used in the study compared to the new vessel.

Throughout the study assumptions regarding the operational conditions of the vessel are made. These are that the hotel load during sailing is running 20% on nitrogen and hydraulic power pack and 80% in normal condition. In reality the distribution among these different modes of operation will change depending on the cargo load and decisions made by the operators. Therefore, it should be recognized that for cases where the vessel is running above 20% on nitrogen and/or hydraulic power pack the results presented in this project will be an optimistic estimation.

Another assumption regarding the operation of the vessel is that the boiler is running 20% of the time. This is dependent on the amount of tank cleaning, heating of cargo and heating of bunker fuel that is required during the leg. From the operational data the average running hour of the boiler is 15% which gives a margin of 5% for this assumption. However, for some cases where the boiler is used for longer amounts the results in the study will be optimistic.

The sea-margin calculated in this project is calculated from using the weather data which is based on an observational approach to categorized wind and wave forces. Therefore, it is no precise measurement of the wind speed and wave forces. An observational approach can be subjected to different assessment by different people observing the weather.

In this project the sea-margin is accounting for everything that is not accounted for by the speed power curve. Including the forces from wind, waves, current and swells it will also account for fouling and general wear and tear of the hull. It is also a constant sea-margin throughout the whole sailing time for the vessel during a leg. In reality the weather is changing within each leg, so this assumption will result in some noise in the calculations of the fuel consumption by the main engine.

The power output for lower drafts than the design draft is extrapolated from the speed power curves for the design and scantling draft. Extrapolations are not as accurate as interpolations and this approach may lead to some noise when calculating the fuel consumption by the main engine for low cargo loads. Furthermore, the speed power curves are approximated to be a third order polynomial function. For slow speeds close to 10 knots this approximation is not valid as the power required is increasing with the deacceleration of the vessel. However, as the operational speed for the vessel should be above 11 knots this is not impacting the results.

The mean speed during sailing is used to find the power output for a given leg, not accounting for the speed profile during the leg, nor the maneuvering in and out of port. Since this is sailing on deep-sea with sailing times of several days this is a fair assumption as both small changes in speed during the leg and maneuvering is negligible.

In total the accuracy of the model for the fuel consumption is good, but it overestimates the values about 5% on average. The reason for this is related to the aggregate impact from all the assumptions and noise in the calculation for the fuel consumption from the main engine, auxiliary engines and the boiler. However, this is acceptable as the model it is fairly accurate. It should be mentioned that the error in the fuel consumption model is going to impact the operational study. Therefore, the results from the operational study are more likely to be pessimistic rather than optimistic.

The calculation for the hydrogen required in this project is using the average fuel cell efficiency. However, fuel cells are deteriorating over time, resulting in lower efficiency over time. Therefore, the results that are found in this project is the average performance of the vessel and not examining the fuel cells at the end of life (EoL).

For the break-even price there is currently no CO2 tax, therefore the tax used in this study is an assumption. When more information about this tax is provided the break-even price must be re-evaluated. Also, due to lack of data the C02 emissions per kg fuel is values taken for a lower power rating engine than the one that the vessel is equipped with. Finding the correct value would improve the estimation. However, for the purpose of this project the break-even price serves as a good benchmark to gauge the economic competitiveness of hydrogen.

The bunkering ports identified in this study are based on the current route of the vessel and alternative routes are not explored. This might omit finding some more suitable ports that is not included in the current route for the vessel. In this paper the ports that the vessel would require to bunkering most of the time if sailing on hydrogen are the ones that are identified as the best candidates for development of hydrogen bunkering infrastructure. Another approach could have been to develop the bunkering infrastructure in the ports that results in the shortest trans-Atlantic leg. By doing this then the required vessels would not have to sail the long legs. However, this would also require the vessel to stop in a port with the sole intention of bunkering before the leg. This could result in a detour and would not be the optimal route for the vessel and would reduce its competitiveness compared to vessels sailing on conventional fuels.

The study shows promising results for the development of a hydrogen driven chemical carrier sailing across the Atlantic Ocean with the current technology. Further investigations into the amount of hydrogen that can be stored on the vessel as well as exploring the possibility of a hybrid solution in more detail would be natural next steps. From this project it can be concluded that at least 60% of a trans-Atlantic leg will be able to be powered by pure LH2, resulting in a good reduction of the use of HFO.

Chapter 10

Conclusion

The conclusion of the project is that there is a good potential for the application of hydrogen as fuel for deep-sea chemical shipping. Currently a hybrid option is the best solution as this would allow the vessel to sail over 60% of trans-Atlantic legs under most circumstances without reducing payload capacity. If the vessel should be run on pure hydrogen it would require at least 10 fuel tanks installed. This project shows that it is possible to store 8 tanks on the deck of the vessel without compromising on its capacity.

There is not a restriction related to the feasibility of installing a high enough power rating for the fuel cell system to power all the loads on-board. The limitation lays in the amount of hydrogen that can be stored on the ship. This is an interesting finding which can prompt chemical shipping companies to further investigate the potential of developing a hydrogen driven vessel for deep-sea routes.

From an economic perspective a reduction in the green hydrogen price would require to drop with 65%. An alternative is to operate the vessel on blue hydrogen which is less expensive until the price of green hydrogen is reduced.

As of today, bunkering opportunities are also a limitation for the feasibility of hydrogen driven chemical carriers. Hydrogen bunkering infrastructure must be built in the Port of Houston and the Port of Antwerp before it is viable to operate the vessel.

Chapter 11

Further Work

According to this study chemical carriers sailing in deep-sea have a good potential for the use of hydrogen as fuel. Continued investigations into the development of hybrid solutions for the vessel is a promising field. Examining several vessels rather than only one, as in this project, using AIS data to study the performance of hybrid solutions.

Furthermore, considering energy reducing measures to determine how this will impact the feasibility of the ship could be a potential area that can yield some interesting results.

Coming up with an improved fuel tank arrangement that are not similar to the initial general arrangement of the vessel are an interesting aspect to consider. Examining larger vessels could also be a potential where there are in general more available space. Furthermore, it is interesting to explore the impact of reducing the capacity of the vessel to fit more hydrogen on-board to be able to complete a full trans-Atlantic leg.

A thorough cost assessment of machinery and operational cost for a chemical carrier sailing in deep-sea is another angle that can be interesting to look into. This will further assess the competitiveness of hydrogen and determine when the best time to invest in a hydrogen driven vessel will be.

Studies regarding bunkering potential for the ports of Houston and Antwerp should be considered. Look into the current state of the hydrogen supply chain and how far the development in these ports have been going. Alternatively examining other port candidates by considering a several deep-sea chemical carriers rather than one. This will give a better overview of the ports where the bunkering infrastructure can be developed.

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Appendix A

Fuel Properties

A table presenting the density and energy density of HFO and LH2. These values are used for various calculations throughout the thesis. As HFO is used throughout the thesis, the density and energy density of MDO and MGO are not used. The density for HFO is defined in MARPOL (1973) to have a density of more than 900 kg/m3[5]. Therefore, a density 950 kg/m3 is used in the project. The energy density to HFO and LH2 are taken from DNV GL[2]. The density for hydrogen in this project is provided by Norled.

Table A.0.1: Fuel Properties

Fuel Type	**Density (kg/m3)**	**Energy Density (MJ/kg)**
HFO	950	41
MDO	-	-
MGO	-	-
LH2	65	120

Appendix B

Route data

The general data for the initial route and the trans-Atlantic route are displayed to give an overview of the sailing distances, speeds and cargo load for the two different routes. This is a summery of some of the data found in the operational data.

B.1 Initial route

The general route data for the initial route of the vessel.

Table B.1.1: General data, Initial route

Voyage	Leg	From	To	Departures	Arrivals	Time @ port (h)	Sailing time (h)	Manoeuvring total time (h)	Waiting time (h)	Total time (h)	Distance (nm)	Speed (kts)	Cargo (Mt)
1	1	FRELEH	SNDKR	04/11/2019	12/11/2019	79	189,8	0	0	189,8	2340	12,33	0
	2	SNDKR	EGSCN	15/11/2019	26/11/2019	25,2	267,5	0	0	267,5	3440	12,86	31559,02
	3	EGSCN	INIXY	27/11/2019	07/12/2019	55,2	234,1	0	1	235,1	2897	12,38	31559,02
2	1	INIXY	AEFJR	09/12/2019	12/12/2019	13,25	67	0	2,5	69,5	854	12,75	0
	2	AEFJR	SAJUI	13/12/2019	15/12/2019	149,25	56,6	0	0	56,6	683	12,07	0
	3	SAJUI	AERUW	21/12/2019	22/12/2019	42,75	22,5	0	0	22,5	300	13,33	25516,132
	4	AERUW	AEFJR	24/12/2019	25/12/2019	15	26,5	0	0	26,5	342	12,91	31261,659
	5	AEFJR	EGSCN	26/12/2019	03/01/2020	24	200,7	0	2,3	203	2700	13,45	31261,659
	6	EGSCN	ESTAR	04/01/2020	10/01/2020	32,5	137,5	0	2	139,5	1643	11,95	31261,659
	7	ESTAR	BEANR	11/01/2020	18/01/2020	273	141,4	0	5,1	146,5	1823	12,89	27294,212
3	1	BEANR	ESCAR	29/01/2020	03/02/2020	53	132,5	0	0	132,5	1670	12,60	0
	2	ESCAR	SNDKR	06/02/2020	11/02/2020	51	130	0	0	130	1794	13,80	6000
	3	SNDKR	ZACPT	13/02/2020	26/02/2020	76	301,5	0	0	301,5	3647	12,10	25814,203
	4	ZACPT	ZADUR	29/02/2020	03/03/2020	112,3	83,5	0	0	83,5	866	10,37	20814,203
	5	ZADUR	INIXY	08/03/2020	21/03/2020	45,9	309	0	0	309	4017	13,00	19814,203
4	1	INIXY	AEFJR	23/03/2020	26/03/2020	13,5	75,5	0	0	75,5	857	11,35	0
	2	AEFJR	SAJUI	27/03/2020	28/03/2020	189,8	35	0	0	35	493	14,09	0
	3	SAJUI	SAYNB	05/04/2020	14/04/2020	143,5	205,7	0	0,8	206,5	2702	13,14	14305,701
	4	SAYNB	EGSCN	20/04/2020	21/04/2020	29,3	37	0	0	37	476	12,86	24240,946
	5	EGSCN	ESTAR	22/04/2020	28/04/2020	22	128	0	0	128	1619	12,65	24240,946
	6	ESTAR	ESALG	29/04/2020	30/04/2020	64,2	39	0	0	39	484	12,41	19523,744
	7	ESALG	ESHUV	03/05/2020	03/05/2020	51,2	9	0	0	9	119	13,22	12848,822
	8	ESHUV	PTSIE	05/05/2020	06/05/2020	36,6	16,5	0	0	16,5	202	12,24	7630,779
5	1	PTSIE	EGSCN	08/05/2020	14/05/2020	27,5	153,7	0	0	153,7	2190	14,25	0
	2	EGSCN	JOAQJ	15/05/2020	16/05/2020	67,4	20,3	0	0	20,3	281	13,84	0
	3	JOAQJ	INIXY	19/05/2020	28/05/2020	50,8	220,4	0	1,6	222	2852	12,94	31503,3
6	1	INIXY	BHSIT	30/05/2020	03/06/2020	42	94,1	0	0,4	94,5	1202	12,77	0
	2	BHSIT	SAJUI	05/06/2020	05/06/2020	160,2	8,8	0	0	8,8	106	12,05	11535,22
	3	SAJUI	AEFJR	12/06/2020	13/06/2020	11	37	0	0	37	456	12,32	30762,572
	4	AEFJR	EGSCN	14/06/2020	24/06/2020	35,7	235,7	0	1,3	237	2692	11,42	30762,572
	5	EGSCN	ESTAR	25/06/2020	30/06/2020	43	126	0	0	126	1618	12,84	30762,572
	6	ESTAR	BEANR	02/07/2020	09/07/2020	181,8	152	0	0	152	1824	12,00	27034,365
	7	BEANR	NLRTM	16/07/2020	16/07/2020	38	6,5	0	0	6,5	78	12,00	3096,449
7	1	NLRTM	SNDKR	18/07/2020	26/07/2020	93,5	184	0	0	184	2590	14,08	0
	2	SNDKR	EGSCN	30/07/2020	10/08/2020	32,8	278,9	0	1,6	280,5	3421	12,27	31602,478
	3	EGSCN	INIXY	12/08/2020	21/08/2020	38	220,7	0	0	220,7	2915	13,21	31602,478
8	1	INIXY	AEFJR	22/08/2020	26/08/2020	38	66,5	0	9,25	75,75	814	12,24	0
	2	AEFJR	QAUMS	27/08/2020	28/08/2020	91,5	28,3	0	0	28,3	379	13,39	0
	3	QAUMS	SAJUI	01/09/2020	02/09/2020	150,5	20,5	0	0	20,5	303	14,78	10553,582
	4	SAJUI	AEFJR	08/09/2020	10/09/2020	2,5	38,5	0	0	38,5	506	13,14	28225,047
	5	AEFJR	EGSCN	10/09/2020	19/09/2020	31,75	214,5	0	1	215,5	2702	12,60	28225,047
	6	EGSCN	FRLEH	20/09/2020	30/09/2020	48,1	241,3	0	0	241,3	3108	12,88	28225,047
	7	FRLEH	BEANR	02/10/2020	03/10/2020	155,4	19	0	0	19	217	11,42	23743,781
	8	BEANR	GBFLU	10/10/2020	10/10/2020	82,75	2,5	0	0	2,5	31	12,40	0
9	1	GBFLU	SNDKR	13/10/2020	21/10/2020	89	179,8	0	0	179,8	2542	14,14	0
	2	SNDKR	EGSCN	24/10/2020	04/11/2020	-	185	0	0	185	2384	12,89	31499,889

B.2 Trans-Atlantic Route

General data for the trans-Atlantic route. Note that this is operational data from another vessel and not the same vessel that is sailing on the initial route that is being studied in the project.

Table B.2.1: General Data, Trans-Atlantic Route

Voyage	Leg	From	To	Time at port (h)	Sailing time (h)	Waiting time (h)	Total time (h)	Distance (nm)	Mean transit speed (knots)
1	1	BEANR	USHOU	381	371	0	371	4576	12,33
2	1	USHOU	BEANR	139,48	386	0,02	386,02	5219	13,52
	2	BEANR	NLRTM	132	7,5	0	7,5	89	11,87
3	1	NLRTM	RUULU	127,5	125	0	125	1457	11,66
	2	RUULU	LVRIX	31,5	30,5	0	30,5	409	13,41
	3	LVRIX	LVVNT	107	11	0	11	127	11,55
	4	LVVNT	LTKLJ	115,52	7,5	0	7,5	99	13,20
	5	LTKLJ	PRGUY	95	315,5	0	315,5	4969	15,75
	6	PRGUY	PRSJU	8	16	0	16	192	12,00
	7	PRSJU	USHOU	267,8	149	0	149	1891	12,69
4	1	USHOU	USTXT	24,2	1,2	0	1,2	0	12,00
	2	USTXT	USBTR	133,4	26,5	0	26,5	340	12,83
	3	USBTR	BEANR	156,5	347,4	0	347,4	4803	13,83
	4	BEANR	NLRTM	244,1	43,7	0	43,7	422	9,66
	5	NLRTM	FRLEH	29,7	19,2	0	19,2	254	13,23
5	1	FRLEH	USHOU	40,9	397,8	0	397,8	5159	12,97
	2	USHOU	USHOU	40,1	36,5	0	36,5	362	9,92
	3	USHOU	USHOU	141,9	59,4	24	83,4	631	10,62
	4	USHOU	USHOU	181,7	26,8	0	26,8	294	10,97
6	1	USHOU	BEANR	168,8	419,2	0	419,2	5420	12,93
	2	BEANR	NLRTM	89,5	59,7	0	59,7	583	9,77
7	1	NLRTM	USHOU	-	349	0	349	5128	14,69
8	1	USHOU	USFPO	140,5	12	0	12	127	10,58
	2	USFPO	BEANR	-	418	0	418	5275	12,62

Appendix C

Propulsion Power

The interpolated power output for the mean speed during each leg in the initial route. Used for comparing the estimated values against the actual values to determine the accuracy of the estimation. The shaft power in this table is for calm weather and does not account for weather conditions. To account for the weather the shaft power is increased by the sea-margin.

Table C.0.1: Required Propulsion Power, Initial Route

Voyage	**Leg**	**Cargo load (mt)**	**Estimated draft (m)**	**Speed (knots)**	**Shaft Power (kW)**		
					10,4m	**9,7m**	**Estimated Draft**
1	1	0	6,5	12,33	2863	2657	1701,02
	2	31559,02	10,5	12,86	3240	2998	3276,94
	3	31559,02	10,5	12,38	2892	2683	2924,49
2	1	0	6,5	12,75	3151	2916	1826,23
	2	0	6,5	12,07	2714	2528	1664,85
	3	25516,132	9,9	13,33	3655	3396	3464,87
	4	31261,659	10,5	12,91	3277	3033	3304,21
	5	31261,659	10,5	13,45	3771	3512	3800,28
	6	31261,659	10,5	11,95	2654	2477	2673,96
	7	27294,212	10,1	12,89	3266	3023	3153,57
3	1	0	6,5	12,60	3046	2820	1772,63
	2	6000	7,4	13,80	4134	3881	3042,24
	3	25814,203	9,9	12,10	2729	2541	2599,41
	4	20814,203	9,4	10,37	2357	2230	2167,19
	5	19814,203	9,2	13,00	3355	3107	2940,41
4	1	0	6,5	11,35	2430	2294	1660,84
	2	0	6,5	14,09	4460	4226	3136,74
	3	14305,701	8,5	13,14	3473	3219	2797,91
	4	24240,946	9,7	12,86	3244	3002	3017,58
	5	24240,946	9,7	12,65	3078	2850	2864,28
	6	19523,744	9,2	12,41	2915	2703	2549,93
	7	12848,822	8,3	13,22	3551	3295	2798,48
	8	7630,779	7,6	12,24	2811	2612	2017,59
5	1	0	6,5	14,25	4657	4439	3424,96
	2	0	6,5	13,84	4181	3930	2766,02
	3	31503,3	10,5	12,94	3305	3059	3340,88
6	1	0	6,5	12,77	3172	2936	1837,98
	2	11535,22	8,2	12,05	2702	2518	2114,08
	3	30762,572	10,4	12,32	2861	2655	2869,32
	4	30762,572	10,4	11,42	2450	2309	2455,58
	5	30762,572	10,4	12,84	3225	2985	3235,30
	6	27034,365	10,0	12,00	2679	2498	2588,40
	7	3096,449	6,9	12,00	2679	2498	1785,15
7	1	0	6,5	14,08	4449	4213	3120,73
	2	31602,478	10,5	12,27	2825	2624	2857,40
	3	31602,478	10,5	13,21	3538	3282	3578,76
8	1	0	6,5	12,24	2810	2611	1685,76
	2	0	6,5	13,39	3712	3452	2250,29
	3	10553,582	8,0	14,78	5354	5223	4911,24
	4	28225,047	10,2	13,14	3479	3225	3396,94
	5	28225,047	10,2	12,60	3041	2816	2968,32
	6	28225,047	10,2	12,88	3256	3014	3177,67
	7	23743,781	9,7	11,42	2450	2309	2307,00
	8	0	6,5	12,40	2908	2697	1715,91
9	1	0	6,5	14,14	4523	4293	3225,54
	2	31499,889	10,5	12,89	3261	3018	3296,59

The interpolated power output for the mean speed during each leg in the trans-Atlantic route.

Table C.0.2: Required Propulsion Power, Trans-Atlantic Route

Voyage	**Leg**	**Cargo load (mt)**	**Estimated draft (m)**	**Speed (knots)**	**Shaft Power (kW)**		
					10,4m	**9,7m**	**Estimated Draft**
1	1	0	6,5	12,33	2866,71	2660,11	1702,08
2	1	29805,502	10,3	13,52	3839,08	3579,67	3814,81
	2	10590,758	8,0	11,87	2615,46	2444,76	2039,07
3	1	0	6,5	11,66	2527,92	2372,49	1651,72
	2	29340,352	10,3	13,41	3728,75	3469,39	3687,10
	3	21659,205	9,5	11,55	2488,50	2340,46	2287,67
	4	8294,554	7,7	13,20	3530,66	3274,96	2548,92
	5	28640,894	10,2	15,75	6821,62	7021,58	6874,11
	6	0	6,5	12,00	2679,18	2498,32	1659,61
	7	0	6,5	12,69	3109,98	2878,32	1804,08
4	1	21634,379	9,4	12,00	2679,18	2498,32	2433,06
	2	23646,361	9,7	12,83	3216,34	2976,40	2968,95
	3	31499,889	10,5	13,83	4162,16	3910,40	4198,75
	4	13994,734	8,5	9,66	2547,77	2344,99	1996,58
	5	17043,599	8,9	13,23	3557,35	3300,89	3004,30
5	1	0	6,5	12,97	3328,90	3081,87	1936,32
	2	0	6,5	9,92	2453,54	2288,96	1525,74
	3	0	6,5	10,62	2340,01	2220,76	1667,79
	4	15898,124	8,7	10,97	2357,40	2236,12	2070,65
6	1	31499,889	10,5	12,93	3296,23	3051,08	3331,86
	2	7407,789	7,6	9,77	2505,02	2319,76	1759,81
7	1	0	6,5	14,69	5234,33	5085,18	4393,56
8	1	27853,711	10,1	10,58	2341,05	2221,16	2295,62
	2	31499,889	10,5	12,62	3057,66	2830,65	3090,65

Appendix D

Hotel Load

The calculated hotel loads for both the initial route and the trans-Atlantic route are presented. The hotel load includes the scrubber load for the initial route. At sea the hotel load in the electrical load table were deviating from the values observed by the electrical supervisor on-board the vessel. He was contacted to give the value for normal condition as 500 kW and 700 kW with nitrogen or hydraulic power pack. On top of that there is the scrubber load of 200 kW in both modes of operation.

Table D.0.1: Hotel Load, Initial Route

Voyage	**Leg**	**Cargo (mt)**	**Loading / Unloading Time (h)**	**Hotel Load (kW)**	
				At Sea	**At Port**
1	1	0	20,70	900	940,98
	2	31559	0,00	900	560,50
	3	31559	20,70	900	1105,03
2	1	0	0,00	900	560,50
	2	0	16,74	900	723,33
	3	25516	3,77	900	688,51
	4	31262	0,00	900	560,50
	5	31262	0,00	900	560,50
	6	31262	2,60	900	676,77
	7	27294	17,90	900	655,72
3	1	0	3,94	900	668,32
	2	6000	13,00	900	930,54
	3	25814	3,28	900	623,16
	4	20814	0,66	900	568,98
	5	19814	13,00	900	971,65
4	1	0	0,00	900	560,50
	2	0	9,38	900	632,29
	3	14306	6,52	900	626,44
	4	24241	0,00	900	560,50
	5	24241	3,09	900	764,72
	6	19524	4,38	900	659,53
	7	12849	3,42	900	657,57
	8	7631	5,01	900	759,08
5	1	0	0,00	900	560,50
	2	0	20,66	900	1005,68
	3	31503	20,66	900	1151,15
6	1	0	7,57	900	822,09
	2	11535	12,61	900	674,81
	3	30763	0,00	900	560,50
	4	30763	0,00	900	560,50
	5	30763	2,45	900	643,08
	6	27034	15,70	900	685,91
	7	3096	2,03	900	638,11
7	1	0	20,73	900	882,42
	2	31602	0,00	900	560,50
	3	31602	20,73	900	1352,60
8	1	0	0,00	900	560,50
	2	0	6,92	900	670,35
	3	10554	11,59	900	672,33
	4	28225	0,00	900	560,50
	5	28225	0,00	900	560,50
	6	28225	2,94	900	649,24
	7	23744	15,57	900	706,03
	8	0	0,00	900	560,50
9	1	0	20,66	900	897,60
	2	31500	20,66	900	No Data

The hotel load for the trans-Atlantic route does not include the scrubber load.

Table D.0.2: Hotel Load, Trans-Atlantic Route

Voyage	**Leg**	**Cargo Load (mt)**	**Loading / Unloading Time (h)**	**Hotel Load (kW)**	
				At Sea	**At Port**
1	1	0	19,55	500	572,00
2	1	29806	12,60	500	628,70
	2	10591	6,95	500	573,91
3	1	0	19,24	500	716,66
	2	29340	5,04	500	729,73
	3	21659	8,77	500	616,46
	4	8295	13,35	500	665,24
	5	28641	18,79	500	784,63
	6	0	0,00	500	497,50
	7	0	14,19	500	574,44
4	1	21634	1,32	500	576,68
	2	23646	5,51	500	557,45
	3	32044	11,84	500	607,34
	4	13995	2,00	500	509,40
	5	17044	11,18	500	1044,03
5	1	0	0,00	500	497,50
	2	0	0,00	500	497,50
	3	0	10,43	500	604,20
	4	15898	11,37	500	588,33
6	1	33228	16,94	500	643,18
	2	7408	4,86	500	576,33
7	1	0	18,27	500	No Data
8	1	27854	3,28	500	531,38
	2	32852	No Data	500	No Data

Appendix E

Sea-Margin

The sea-margins for the legs in the initial and trans-Atlantic routes are presented respectively. The sea-margin in this project is accounting for more than just the weather conditions, but other factors like the fouling and wear and tear of the hull.

Table E.0.1: Sea-Margin, Initial Route

Voyage	Leg	Avg direction wind, waves (degrees)	Avg wind force (Bft)	Avg sea-state (Douglas)	Avg direction swell (degrees)	Avg swell force (Douglas)	Sea-margin (%)
1	1	141	6,25	4,67	186	2,56	86,82
	2	132	5,23	3,85	178	1,69	77,60
	3	150	5,42	4,08	107	1,83	79,32
2	1	214	4	2,6	146	0,32	66,48
	2	85	3	2	0	0	57,44
	3	225	2,67	1,67	45	0	54,46
	4	173	3	2,66	0	0	57,44
	5	129	4,1	3	68	0,9	67,39
	6	193	6,57	5	206	2,71	89,71
	7	200	5,75	4,5	200	2,71	82,30
3	1	195	5,57	4,71	158	1,43	80,67
	2	77	4,29	3,57	65	1,43	69,10
	3	156	4,57	3,64	103	1,93	71,63
	4	113	5,4	4	68	2,7	79,14
	5	113	4,43	3,5	85	1,61	70,37
4	1	300	3	2,25	195	0,63	57,44
	2	150	3,67	2,67	105	0,73	63,50
	3	191	4,2	3,1	167	1,3	68,29
	4	315	3,67	2,67	315	0,76	63,50
	5	302	4,29	3,71	257	2,31	69,10
	6	285	4	3,33	285	1	66,48
	7	45	2	1,5	0	0	48,40
	8	315	4	2,5	293	1,6	66,48
5	1	257	3,88	3	257	1,16	65,40
	2	327	4	3	327	0,75	66,48
	3	188	3,82	2,64	131	1,32	64,85
6	1	281	4,8	3,8	281	1,8	73,71
	2	158	4,5	3,5	158	1,5	71,00
	3	173	3	2	0	0	57,44
	4	227	5,73	4,36	225	2,65	82,12
	5	273	5,71	4	283	1,93	81,94
	6	101	5,38	4,5	84	2,94	78,96
	7	270	4	2,5	135	0,15	66,48
7	1	112,5	4,44	3,67	93	1,17	70,46
	2	137	5	4,07	71	0,54	75,52
	3	196	5	4,18	0	0	75,52
8	1	191	4,8	3,8	0	0	73,71
	2	90	3,33	3	0	0	60,43
	3	45	4,5	2,5	0	0	71,00
	4	150	3,33	2,67	0	0	60,43
	5	207	4,4	3,6	0	0	70,10
	6	118	5,5	4,08	174	0,78	80,04
	7	158	3,5	3	225	0,25	61,96
	8	270	2	0	0	0	48,40
9	1	107	4,11	3	79	0,53	67,48
	2	60	5,22	4	248	1,48	77,51

Table E.0.2: Sea-Margin, Trans-Atlantic Route

Voyage	**Leg**	**Average wind force (Beaufort)**	**Sea-margin (%)**
1	1	4,3	68,7
2	1	3,9	65,5
	2	4,0	66,5
3	1	3,8	64,2
	2	3,3	60,4
	3	5,5	80,0
	4	7,0	93,6
	5	3,8	64,7
	6	3,0	57,4
	7	3,3	59,7
4	1	1,0	39,4
	2	3,7	63,5
	3	3,5	62,0
	4	4,5	71,0
	5	1,5	43,9
5	1	3,6	63,0
	2	3,3	60,4
	3	4,0	66,5
	4	3,5	62,0
6	1	4,2	67,8
	2	3,8	64,2
7	1	4,2	68,2
8	1	3,0	57,4
	2	4,5	70,7

Appendix F

Fuel Consumption

Results from the fuel consumption calculations described in section 5

F.1 Case Routes

The fuel consumption for the case routes are calculated. Here the volume of the fuel in m3. The reason for using the volume is because the operational data were providing the fuel consumption in m3. Therefore, to be able to compare the calculated fuel consumption with the actual fuel consumption the volume and not the weight was calculate.

Table F.1.1: Fuel Consumption, Initial Route

Voyage	Leg	Fuel Consumed At Sea				Fuel Consumed At Port				At Sea + At Port
		ME (m3)	AE (m3)	Boiler (m3)	Total (m3)	ME (m3)	AE (m3)	Boiler (m3)	Total (m3)	Total (m3)
1	1	110,00	29,45	15,80	155,25	0	17,75	4,25	22,00	177,25
	2	283,38	41,51	2,22	327,11	0	3,37	1,42	4,79	331,90
	3	224,55	36,48	3,28	264,31	0	14,56	3,03	17,59	281,90
2	1	38,54	10,78	12,34	61,66	0	1,77	0,75	2,52	64,18
	2	27,06	8,78	1,50	37,34	0	25,77	7,56	33,33	70,67
	3	21,96	3,49	1,13	26,58	0	7,03	2,37	9,40	35,97
	4	24,95	4,11	2,22	31,28	0	2,01	0,85	2,86	34,14
	5	233,87	31,50	10,95	276,32	0	3,21	1,35	4,56	280,88
	6	129,05	21,65	17,61	168,31	0	5,25	1,82	7,07	175,38
	7	148,25	22,73	18,27	189,25	0	42,74	12,33	55,06	244,32
3	1	77,39	20,56	17,97	115,92	0	8,46	2,91	11,37	127,29
	2	121,97	20,17	3,96	146,10	0	11,33	2,81	14,14	160,24
	3	245,31	46,79	6,85	298,94	0	11,31	4,10	15,40	314,35
	4	59,12	12,96	1,86	73,94	0	15,25	5,87	21,13	95,06
	5	282,30	47,95	13,59	343,83	0	10,65	2,54	13,18	357,02
4	1	36,00	11,72	4,96	52,68	0	1,81	0,77	2,57	55,25
	2	32,73	5,43	0,76	38,92	0	28,65	9,27	37,92	76,85
	3	177,32	32,04	1,13	210,49	0	21,46	7,31	28,77	239,26
	4	33,29	5,74	0,00	39,03	0	3,92	1,64	5,56	44,59
	5	113,06	19,86	4,63	137,56	0	4,02	1,24	5,26	142,81
	6	30,19	6,05	5,61	41,85	0	10,11	3,50	13,60	55,45
	7	6,82	1,40	0,38	8,59	0	8,04	2,82	10,85	19,45
	8	10,11	2,56	2,22	14,89	0	6,63	2,04	8,67	23,56
5	1	158,78	23,85	9,15	191,78	0	3,68	1,54	5,22	197,00
	2	17,05	3,15	0,00	20,20	0	16,18	3,66	19,84	40,04
	3	221,37	34,45	0,38	256,20	0	13,96	2,80	16,76	272,96
6	1	54,79	14,66	0,38	69,84	0	8,24	2,33	10,57	80,41
	2	5,80	1,37	0,00	7,17	0	25,81	8,04	33,85	41,01
	3	30,48	5,74	0,00	36,22	0	1,47	0,62	2,10	38,32
	4	192,72	36,78	2,22	231,72	0	4,78	1,99	6,77	238,48
	5	135,26	19,55	2,93	157,74	0	6,60	2,38	8,98	166,72
	6	128,40	23,59	9,68	161,67	0	29,77	8,95	38,72	200,39
	7	3,52	1,01	0,38	4,91	0	5,79	2,11	7,90	12,81
7	1	178,50	28,55	9,68	216,74	0	19,70	4,97	24,67	241,40
	2	255,09	43,53	0,00	298,62	0	4,39	1,83	6,22	304,84
	3	252,82	34,25	0,00	287,07	0	12,27	2,11	14,38	301,45
8	1	34,18	11,75	0,00	45,93	0	5,08	2,11	7,20	53,13
	2	18,63	4,39	0,00	23,02	0	14,64	4,87	19,51	42,54
	3	31,40	3,18	0,00	34,58	0	24,16	7,62	31,77	66,35
	4	38,26	5,97	1,50	45,73	0	0,33	0,14	0,48	46,21
	5	195,67	33,44	11,43	240,53	0	4,25	1,77	6,02	246,56
	6	251,76	37,44	18,03	307,23	0	7,46	2,65	10,11	317,34
	7	12,95	2,95	5,92	21,82	0	26,19	7,83	34,02	55,84
	8	1,16	0,39	0,00	1,55	0	11,07	4,44	15,51	17,06
9	1	177,13	27,90	13,97	219,00	0	19,07	4,75	23,82	242,82
	2	197,43	28,71	3,28	229,41	0	No Data	No Data	No Data	229,41

Table F.1.2: Fuel Consumption, Trans-Atlantic Route

Voyage	**Leg**	**Fuel Consumed At Sea**				**Fuel Consumed At Port**				**At Sea + At Port**
		ME (m3)	**AE (m3)**	**Boiler (m3)**	**Total (m3)**	**ME (m3)**	**AE (m3)**	**Boiler (m3)**	**Total (m3)**	**Total (m3)**
1	1	194,32	44,29	8,03	246,64	0,00	53,05	15,37	68,42	315,06
2	1	444,40	46,08	17,77	508,25	0,00	21,96	7,13	29,08	537,33
	2	4,64	0,90	1,50	7,03	0,00	19,11	6,79	25,89	32,93
3	1	61,83	14,92	19,74	96,50	0,00	22,83	6,58	29,42	125,91
	2	32,90	3,64	0,76	37,30	0,00	6,51	1,76	8,27	45,57
	3	8,26	1,31	0,00	9,58	0,00	16,77	5,62	22,39	31,96
	4	6,75	0,90	0,00	7,64	0,00	19,37	6,03	25,39	33,04
	5	651,31	37,66	0,00	688,97	0,00	18,82	5,04	23,86	712,83
	6	7,62	1,91	0,00	9,53	0,00	1,97	0,46	2,43	11,96
	7	78,29	17,79	29,19	125,27	0,00	37,75	12,15	49,90	175,17
4	1	0,74	0,14	0,00	0,89	0,00	4,35	1,36	5,71	6,60
	2	23,46	3,16	1,13	27,75	0,00	18,77	6,85	25,63	53,38
	3	430,84	41,47	11,89	484,20	0,00	23,71	7,88	31,59	515,78
	4	27,21	5,22	9,81	42,24	0,00	30,71	11,34	42,04	84,28
	5	15,14	2,29	1,50	18,92	0,00	8,42	1,66	10,09	29,01
5	1	228,91	47,48	16,22	292,61	0,00	5,88	2,27	8,15	300,76
	2	16,29	4,36	2,22	22,87	0,00	5,78	2,23	8,01	30,88
	3	30,08	9,96	6,85	46,88	0,00	21,49	7,23	28,72	75,61
	4	16,39	3,20	4,96	24,55	0,00	26,54	8,94	35,48	60,03
6	1	427,51	50,04	8,03	485,58	0,00	26,94	8,40	35,34	520,92
	2	31,46	7,13	10,07	48,66	0,00	13,33	4,77	18,11	66,77
7	1	470,34	41,66	16,72	528,72	0,00	No Data	No Data	No Data	528,72
8	1	7,91	1,43	7,45	16,79	0,00	18,84	7,17	26,02	42,81
	2	402,24	49,90	83,58	535,72	0,00	No Data	No Data	No Data	535,72

F.2 Main Engine

Here the fuel consumption for the main engine is presented under different operational conditions described in 6.1. The calculation of the fuel consumption is described in 5.2 This is the weight of the fuel in tons and not the volume.

Table F.2.1: Fuel Consumption in Good Weather

Speed (knots)	**Distance (nm)**												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	52,21	78,31	104,42	130,52	156,62	182,73	208,83	234,94	261,04	287,15	313,25	339,35	365,46
11,1	52,07	78,11	104,14	130,18	156,21	182,25	208,29	234,32	260,36	286,39	312,43	338,46	364,50
11,2	52,02	78,03	104,04	130,06	156,07	182,08	208,09	234,10	260,11	286,12	312,13	338,14	364,16
11,3	52,06	78,09	104,12	130,14	156,17	182,20	208,23	234,26	260,29	286,32	312,35	338,37	364,40
11,4	52,17	78,26	104,35	130,44	156,52	182,61	208,70	234,79	260,87	286,96	313,05	339,13	365,22
11,5	52,37	78,55	104,74	130,92	157,11	183,29	209,48	235,66	261,85	288,03	314,22	340,40	366,59
11,6	52,64	78,96	105,28	131,60	157,92	184,24	210,56	236,88	263,20	289,52	315,85	342,17	368,49
11,7	52,98	79,48	105,97	132,46	158,95	185,45	211,94	238,43	264,92	291,42	317,91	344,40	370,89
11,8	53,40	80,10	106,80	133,50	160,20	186,90	213,59	240,29	266,99	293,69	320,39	347,09	373,79
11,9	53,88	80,82	107,76	134,70	161,64	188,58	215,52	242,46	269,40	296,34	323,28	350,22	377,16
12	54,43	81,64	108,85	136,07	163,28	190,49	217,71	244,92	272,13	299,35	326,56	353,77	380,99
12,1	55,04	82,55	110,07	137,59	165,11	192,63	220,14	247,66	275,18	302,70	330,22	357,73	385,25
12,2	55,71	83,56	111,41	139,26	167,12	194,97	222,82	250,68	278,53	306,38	334,23	362,09	389,94
12,3	56,43	84,65	112,87	141,08	169,30	197,52	225,73	253,95	282,17	310,38	338,60	366,81	395,03
12,4	57,22	85,82	114,43	143,04	171,65	200,26	228,87	257,47	286,08	314,69	343,30	371,91	400,51
12,5	58,05	87,08	116,11	145,13	174,16	203,19	232,21	261,24	290,27	319,29	348,32	377,35	406,37
12,6	58,94	88,41	117,88	147,35	176,83	206,30	235,77	265,24	294,71	324,18	353,65	383,12	412,59
12,7	59,88	89,82	119,76	149,70	179,64	209,58	239,52	269,46	299,40	329,34	359,28	389,22	419,16
12,8	60,87	91,30	121,73	152,16	182,60	213,03	243,46	273,90	304,33	334,76	365,19	395,63	426,06
12,9	61,90	92,85	123,79	154,74	185,69	216,64	247,59	278,54	309,49	340,44	371,38	402,33	433,28
13	62,97	94,46	125,95	157,43	188,92	220,41	251,89	283,38	314,87	346,35	377,84	409,32	440,81
13,1	64,09	96,14	128,18	160,23	192,27	224,32	256,36	288,41	320,45	352,50	384,55	416,59	448,64
13,2	65,25	97,87	130,50	163,12	195,75	228,37	261,00	293,62	326,25	358,87	391,50	424,12	456,75
13,3	66,45	99,67	132,89	166,12	199,34	232,56	265,79	299,01	332,23	365,46	398,68	431,90	465,13
13,4	67,68	101,52	135,36	169,20	203,04	236,88	270,72	304,56	338,41	372,25	406,09	439,93	473,77
13,5	68,95	103,43	137,90	172,38	206,85	241,33	275,80	310,28	344,76	379,23	413,71	448,18	482,66
13,6	70,26	105,38	140,51	175,64	210,77	245,89	281,02	316,15	351,28	386,41	421,53	456,66	491,79
13,7	71,59	107,39	143,19	178,98	214,78	250,57	286,37	322,17	357,96	393,76	429,56	465,35	501,15
13,8	72,96	109,44	145,92	182,40	218,88	255,36	291,84	328,32	364,81	401,29	437,77	474,25	510,73
13,9	74,36	111,54	148,72	185,90	223,08	260,26	297,44	334,62	371,80	408,98	446,16	483,34	520,52
14	75,79	113,68	151,57	189,47	227,36	265,25	303,14	341,04	378,93	416,82	454,72	492,61	530,50

Table F.2.2: Fuel Consumption in Moderate Weather

Speed (knots)	**Distance (nm)**												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	61,35	92,03	122,70	153,38	184,05	214,73	245,40	276,08	306,76	337,43	368,11	398,78	429,46
11,1	61,19	91,79	122,38	152,98	183,57	214,17	244,76	275,36	305,95	336,55	367,14	397,74	428,33
11,2	61,13	91,70	122,26	152,83	183,40	213,96	244,53	275,10	305,66	336,23	366,79	397,36	427,93
11,3	61,17	91,76	122,35	152,93	183,52	214,11	244,70	275,28	305,87	336,46	367,04	397,63	428,22
11,4	61,31	91,97	122,62	153,28	183,93	214,59	245,25	275,90	306,56	337,21	367,87	398,52	429,18
11,5	61,54	92,31	123,08	153,85	184,62	215,39	246,16	276,93	307,70	338,48	369,25	400,02	430,79
11,6	61,86	92,79	123,72	154,65	185,58	216,51	247,44	278,37	309,30	340,23	371,16	402,09	433,02
11,7	62,26	93,40	124,53	155,66	186,79	217,92	249,05	280,19	311,32	342,45	373,58	404,71	435,84
11,8	62,75	94,12	125,50	156,87	188,25	219,62	251,00	282,37	313,75	345,12	376,50	407,87	439,25
11,9	63,32	94,97	126,63	158,29	189,95	221,61	253,26	284,92	316,58	348,24	379,90	411,55	443,21
12	63,96	95,94	127,92	159,90	191,87	223,85	255,83	287,81	319,79	351,77	383,75	415,73	447,71
12,1	64,67	97,01	129,35	161,69	194,02	226,36	258,70	291,03	323,37	355,71	388,04	420,38	452,72
12,2	65,46	98,19	130,92	163,65	196,38	229,11	261,84	294,57	327,30	360,03	392,76	425,50	458,23
12,3	66,32	99,47	132,63	165,79	198,95	232,10	265,26	298,42	331,58	364,74	397,89	431,05	464,21
12,4	67,24	100,85	134,47	168,09	201,71	235,33	268,94	302,56	336,18	369,80	403,42	437,03	470,65
12,5	68,22	102,33	136,44	170,55	204,66	238,77	272,88	306,99	341,10	375,21	409,32	443,43	477,54
12,6	69,26	103,90	138,53	173,16	207,79	242,42	277,06	311,69	346,32	380,95	415,58	450,21	484,85
12,7	70,37	105,55	140,73	175,92	211,10	246,28	281,46	316,65	351,83	387,01	422,20	457,38	492,56
12,8	71,52	107,29	143,05	178,81	214,57	250,34	286,10	321,86	357,62	393,39	429,15	464,91	500,67
12,9	72,74	109,11	145,47	181,84	218,21	254,58	290,95	327,32	363,68	400,05	436,42	472,79	509,16
13	74,00	111,00	148,00	185,00	222,00	259,00	296,00	333,00	370,00	407,01	444,01	481,01	518,01
13,1	75,31	112,97	150,63	188,29	225,94	263,60	301,26	338,92	376,57	414,23	451,89	489,54	527,20
13,2	76,68	115,01	153,35	191,69	230,03	268,37	306,70	345,04	383,38	421,72	460,05	498,39	536,73
13,3	78,08	117,12	156,17	195,21	234,25	273,29	312,33	351,37	390,41	429,45	468,50	507,54	546,58
13,4	79,53	119,30	159,07	198,83	238,60	278,37	318,13	357,90	397,67	437,43	477,20	516,97	556,73
13,5	81,03	121,54	162,05	202,57	243,08	283,59	324,10	364,62	405,13	445,64	486,16	526,67	567,18
13,6	82,56	123,84	165,12	206,40	247,68	288,96	330,24	371,51	412,79	454,07	495,35	536,63	577,91
13,7	84,13	126,20	168,26	210,33	252,39	294,46	336,52	378,59	420,65	462,72	504,78	546,85	588,91
13,8	85,74	128,61	171,48	214,35	257,21	300,08	342,95	385,82	428,69	471,56	514,43	557,30	600,17
13,9	87,38	131,07	174,76	218,45	262,14	305,83	349,52	393,22	436,91	480,60	524,29	567,98	611,67
14	89,06	133,59	178,12	222,64	267,17	311,70	356,23	400,76	445,29	489,82	534,35	578,88	623,41

Table F.2.3: Fuel Consumption in Bad Weather

Speed (knots)	**Distance (nm)**												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	72,53	108,79	145,05	181,31	217,58	253,84	290,10	326,37	362,63	398,89	435,15	471,42	507,68
11,1	72,34	108,50	144,67	180,84	217,01	253,17	289,34	325,51	361,68	397,84	434,01	470,18	506,35
11,2	72,27	108,40	144,53	180,67	216,80	252,93	289,07	325,20	361,34	397,47	433,60	469,74	505,87
11,3	72,32	108,47	144,63	180,79	216,95	253,11	289,26	325,42	361,58	397,74	433,90	470,06	506,21
11,4	72,48	108,72	144,96	181,20	217,44	253,67	289,91	326,15	362,39	398,63	434,87	471,11	507,35
11,5	72,75	109,12	145,50	181,87	218,25	254,62	291,00	327,37	363,75	400,12	436,50	472,87	509,25
11,6	73,13	109,69	146,25	182,82	219,38	255,94	292,51	329,07	365,63	402,20	438,76	475,32	511,89
11,7	73,60	110,41	147,21	184,01	220,81	257,61	294,42	331,22	368,02	404,82	441,62	478,43	515,23
11,8	74,18	111,27	148,36	185,45	222,54	259,63	296,72	333,81	370,90	407,99	445,08	482,17	519,25
11,9	74,85	112,27	149,70	187,12	224,54	261,97	299,39	336,82	374,24	411,67	449,09	486,51	523,94
12	75,61	113,41	151,22	189,02	226,82	264,63	302,43	340,23	378,04	415,84	453,65	491,45	529,25
12,1	76,45	114,68	152,91	191,13	229,36	267,59	305,82	344,04	382,27	420,50	458,72	496,95	535,18
12,2	77,38	116,08	154,77	193,46	232,15	270,84	309,54	348,23	386,92	425,61	464,30	502,99	541,69
12,3	78,39	117,59	156,79	195,99	235,18	274,38	313,58	352,77	391,97	431,17	470,37	509,56	548,76
12,4	79,48	119,22	158,97	198,71	238,45	278,19	317,93	357,67	397,41	437,15	476,90	516,64	556,38
12,5	80,65	120,97	161,29	201,61	241,94	282,26	322,58	362,90	403,23	443,55	483,87	524,19	564,52
12,6	81,88	122,82	163,76	204,70	245,64	286,58	327,52	368,46	409,40	450,34	491,28	532,22	573,16
12,7	83,18	124,77	166,37	207,96	249,55	291,14	332,73	374,32	415,91	457,50	499,10	540,69	582,28
12,8	84,55	126,83	169,10	211,38	253,66	295,93	338,21	380,48	422,76	465,04	507,31	549,59	591,87
12,9	85,99	128,98	171,97	214,96	257,96	300,95	343,94	386,93	429,93	472,92	515,91	558,90	601,90
13	87,48	131,22	174,96	218,70	262,44	306,18	349,92	393,66	437,40	481,14	524,88	568,62	612,36
13,1	89,03	133,55	178,06	222,58	267,10	311,61	356,13	400,65	445,16	489,68	534,19	578,71	623,23
13,2	90,64	135,96	181,28	226,60	271,92	317,25	362,57	407,89	453,21	498,53	543,85	589,17	634,49
13,3	92,30	138,46	184,61	230,76	276,91	323,07	369,22	415,37	461,52	507,68	553,83	599,98	646,13
13,4	94,02	141,03	188,04	235,05	282,06	329,07	376,08	423,09	470,10	517,11	564,12	611,13	658,14
13,5	95,78	143,68	191,57	239,46	287,35	335,24	383,14	431,03	478,92	526,81	574,70	622,60	670,49
13,6	97,60	146,39	195,19	243,99	292,79	341,59	390,38	439,18	487,98	536,78	585,58	634,37	683,17
13,7	99,45	149,18	198,91	248,63	298,36	348,09	397,81	447,54	497,27	546,99	596,72	646,45	696,17
13,8	101,35	152,03	202,71	253,39	304,06	354,74	405,42	456,09	506,77	557,45	608,13	658,80	709,48
13,9	103,30	154,95	206,59	258,24	309,89	361,54	413,19	464,84	516,48	568,13	619,78	671,43	723,08
14	105,28	157,92	210,56	263,20	315,84	368,48	421,12	473,76	526,39	579,03	631,67	684,31	736,95

F.3 Auxiliary Engines

The fuel consumption for the auxiliary engines is calculated using the equation in section 5.3 for different speeds and distances. This is the weight of the fuel in tons.

Table F.3.1: Hotel Load

Speed (knots)	**Distance (nm)**												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	10,31	15,46	20,62	25,77	30,93	36,08	41,24	46,39	51,55	56,70	61,85	67,01	72,16
11,1	10,22	15,32	20,43	25,54	30,65	35,76	40,86	45,97	51,08	56,19	61,30	66,41	71,51
11,2	10,13	15,19	20,25	25,31	30,38	35,44	40,50	45,56	50,63	55,69	60,75	65,81	70,88
11,3	10,04	15,05	20,07	25,09	30,11	35,12	40,14	45,16	50,18	55,19	60,21	65,23	70,25
11,4	9,95	14,92	19,89	24,87	29,84	34,82	39,79	44,76	49,74	54,71	59,68	64,66	69,63
11,5	9,86	14,79	19,72	24,65	29,58	34,51	39,44	44,37	49,30	54,23	59,17	64,10	69,03
11,6	9,78	14,66	19,55	24,44	29,33	34,22	39,10	43,99	48,88	53,77	58,66	63,54	68,43
11,7	9,69	14,54	19,38	24,23	29,08	33,92	38,77	43,62	48,46	53,31	58,15	63,00	67,85
11,8	9,61	14,42	19,22	24,03	28,83	33,64	38,44	43,25	48,05	52,86	57,66	62,47	67,27
11,9	9,53	14,29	19,06	23,82	28,59	33,35	38,12	42,88	47,65	52,41	57,18	61,94	66,71
12	9,45	14,18	18,90	23,63	28,35	33,08	37,80	42,53	47,25	51,98	56,70	61,43	66,15
12,1	9,37	14,06	18,74	23,43	28,12	32,80	37,49	42,17	46,86	51,55	56,23	60,92	65,60
12,2	9,30	13,94	18,59	23,24	27,89	32,53	37,18	41,83	46,48	51,12	55,77	60,42	65,07
12,3	9,22	13,83	18,44	23,05	27,66	32,27	36,88	41,49	46,10	50,71	55,32	59,93	64,54
12,4	9,15	13,72	18,29	22,86	27,44	32,01	36,58	41,15	45,73	50,30	54,87	59,44	64,02
12,5	9,07	13,61	18,14	22,68	27,22	31,75	36,29	40,82	45,36	49,90	54,43	58,97	63,50
12,6	9,00	13,50	18,00	22,50	27,00	31,50	36,00	40,50	45,00	49,50	54,00	58,50	63,00
12,7	8,93	13,39	17,86	22,32	26,79	31,25	35,72	40,18	44,65	49,11	53,57	58,04	62,50
12,8	8,86	13,29	17,72	22,15	26,58	31,01	35,44	39,87	44,30	48,73	53,16	57,59	62,02
12,9	8,79	13,19	17,58	21,98	26,37	30,77	35,16	39,56	43,95	48,35	52,74	57,14	61,53
13	8,72	13,08	17,45	21,81	26,17	30,53	34,89	39,25	43,62	47,98	52,34	56,70	61,06
13,1	8,66	12,98	17,31	21,64	25,97	30,30	34,63	38,95	43,28	47,61	51,94	56,27	60,60
13,2	8,59	12,89	17,18	21,48	25,77	30,07	34,36	38,66	42,95	47,25	51,55	55,84	60,14
13,3	8,53	12,79	17,05	21,32	25,58	29,84	34,11	38,37	42,63	46,89	51,16	55,42	59,68
13,4	8,46	12,69	16,93	21,16	25,39	29,62	33,85	38,08	42,31	46,54	50,78	55,01	59,24
13,5	8,40	12,60	16,80	21,00	25,20	29,40	33,60	37,80	42,00	46,20	50,40	54,60	58,80
13,6	8,34	12,51	16,68	20,85	25,01	29,18	33,35	37,52	41,69	45,86	50,03	54,20	58,37
13,7	8,28	12,42	16,55	20,69	24,83	28,97	33,11	37,25	41,39	45,53	49,66	53,80	57,94
13,8	8,22	12,33	16,43	20,54	24,65	28,76	32,87	36,98	41,09	45,20	49,30	53,41	57,52
13,9	8,16	12,24	16,32	20,40	24,47	28,55	32,63	36,71	40,79	44,87	48,95	53,03	57,11
14	8,10	12,15	16,20	20,25	24,30	28,35	32,40	36,45	40,50	44,55	48,60	52,65	56,70

F.4 Boiler

The fuel consumption for the boiler is calculated using the equation in section 5.4 for different speeds and distances. This is the weight of the fuel in tons.

Table F.4.1: Fuel Consumed by Boiler

Speed (knots)	**Distance (nm)**												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	5,98	8,50	10,71	12,61	14,21	15,49	16,46	17,12	18,14	19,95	21,76	23,58	25,39
11,1	5,93	8,44	10,64	12,54	14,13	15,42	16,40	17,08	17,97	19,77	21,57	23,36	25,16
11,2	5,88	8,37	10,56	12,46	14,05	15,34	16,34	17,03	17,81	19,59	21,38	23,16	24,94
11,3	5,83	8,31	10,49	12,38	13,97	15,27	16,28	16,99	17,65	19,42	21,19	22,95	24,72
11,4	5,79	8,25	10,42	12,30	13,90	15,20	16,22	16,94	17,50	19,25	21,00	22,75	24,50
11,5	5,74	8,19	10,35	12,23	13,82	15,13	16,16	16,90	17,35	19,08	20,82	22,55	24,29
11,6	5,70	8,13	10,28	12,15	13,75	15,06	16,09	16,85	17,33	18,92	20,64	22,36	24,08
11,7	5,65	8,07	10,21	12,08	13,67	14,99	16,03	16,80	17,30	18,76	20,46	22,17	23,87
11,8	5,61	8,01	10,14	12,00	13,60	14,92	15,97	16,75	17,27	18,60	20,29	21,98	23,67
11,9	5,57	7,95	10,08	11,93	13,52	14,85	15,91	16,70	17,23	18,44	20,12	21,79	23,47
12	5,53	7,90	10,01	11,86	13,45	14,78	15,85	16,65	17,20	18,29	19,95	21,61	23,28
12,1	5,48	7,84	9,94	11,79	13,38	14,71	15,78	16,60	17,16	18,14	19,79	21,43	23,08
12,2	5,44	7,79	9,88	11,72	13,30	14,64	15,72	16,55	17,13	17,99	19,62	21,26	22,89
12,3	5,40	7,73	9,81	11,65	13,23	14,57	15,66	16,50	17,09	17,84	19,46	21,09	22,71
12,4	5,36	7,68	9,75	11,58	13,16	14,50	15,60	16,45	17,05	17,70	19,31	20,92	22,52
12,5	5,33	7,63	9,69	11,51	13,09	14,43	15,53	16,39	17,01	17,56	19,15	20,75	22,34
12,6	5,29	7,58	9,63	11,44	13,02	14,36	15,47	16,34	16,97	17,42	19,00	20,58	22,17
12,7	5,25	7,52	9,57	11,38	12,95	14,30	15,41	16,28	16,93	17,34	18,85	20,42	21,99
12,8	5,21	7,47	9,51	11,31	12,88	14,23	15,34	16,23	16,89	17,32	18,70	20,26	21,82
12,9	5,17	7,42	9,45	11,24	12,82	14,16	15,28	16,18	16,85	17,29	18,56	20,10	21,65
13	5,14	7,37	9,39	11,18	12,75	14,09	15,22	16,12	16,80	17,26	18,42	19,95	21,48
13,1	5,10	7,33	9,33	11,11	12,68	14,03	15,16	16,07	16,76	17,23	18,27	19,80	21,32
13,2	5,07	7,28	9,27	11,05	12,61	13,96	15,09	16,01	16,71	17,20	18,14	19,65	21,16
13,3	5,03	7,23	9,22	10,99	12,55	13,90	15,03	15,96	16,67	17,17	18,00	19,50	21,00
13,4	5,00	7,18	9,16	10,93	12,48	13,83	14,97	15,90	16,62	17,13	17,87	19,35	20,84
13,5	4,96	7,14	9,10	10,86	12,42	13,77	14,91	15,85	16,58	17,10	17,73	19,21	20,69
13,6	4,93	7,09	9,05	10,80	12,35	13,70	14,85	15,79	16,53	17,07	17,60	19,07	20,54
13,7	4,90	7,05	8,99	10,74	12,29	13,64	14,79	15,73	16,48	17,03	17,47	18,93	20,39
13,8	4,86	7,00	8,94	10,68	12,23	13,58	14,73	15,68	16,43	16,99	17,35	18,79	20,24
13,9	4,83	6,96	8,89	10,62	12,16	13,51	14,66	15,62	16,39	16,96	17,33	18,66	20,09
14	4,80	6,91	8,83	10,56	12,10	13,45	14,60	15,57	16,34	16,92	17,31	18,53	19,95

Appendix G

Hydrogen Required

The energy output for the engines and the boiler were calculated based on the energy content of the consumed HFO and the efficiencies of components. Summing the energy consumed at sea for all the components yields the total energy consumed at sea, and likewise for the total energy consumed at port.

$$E_{ME} = K_{ME} \cdot \eta_{ME} \cdot \rho_{HFO} \cdot \upsilon_{HFO} \tag{G.0.1}$$

$$E_{AE}^{S} = K_{AE}^{S} \cdot \eta_{AE} \cdot \rho_{HFO} \cdot \upsilon_{HFO} \tag{G.0.2}$$

$$E_{AE}^{P} = K_{AE}^{P} \cdot \eta_{AE} \cdot \rho_{HFO} \cdot \upsilon_{HFO} \tag{G.0.3}$$

$$E_{B}^{S} = K_{B}^{S} \cdot \eta_{B} \cdot \rho_{HFO} \cdot \upsilon_{HFO} \tag{G.0.4}$$

$$E_{B}^{P} = K_{B}^{P} \cdot \eta_{B} \cdot \rho_{HFO} \cdot \upsilon_{HFO} \tag{G.0.5}$$

$$E^{S} = E_{ME} + E_{AE}^{S} + E_{B}^{S} \tag{G.0.6}$$

$$E^{P} = E_{AE}^{P} + E_{B}^{P} \tag{G.0.7}$$

E^S - Energy consumed at sea in MJ

E^P - Energy consumed at port in MJ

E_{ME} - Energy consumed by main engine in MJ

E_{AE}^S - Energy consumed by auxiliary engines at sea in MJ

E_{AE}^P - Energy consumed by auxiliary engines at port in MJ

E_B^S - Energy consumed by boiler at sea in MJ

E_B^P - Energy consumed by boiler at sea in MJ

η_{ME} - Efficiency of main engine

η_{AE} - Efficiencies of auxiliary engines

η_{B} - Efficiency of boiler

ρ_{HFO} - HFO Density in kg/m3

υ_{HFO} - HFO Energy density in MJ/kg

The efficiencies of the main engine, auxiliary engines and the boiler are provided by Stolt Nielsen described in section 4.1.1. For the main engine it is 38%, for the auxiliary engines it is 38%, and the boiler is 90%.

The hydrogen required to complete each leg is based on the efficiency of the fuel cell system and the energy required to complete the leg. As this will serve as the basis for the selection of fuel cells and average fuel cell system efficiency of 54% is being used for these calculation. In the fuel cell section real data for fuel cell systems will be used. The operational study will be a more detailed account of the performance of the vessel sailing on the trans-Atlantic route. However, the values found here will serve as an initial basis for further study.

$$V^{S}_{H2} = \frac{E^{S}}{\rho_{LH2} \cdot \upsilon_{LH2} \cdot \eta_{FC}} \tag{G.0.8}$$

$$W^{S}_{H2} = V^{S}_{H2} \cdot \rho_{LH2} \tag{G.0.9}$$

$$V^{P}_{H2} = \frac{E^{P}}{\rho_{LH2} \cdot \upsilon_{LH2} \cdot \eta_{FC}} \tag{G.0.10}$$

$$W^{P}_{H2} = V^{P}_{H2} \cdot \rho_{LH2} \tag{G.0.11}$$

$V^{hydrogen,\ sea}$ - Volume of required hydrogen at sea in m3

$V^{hydrogen,\ port}$ - Volume of required hydrogen at port in m3

$W^{hydrogen,\ sea}$ - Weight of required hydrogen at sea in tons

W^{P}_{H2} - Weight of required hydrogen at port in tons

ρ_{LH2} - LH2 density in kg/m3

υ_{LH2} - LH2 energy density in MJ/kg

η_{FC} - Efficiency of fuel cell system

G.1 Trans-Atlantic Route

Table G.1.1: Hydrogen Required

Voyage	Leg	Cargo Load (mt)	Speed (knots)	At Sea	At Port	At Sea		At Port	Power Output (kW)
				Energy Required (MWh)	Energy required (MWh)	Hydrogen required (m3)	Hydrogen required (tons)	Hydrogen required (m3)	
1	1	0	12,33	1059,19	367,81	905,29	58,84	314,37	3772
2	1	29806	13,52	2189,56	159,66	1871,42	121,64	136,46	7213
	2	10591	11,87	37,34	144,65	31,91	2,07	123,64	4295
3	1	0	11,66	507,79	157,98	434,01	28,21	135,02	3612
	2	29340	13,41	157,60	43,90	134,70	8,76	37,52	6815
	3	21659	11,55	39,37	123,68	33,65	2,19	105,71	5019
	4	8295	13,20	31,43	138,30	26,86	1,75	118,20	5835
	5	28641	15,75	2832,64	126,45	2421,06	157,37	108,08	12220
	6	0	12,00	39,20	12,54	33,50	2,18	10,72	3513
	7	0	12,69	679,24	273,54	580,55	37,74	233,80	3781
4	1	21634	12,00	3,64	31,14	3,11	0,20	26,62	4291
	2	23646	12,83	120,44	143,91	102,94	6,69	123,00	5754
	3	32044	13,83	2057,61	174,20	1758,64	114,31	148,89	7700
	4	13995	9,66	228,85	236,63	195,60	12,71	202,25	4314
	5	17044	13,23	86,22	50,82	73,69	4,79	43,43	5223
5	1	0	12,97	1294,29	46,26	1106,23	71,91	39,54	4055
	2	0	9,92	106,52	45,45	91,05	5,92	38,85	3348
	3	0	10,62	231,28	158,80	197,68	12,85	135,72	3677
	4	15898	10,97	128,84	196,20	110,12	7,16	167,69	4254
6	1	33228	12,93	2041,57	192,60	1744,93	113,42	164,61	6492
	2	7408	9,77	256,73	101,29	219,42	14,26	86,57	3790
7	1	0	14,69	2267,84	No Data	1938,33	125,99	No Data	8290
8	1	27854	10,58	110,92	147,31	94,80	6,16	125,91	4514
	2	32852	12,62	2672,77	No Data	2284,42	148,49	No Data	6177

G.2 Propulsion, Hotel Load and Boiler

The hydrogen required for the vessel the fuel cell system provides power to propulsion, hotel load and the boiler for different weathers are presented. In these matrices the required hydrogen are in tons.

Table G.2.1: Hydrogen Required in Good Weather for P, H, B

Speed (knots)	Distance (nm)												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	16,17	24,14	32,04	39,87	47,63	55,31	62,92	70,45	78,07	85,88	93,68	101,49	109,30
11,1	16,10	24,05	31,92	39,72	47,45	55,10	62,69	70,20	77,76	85,54	93,31	101,09	108,87
11,2	16,06	23,98	31,83	39,62	47,33	54,97	62,54	70,04	77,56	85,31	93,07	100,82	108,58
11,3	16,03	23,95	31,79	39,57	47,27	54,91	62,47	69,97	77,46	85,20	92,95	100,69	108,44
11,4	16,03	23,94	31,79	39,57	47,27	54,91	62,49	69,99	77,45	85,20	92,94	100,69	108,44
11,5	16,05	23,97	31,82	39,61	47,33	54,99	62,57	70,09	77,55	85,30	93,06	100,81	108,56
11,6	16,08	24,02	31,89	39,70	47,45	55,12	62,74	70,28	77,76	85,50	93,28	101,05	108,82
11,7	16,13	24,10	32,00	39,84	47,61	55,32	62,97	70,55	78,06	85,80	93,60	101,40	109,20
11,8	16,20	24,20	32,14	40,02	47,83	55,58	63,27	70,89	78,45	86,20	94,03	101,87	109,70
11,9	16,28	24,33	32,32	40,24	48,10	55,89	63,63	71,30	78,91	86,68	94,56	102,44	110,32
12	16,38	24,48	32,52	40,50	48,41	56,26	64,06	71,79	79,45	87,25	95,18	103,11	111,05
12,1	16,50	24,66	32,76	40,79	48,77	56,69	64,54	72,34	80,07	87,90	95,90	103,89	111,88
12,2	16,63	24,85	33,02	41,13	49,17	57,16	65,09	72,96	80,76	88,64	96,70	104,75	112,81
12,3	16,77	25,07	33,31	41,49	49,62	57,68	65,69	73,64	81,52	89,45	97,58	105,71	113,85
12,4	16,93	25,31	33,63	41,90	50,10	58,25	66,34	74,38	82,35	90,34	98,55	106,76	114,97
12,5	17,10	25,57	33,98	42,33	50,63	58,87	67,05	75,17	83,24	91,30	99,59	107,89	116,19
12,6	17,29	25,85	34,35	42,80	51,19	59,53	67,81	76,03	84,20	92,32	100,72	109,11	117,50
12,7	17,48	26,14	34,74	43,29	51,79	60,23	68,61	76,94	85,21	93,43	101,91	110,40	118,89
12,8	17,69	26,45	35,16	43,82	52,42	60,97	69,46	77,90	86,28	94,61	103,17	111,77	120,37
12,9	17,91	26,78	35,60	44,37	53,09	61,75	70,35	78,91	87,41	95,86	104,50	113,21	121,92
13	18,14	27,13	36,07	44,95	53,78	62,56	71,29	79,97	88,59	97,16	105,89	114,72	123,54
13,1	18,38	27,49	36,55	45,56	54,51	63,42	72,27	81,07	89,82	98,52	107,35	116,30	125,24
13,2	18,63	27,86	37,05	46,19	55,27	64,30	73,29	82,22	91,10	99,93	108,87	117,94	127,01
13,3	18,89	28,25	37,57	46,84	56,06	65,22	74,34	83,41	92,43	101,39	110,44	119,64	128,84
13,4	19,15	28,66	38,11	47,52	56,87	66,18	75,43	84,64	93,80	102,90	112,06	121,40	130,74
13,5	19,43	29,07	38,67	48,21	57,71	67,16	76,56	85,91	95,21	104,46	113,74	123,22	132,70
13,6	19,72	29,50	39,24	48,93	58,58	68,17	77,72	87,22	96,67	106,07	115,47	125,10	134,72
13,7	20,01	29,94	39,83	49,67	59,46	69,21	78,91	88,56	98,16	107,72	117,25	127,02	136,79
13,8	20,31	30,40	40,44	50,43	60,38	70,28	80,13	89,93	99,69	109,41	119,07	129,00	138,92
13,9	20,62	30,86	41,06	51,21	61,31	71,37	81,38	91,34	101,26	111,14	120,97	131,02	141,10
14	20,94	31,34	41,69	52,00	62,26	72,48	82,66	92,78	102,87	112,91	122,90	133,09	143,32

Table G.2.2: Hydrogen Required in Moderate Weather for P, H, B

Speed (knots)	**Distance (nm)**												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	18,33	27,38	36,36	45,27	54,10	62,86	71,55	80,16	88,86	97,75	106,63	115,52	124,41
11,1	18,26	27,28	36,22	45,10	53,90	62,64	71,30	79,88	88,52	97,38	106,23	115,08	123,93
11,2	18,21	27,21	36,14	44,99	53,78	62,50	71,14	79,72	88,31	97,14	105,97	114,80	123,63
11,3	18,19	27,18	36,10	44,95	53,73	62,44	71,08	79,65	88,22	97,04	105,86	114,68	123,50
11,4	18,19	27,18	36,10	44,96	53,74	62,46	71,11	79,70	88,24	97,06	105,89	114,71	123,53
11,5	18,21	27,22	36,15	45,02	53,83	62,56	71,23	79,84	88,37	97,21	106,05	114,88	123,72
11,6	18,26	27,28	36,25	45,14	53,98	62,74	71,44	80,07	88,64	97,47	106,33	115,19	124,06
11,7	18,32	27,38	36,38	45,32	54,18	62,99	71,73	80,40	89,01	97,85	106,75	115,64	124,54
11,8	18,41	27,51	36,56	45,54	54,45	63,31	72,10	80,82	89,48	98,34	107,28	116,22	125,16
11,9	18,51	27,67	36,77	45,81	54,78	63,69	72,54	81,32	90,05	98,93	107,92	116,92	125,91
12	18,63	27,86	37,02	46,12	55,16	64,14	73,06	81,91	90,70	99,63	108,68	117,74	126,80
12,1	18,77	28,07	37,31	46,48	55,60	64,65	73,64	82,58	91,45	100,42	109,55	118,68	127,80
12,2	18,93	28,31	37,63	46,88	56,08	65,22	74,30	83,32	92,28	101,30	110,51	119,72	128,93
12,3	19,11	28,57	37,98	47,33	56,62	65,85	75,02	84,13	93,19	102,28	111,58	120,88	130,18
12,4	19,30	28,86	38,36	47,81	57,20	66,53	75,80	85,02	94,18	103,35	112,74	122,14	131,53
12,5	19,50	29,17	38,78	48,33	57,83	67,27	76,65	85,97	95,24	104,49	113,99	123,49	132,99
12,6	19,72	29,50	39,22	48,89	58,50	68,05	77,55	86,99	96,38	105,72	115,34	124,95	134,56
12,7	19,96	29,85	39,70	49,48	59,21	68,89	78,51	88,08	97,59	107,05	116,76	126,49	136,22
12,8	20,21	30,23	40,20	50,11	59,97	69,77	79,52	89,22	98,86	108,45	118,27	128,12	137,98
12,9	20,47	30,62	40,72	50,77	60,76	70,70	80,59	90,42	100,20	109,93	119,85	129,84	139,83
13	20,74	31,03	41,27	51,46	61,59	71,67	81,70	91,68	101,61	111,48	121,51	131,64	141,77
13,1	21,03	31,46	41,85	52,18	62,46	72,69	82,87	92,99	103,07	113,09	123,25	133,52	143,79
13,2	21,32	31,91	42,44	52,93	63,36	73,74	84,08	94,36	104,59	114,76	125,05	135,47	145,89
13,3	21,63	32,37	43,07	53,71	64,30	74,84	85,33	95,77	106,16	116,50	126,92	137,50	148,07
13,4	21,95	32,85	43,71	54,51	65,26	75,97	86,62	97,23	107,79	118,29	128,85	139,59	150,33
13,5	22,28	33,35	44,37	55,34	66,26	77,13	87,96	98,74	109,46	120,14	130,85	141,75	152,65
13,6	22,62	33,86	45,05	56,19	67,29	78,33	89,33	100,28	111,19	122,04	132,90	143,97	155,05
13,7	22,97	34,38	45,75	57,07	68,34	79,57	90,75	101,88	112,96	124,00	135,01	146,26	157,51
13,8	23,33	34,92	46,47	57,97	69,42	80,83	92,19	103,51	114,78	126,00	137,17	148,60	160,03
13,9	23,69	35,47	47,20	58,89	70,53	82,13	93,67	105,18	116,63	128,04	139,41	151,00	162,62
14	24,07	36,03	47,96	59,83	71,66	83,45	95,19	106,88	118,53	130,14	141,70	153,45	165,26

Table G.2.3: Hydrogen Required in Bad Weather for P, H, B

Speed (knots)	**Distance (nm)**												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	20,96	31,34	41,64	51,86	62,02	72,10	82,10	92,03	102,05	112,26	122,46	132,67	142,87
11,1	20,89	31,22	41,49	51,68	61,80	71,84	81,82	91,72	101,68	111,85	122,01	132,18	142,35
11,2	20,84	31,15	41,39	51,56	61,67	71,70	81,65	91,54	101,45	111,60	121,74	131,89	142,03
11,3	20,82	31,12	41,36	51,52	61,62	71,65	81,60	91,49	101,37	111,50	121,64	131,78	141,91
11,4	20,82	31,13	41,37	51,55	61,65	71,69	81,66	91,56	101,42	111,56	121,70	131,84	141,99
11,5	20,86	31,18	41,45	51,64	61,77	71,83	81,82	91,74	101,60	111,76	121,92	132,08	142,24
11,6	20,92	31,27	41,57	51,79	61,95	72,05	82,08	92,04	101,94	112,10	122,29	132,48	142,67
11,7	21,00	31,40	41,74	52,01	62,22	72,36	82,44	92,45	102,40	112,57	122,81	133,04	143,28
11,8	21,10	31,56	41,95	52,28	62,55	72,75	82,89	92,96	102,97	113,18	123,47	133,75	144,04
11,9	21,23	31,76	42,21	52,61	62,95	73,22	83,43	93,57	103,66	113,90	124,26	134,61	144,97
12	21,38	31,98	42,52	53,00	63,41	73,76	84,06	94,29	104,45	114,75	125,18	135,61	146,05
12,1	21,55	32,24	42,87	53,43	63,94	74,38	84,77	95,09	105,35	115,71	126,23	136,75	147,27
12,2	21,75	32,53	43,25	53,92	64,53	75,07	85,56	95,98	106,35	116,78	127,40	138,02	148,63
12,3	21,96	32,85	43,68	54,46	65,17	75,83	86,42	96,96	107,45	117,96	128,69	139,41	150,14
12,4	22,19	33,20	44,14	55,04	65,87	76,65	87,37	98,03	108,63	119,25	130,09	140,93	151,77
12,5	22,44	33,57	44,64	55,66	66,63	77,53	88,38	99,17	109,91	120,63	131,59	142,56	153,53
12,6	22,70	33,97	45,18	56,33	67,43	78,48	89,46	100,40	111,27	122,10	133,20	144,30	155,40
12,7	22,98	34,39	45,75	57,05	68,29	79,48	90,61	101,69	112,72	123,69	134,91	146,16	157,40
12,8	23,28	34,84	46,35	57,80	69,19	80,54	91,83	103,06	114,24	125,37	136,72	148,11	159,51
12,9	23,59	35,31	46,98	58,59	70,14	81,65	93,10	104,50	115,84	127,13	138,62	150,17	161,72
13	23,92	35,81	47,64	59,41	71,14	82,81	94,43	106,00	117,51	128,98	140,61	152,32	164,04
13,1	24,26	36,32	48,32	60,27	72,17	84,02	95,82	107,56	119,26	130,90	142,68	154,57	166,46
13,2	24,62	36,86	49,04	61,17	73,25	85,28	97,26	109,19	121,07	132,90	144,83	156,90	168,97
13,3	24,99	37,41	49,78	62,10	74,37	86,59	98,76	110,88	122,95	134,96	147,06	159,32	171,57
13,4	25,37	37,98	50,55	63,06	75,52	87,94	100,30	112,62	124,88	137,10	149,37	161,82	174,26
13,5	25,77	38,58	51,34	64,05	76,71	89,33	101,89	114,41	126,88	139,30	151,75	164,39	177,04
13,6	26,17	39,18	52,15	65,07	77,94	90,76	103,53	116,26	128,94	141,57	154,20	167,05	179,90
13,7	26,59	39,81	52,99	66,11	79,19	92,23	105,21	118,15	131,05	143,89	156,71	169,77	182,83
13,8	27,01	40,45	53,84	67,19	80,48	93,73	106,94	120,10	133,21	146,27	159,29	172,56	185,84
13,9	27,45	41,11	54,72	68,28	81,80	95,28	108,70	122,08	135,42	148,71	161,95	175,42	188,91
14	27,90	41,78	55,61	69,40	83,15	96,85	110,50	124,11	137,68	151,20	164,67	178,34	192,06

G.3 Propulsion and Hotel Load

The hydrogen required for the vessel the fuel cell system provides power to propulsion and hotel load for different weathers are presented. In these matrices the required hydrogen are in tons.

Table G.3.1: Hydrogen Required in Good Weather for P, H

Speed (knots)	**Distance (nm)**												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	14,76	22,14	29,52	36,89	44,27	51,65	59,03	66,41	73,79	81,17	88,55	95,93	103,31
11,1	14,70	22,06	29,41	36,76	44,11	51,46	58,81	66,17	73,52	80,87	88,22	95,57	102,93
11,2	14,67	22,01	29,34	36,68	44,01	51,35	58,68	66,02	73,35	80,69	88,02	95,36	102,69
11,3	14,66	21,99	29,32	36,64	43,97	51,30	58,63	65,96	73,29	80,62	87,95	95,28	102,60
11,4	14,66	22,00	29,33	36,66	43,99	51,33	58,66	65,99	73,32	80,65	87,99	95,32	102,65
11,5	14,69	22,04	29,38	36,73	44,07	51,42	58,76	66,11	73,45	80,80	88,14	95,49	102,83
11,6	14,73	22,10	29,47	36,84	44,20	51,57	58,94	66,30	73,67	81,04	88,40	95,77	103,14
11,7	14,80	22,19	29,59	36,99	44,39	51,78	59,18	66,58	73,98	81,38	88,77	96,17	103,57
11,8	14,87	22,31	29,75	37,18	44,62	52,06	59,50	66,93	74,37	81,81	89,24	96,68	104,12
11,9	14,97	22,45	29,94	37,42	44,91	52,39	59,87	67,36	74,84	82,33	89,81	97,30	104,78
12	15,08	22,62	30,16	37,70	45,24	52,78	60,32	67,85	75,39	82,93	90,47	98,01	105,55
12,1	15,20	22,81	30,41	38,01	45,61	53,21	60,82	68,42	76,02	83,62	91,23	98,83	106,43
12,2	15,34	23,02	30,69	38,36	46,03	53,70	61,38	69,05	76,72	84,39	92,06	99,74	107,41
12,3	15,50	23,25	31,00	38,74	46,49	54,24	61,99	69,74	77,49	85,24	92,99	100,74	108,49
12,4	15,67	23,50	31,33	39,16	47,00	54,83	62,66	70,49	78,33	86,16	93,99	101,82	109,66
12,5	15,85	23,77	31,69	39,61	47,54	55,46	63,38	71,31	79,23	87,15	95,07	103,00	110,92
12,6	16,04	24,06	32,08	40,10	48,12	56,13	64,15	72,17	80,19	88,21	96,23	104,25	112,27
12,7	16,24	24,36	32,49	40,61	48,73	56,85	64,97	73,09	81,22	89,34	97,46	105,58	113,70
12,8	16,46	24,69	32,92	41,15	49,38	57,61	65,84	74,07	82,30	90,53	98,76	106,99	115,22
12,9	16,69	25,03	33,37	41,72	50,06	58,40	66,75	75,09	83,43	91,78	100,12	108,46	116,81
13	16,92	25,39	33,85	42,31	50,77	59,24	67,70	76,16	84,62	93,09	101,55	110,01	118,47
13,1	17,17	25,76	34,35	42,93	51,52	60,10	68,69	77,28	85,86	94,45	103,04	111,62	120,21
13,2	17,43	26,15	34,86	43,58	52,29	61,01	69,72	78,44	87,15	95,87	104,58	113,30	122,02
13,3	17,70	26,55	35,40	44,25	53,09	61,94	70,79	79,64	88,49	97,34	106,19	115,04	123,89
13,4	17,97	26,96	35,95	44,94	53,92	62,91	71,90	80,89	89,87	98,86	107,85	116,83	125,82
13,5	18,26	27,39	36,52	45,65	54,78	63,91	73,04	82,17	91,30	100,43	109,56	118,69	127,82
13,6	18,55	27,83	37,11	46,38	55,66	64,94	74,21	83,49	92,76	102,04	111,32	120,59	129,87
13,7	18,85	28,28	37,71	47,14	56,56	65,99	75,42	84,84	94,27	103,70	113,13	122,55	131,98
13,8	19,16	28,74	38,33	47,91	57,49	67,07	76,65	86,23	95,82	105,40	114,98	124,56	134,14
13,9	19,48	29,22	38,96	48,70	58,44	68,18	77,92	87,66	97,40	107,14	116,87	126,61	136,35
14	19,80	29,70	39,60	49,51	59,41	69,31	79,21	89,11	99,01	108,91	118,81	128,71	138,62

Table G.3.2: Hydrogen Required in Moderate Weather for P, H

Speed (knots)	**Distance (nm)**												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	16,92	25,37	33,83	42,29	50,75	59,21	67,66	76,12	84,58	93,04	101,50	109,95	118,41
11,1	16,86	25,28	33,71	42,14	50,57	59,00	67,42	75,85	84,28	92,71	101,14	109,57	117,99
11,2	16,82	25,23	33,64	42,05	50,46	58,87	67,28	75,69	84,11	92,52	100,93	109,34	117,75
11,3	16,81	25,21	33,62	42,02	50,43	58,83	67,24	75,64	84,05	92,45	100,86	109,26	117,67
11,4	16,82	25,23	33,64	42,05	50,46	58,87	67,29	75,70	84,11	92,52	100,93	109,34	117,75
11,5	16,86	25,28	33,71	42,14	50,57	58,99	67,42	75,85	84,28	92,70	101,13	109,56	117,99
11,6	16,91	25,37	33,82	42,28	50,73	59,19	67,64	76,10	84,55	93,01	101,46	109,92	118,37
11,7	16,99	25,48	33,97	42,46	50,96	59,45	67,94	76,44	84,93	93,42	101,92	110,41	118,90
11,8	17,08	25,62	34,16	42,70	51,24	59,78	68,33	76,87	85,41	93,95	102,49	111,03	119,57
11,9	17,20	25,79	34,39	42,99	51,59	60,19	68,78	77,38	85,98	94,58	103,18	111,77	120,37
12	17,33	25,99	34,66	43,32	51,99	60,65	69,32	77,98	86,64	95,31	103,97	112,64	121,30
12,1	17,48	26,22	34,96	43,70	52,44	61,18	69,92	78,66	87,40	96,14	104,88	113,62	122,36
12,2	17,65	26,47	35,29	44,12	52,94	61,76	70,59	79,41	88,23	97,06	105,88	114,70	123,53
12,3	17,83	26,75	35,66	44,58	53,49	62,41	71,32	80,24	89,15	98,07	106,99	115,90	124,82
12,4	18,03	27,05	36,06	45,08	54,09	63,11	72,12	81,14	90,15	99,17	108,18	117,20	126,21
12,5	18,25	27,37	36,49	45,61	54,74	63,86	72,98	82,10	91,23	100,35	109,47	118,60	127,72
12,6	18,47	27,71	36,95	46,19	55,42	64,66	73,90	83,14	92,37	101,61	110,85	120,09	129,32
12,7	18,72	28,08	37,44	46,80	56,16	65,51	74,87	84,23	93,59	102,95	112,31	121,67	131,03
12,8	18,98	28,46	37,95	47,44	56,93	66,41	75,90	85,39	94,88	104,37	113,85	123,34	132,83
12,9	19,25	28,87	38,49	48,11	57,74	67,36	76,98	86,60	96,23	105,85	115,47	125,10	134,72
13	19,53	29,29	39,06	48,82	58,58	68,35	78,11	87,88	97,64	107,40	117,17	126,93	136,70
13,1	19,82	29,73	39,64	49,56	59,47	69,38	79,29	89,20	99,11	109,02	118,93	128,84	138,76
13,2	20,13	30,19	40,26	50,32	60,38	70,45	80,51	90,58	100,64	110,70	120,77	130,83	140,90
13,3	20,44	30,67	40,89	51,11	61,33	71,56	81,78	92,00	102,22	112,45	122,67	132,89	143,11
13,4	20,77	31,16	41,54	51,93	62,32	72,70	83,09	93,48	103,86	114,25	124,63	135,02	145,41
13,5	21,11	31,66	42,22	52,77	63,33	73,88	84,44	94,99	105,55	116,10	126,66	137,21	147,77
13,6	21,46	32,19	42,91	53,64	64,37	75,10	85,83	96,56	107,29	118,01	128,74	139,47	150,20
13,7	21,81	32,72	43,63	54,53	65,44	76,35	87,25	98,16	109,07	119,98	130,88	141,79	152,70
13,8	22,18	33,27	44,36	55,45	66,54	77,63	88,72	99,81	110,90	121,99	133,08	144,16	155,25
13,9	22,55	33,83	45,11	56,38	67,66	78,94	90,21	101,49	112,77	124,04	135,32	146,60	157,87
14	22,94	34,40	45,87	57,34	68,81	80,27	91,74	103,21	114,68	126,14	137,61	149,08	160,55

Table G.3.3: Hydrogen Required in Bad Weather for P, H

Speed (knots)	**Distance (nm)**												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	19,55	29,33	39,11	48,89	58,66	68,44	78,22	87,99	97,77	107,55	117,32	127,10	136,88
11,1	19,49	29,23	38,97	48,72	58,46	68,21	77,95	87,69	97,44	107,18	116,92	126,67	136,41
11,2	19,45	29,17	38,90	48,62	58,35	68,07	77,80	87,52	97,25	106,97	116,70	126,42	136,15
11,3	19,44	29,16	38,88	48,60	58,32	68,04	77,76	87,48	97,20	106,92	116,64	126,36	136,08
11,4	19,46	29,19	38,92	48,64	58,37	68,10	77,83	87,56	97,29	107,02	116,75	126,47	136,20
11,5	19,50	29,25	39,00	48,75	58,50	68,25	78,00	87,76	97,51	107,26	117,01	126,76	136,51
11,6	19,57	29,35	39,14	48,92	58,71	68,49	78,28	88,06	97,85	107,63	117,42	127,20	136,99
11,7	19,66	29,49	39,33	49,16	58,99	68,82	78,65	88,48	98,32	108,15	117,98	127,81	137,64
11,8	19,78	29,67	39,56	49,45	59,34	69,23	79,12	89,01	98,90	108,79	118,68	128,57	138,46
11,9	19,92	29,88	39,84	49,80	59,75	69,71	79,67	89,63	99,59	109,55	119,51	129,47	139,43
12	20,08	30,12	40,16	50,20	60,24	70,28	80,31	90,35	100,39	110,43	120,47	130,51	140,55
12,1	20,26	30,39	40,52	50,65	60,78	70,91	81,04	91,17	101,30	111,43	121,56	131,69	141,82
12,2	20,46	30,69	40,92	51,15	61,38	71,62	81,85	92,08	102,31	112,54	122,77	133,00	143,23
12,3	20,68	31,02	41,36	51,71	62,05	72,39	82,73	93,07	103,41	113,75	124,09	134,43	144,78
12,4	20,92	31,38	41,84	52,30	62,76	73,23	83,69	94,15	104,61	115,07	125,53	135,99	146,45
12,5	21,18	31,77	42,36	52,95	63,54	74,13	84,71	95,30	105,89	116,48	127,07	137,66	148,25
12,6	21,45	32,18	42,91	53,63	64,36	75,09	85,81	96,54	107,27	117,99	128,72	139,44	150,17
12,7	21,74	32,62	43,49	54,36	65,23	76,10	86,98	97,85	108,72	119,59	130,46	141,34	152,21
12,8	22,05	33,08	44,10	55,13	66,15	77,18	88,20	99,23	110,25	121,28	132,30	143,33	154,36
12,9	22,37	33,56	44,75	55,93	67,12	78,31	89,49	100,68	111,86	123,05	134,24	145,42	156,61
13	22,71	34,06	45,42	56,77	68,13	79,48	90,84	102,19	113,55	124,90	136,26	147,61	158,97
13,1	23,06	34,59	46,12	57,65	69,18	80,71	92,24	103,77	115,30	126,83	138,36	149,89	161,42
13,2	23,42	35,14	46,85	58,56	70,27	81,99	93,70	105,41	117,12	128,84	140,55	152,26	163,97
13,3	23,80	35,70	47,60	59,51	71,41	83,31	95,21	107,11	119,01	130,91	142,81	154,71	166,62
13,4	24,19	36,29	48,38	60,48	72,58	84,67	96,77	108,86	120,96	133,06	145,15	157,25	169,34
13,5	24,59	36,89	49,19	61,48	73,78	86,08	98,38	110,67	122,97	135,27	147,56	159,86	172,16
13,6	25,01	37,51	50,01	62,52	75,02	87,52	100,03	112,53	125,03	137,54	150,04	162,54	175,05
13,7	25,43	38,15	50,86	63,58	76,29	89,01	101,72	114,44	127,16	139,87	152,59	165,30	178,02
13,8	25,87	38,80	51,73	64,66	77,60	90,53	103,46	116,40	129,33	142,26	155,19	168,13	181,06
13,9	26,31	39,47	52,62	65,78	78,93	92,09	105,24	118,40	131,55	144,71	157,86	171,02	184,17
14	26,76	40,15	53,53	66,91	80,29	93,68	107,06	120,44	133,82	147,20	160,59	173,97	187,35

G.4 Propulsion

The hydrogen required for the vessel the fuel cell system provides power to propulsion only for different weathers are presented. In these matrices the required hydrogen are in tons.

Table G.4.1: Hydrogen Required in Good Weather for P

Speed (knots)	**Distance (nm)**												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	12,32	18,49	24,65	30,81	36,97	43,14	49,30	55,46	61,62	67,78	73,95	80,11	86,27
11,1	12,29	18,44	24,58	30,73	36,88	43,02	49,17	55,31	61,46	67,61	73,75	79,90	86,04
11,2	12,28	18,42	24,56	30,70	36,84	42,98	49,12	55,26	61,40	67,54	73,68	79,82	85,96
11,3	12,29	18,43	24,58	30,72	36,87	43,01	49,15	55,30	61,44	67,59	73,73	79,88	86,02
11,4	12,32	18,47	24,63	30,79	36,95	43,11	49,27	55,42	61,58	67,74	73,90	80,06	86,21
11,5	12,36	18,54	24,72	30,91	37,09	43,27	49,45	55,63	61,81	67,99	74,17	80,36	86,54
11,6	12,43	18,64	24,85	31,07	37,28	43,49	49,71	55,92	62,13	68,35	74,56	80,77	86,99
11,7	12,51	18,76	25,02	31,27	37,52	43,78	50,03	56,28	62,54	68,79	75,05	81,30	87,55
11,8	12,61	18,91	25,21	31,51	37,82	44,12	50,42	56,72	63,03	69,33	75,63	81,93	88,24
11,9	12,72	19,08	25,44	31,80	38,16	44,52	50,88	57,24	63,60	69,95	76,31	82,67	89,03
12	12,85	19,27	25,70	32,12	38,54	44,97	51,39	57,82	64,24	70,66	77,09	83,51	89,94
12,1	12,99	19,49	25,98	32,48	38,98	45,47	51,97	58,46	64,96	71,46	77,95	84,45	90,94
12,2	13,15	19,72	26,30	32,87	39,45	46,02	52,60	59,17	65,75	72,32	78,90	85,47	92,05
12,3	13,32	19,98	26,64	33,30	39,96	46,63	53,29	59,95	66,61	73,27	79,93	86,59	93,25
12,4	13,51	20,26	27,01	33,77	40,52	47,27	54,03	60,78	67,53	74,29	81,04	87,79	94,55
12,5	13,70	20,56	27,41	34,26	41,11	47,96	54,82	61,67	68,52	75,37	82,22	89,08	95,93
12,6	13,91	20,87	27,83	34,78	41,74	48,70	55,66	62,61	69,57	76,53	83,48	90,44	97,40
12,7	14,14	21,20	28,27	35,34	42,41	49,47	56,54	63,61	70,68	77,74	84,81	91,88	98,95
12,8	14,37	21,55	28,74	35,92	43,10	50,29	57,47	64,66	71,84	79,02	86,21	93,39	100,58
12,9	14,61	21,92	29,22	36,53	43,83	51,14	58,45	65,75	73,06	80,36	87,67	94,98	102,28
13	14,87	22,30	29,73	37,16	44,60	52,03	59,46	66,89	74,33	81,76	89,19	96,63	104,06
13,1	15,13	22,69	30,26	37,82	45,39	52,95	60,52	68,08	75,65	83,21	90,78	98,34	105,91
13,2	15,40	23,10	30,81	38,51	46,21	53,91	61,61	69,31	77,01	84,72	92,42	100,12	107,82
13,3	15,69	23,53	31,37	39,21	47,06	54,90	62,74	70,58	78,43	86,27	94,11	101,96	109,80
13,4	15,98	23,97	31,95	39,94	47,93	55,92	63,91	71,90	79,88	87,87	95,86	103,85	111,84
13,5	16,28	24,41	32,55	40,69	48,83	56,97	65,11	73,24	81,38	89,52	97,66	105,80	113,94
13,6	16,58	24,88	33,17	41,46	49,75	58,05	66,34	74,63	82,92	91,22	99,51	107,80	116,09
13,7	16,90	25,35	33,80	42,25	50,70	59,15	67,60	76,05	84,50	92,95	101,40	109,85	118,30
13,8	17,22	25,83	34,45	43,06	51,67	60,28	68,89	77,50	86,12	94,73	103,34	111,95	120,56
13,9	17,55	26,33	35,11	43,88	52,66	61,44	70,21	78,99	87,77	96,54	105,32	114,10	122,87
14	17,89	26,84	35,78	44,73	53,67	62,62	71,56	80,51	89,45	98,40	107,34	116,29	125,23

Table G.4.2: *Hydrogen Required in Moderate Weather for P*

Speed (knots)	**Distance (nm)**												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	14,48	21,72	28,97	36,21	43,45	50,69	57,93	65,17	72,41	79,65	86,90	94,14	101,38
11,1	14,44	21,67	28,89	36,11	43,33	50,56	57,78	65,00	72,22	79,45	86,67	93,89	101,11
11,2	14,43	21,65	28,86	36,08	43,29	50,51	57,72	64,94	72,15	79,37	86,59	93,80	101,02
11,3	14,44	21,66	28,88	36,10	43,32	50,54	57,76	64,98	72,20	79,42	86,64	93,86	101,09
11,4	14,47	21,71	28,95	36,18	43,42	50,66	57,89	65,13	72,37	79,60	86,84	94,08	101,31
11,5	14,53	21,79	29,05	36,32	43,58	50,85	58,11	65,37	72,64	79,90	87,16	94,43	101,69
11,6	14,60	21,90	29,21	36,51	43,81	51,11	58,41	65,71	73,01	80,31	87,62	94,92	102,22
11,7	14,70	22,05	29,40	36,74	44,09	51,44	58,79	66,14	73,49	80,84	88,19	95,54	102,89
11,8	14,81	22,22	29,63	37,03	44,44	51,84	59,25	66,66	74,06	81,47	88,88	96,28	103,69
11,9	14,95	22,42	29,89	37,37	44,84	52,31	59,79	67,26	74,73	82,21	89,68	97,15	104,62
12	15,10	22,65	30,20	37,75	45,29	52,84	60,39	67,94	75,49	83,04	90,59	98,14	105,69
12,1	15,27	22,90	30,53	38,17	45,80	53,43	61,07	68,70	76,34	83,97	91,60	99,24	106,87
12,2	15,45	23,18	30,91	38,63	46,36	54,08	61,81	69,54	77,26	84,99	92,72	100,44	108,17
12,3	15,65	23,48	31,31	39,14	46,96	54,79	62,62	70,45	78,27	86,10	93,93	101,75	109,58
12,4	15,87	23,81	31,74	39,68	47,62	55,55	63,49	71,42	79,36	87,29	95,23	103,17	111,10
12,5	16,10	24,16	32,21	40,26	48,31	56,36	64,42	72,47	80,52	88,57	96,62	104,68	112,73
12,6	16,35	24,53	32,70	40,88	49,05	57,23	65,40	73,58	81,75	89,93	98,10	106,28	114,45
12,7	16,61	24,92	33,22	41,53	49,83	58,14	66,44	74,75	83,05	91,36	99,66	107,97	116,27
12,8	16,88	25,33	33,77	42,21	50,65	59,09	67,54	75,98	84,42	92,86	101,30	109,75	118,19
12,9	17,17	25,76	34,34	42,93	51,51	60,10	68,68	77,27	85,85	94,44	103,02	111,61	120,19
13	17,47	26,20	34,94	43,67	52,41	61,14	69,87	78,61	87,34	96,08	104,81	113,55	122,28
13,1	17,78	26,67	35,56	44,45	53,34	62,23	71,12	80,00	88,89	97,78	106,67	115,56	124,45
13,2	18,10	27,15	36,20	45,25	54,30	63,35	72,40	81,45	90,50	99,55	108,60	117,65	126,70
13,3	18,43	27,65	36,86	46,08	55,30	64,51	73,73	82,95	92,16	101,38	110,59	119,81	129,03
13,4	18,77	28,16	37,55	46,94	56,32	65,71	75,10	84,49	93,87	103,26	112,65	122,04	131,42
13,5	19,13	28,69	38,25	47,82	57,38	66,94	76,51	86,07	95,64	105,20	114,76	124,33	133,89
13,6	19,49	29,23	38,98	48,72	58,47	68,21	77,96	87,70	97,44	107,19	116,93	126,68	136,42
13,7	19,86	29,79	39,72	49,65	59,58	69,51	79,44	89,37	99,30	109,23	119,16	129,09	139,02
13,8	20,24	30,36	40,48	50,60	60,72	70,84	80,96	91,08	101,20	111,32	121,44	131,56	141,68
13,9	20,63	30,94	41,25	51,57	61,88	72,20	82,51	92,82	103,14	113,45	123,76	134,08	144,39
14	21,02	31,53	42,05	52,56	63,07	73,58	84,09	94,60	105,12	115,63	126,14	136,65	147,16

Table G.4.3: Hydrogen Required in Bad Weather for P

Speed (knots)	**Distance (nm)**												
	1000	**1500**	**2000**	**2500**	**3000**	**3500**	**4000**	**4500**	**5000**	**5500**	**6000**	**6500**	**7000**
11	17,12	25,68	34,24	42,80	51,36	59,92	68,48	77,04	85,60	94,16	102,72	111,28	119,84
11,1	17,08	25,61	34,15	42,69	51,23	59,76	68,30	76,84	85,38	93,92	102,45	110,99	119,53
11,2	17,06	25,59	34,12	42,65	51,18	59,71	68,24	76,77	85,30	93,83	102,36	110,89	119,42
11,3	17,07	25,61	34,14	42,68	51,21	59,75	68,28	76,82	85,36	93,89	102,43	110,96	119,50
11,4	17,11	25,66	34,22	42,77	51,33	59,88	68,44	76,99	85,55	94,10	102,66	111,21	119,77
11,5	17,17	25,76	34,35	42,93	51,52	60,11	68,69	77,28	85,87	94,45	103,04	111,63	120,21
11,6	17,26	25,89	34,52	43,16	51,79	60,42	69,05	77,68	86,31	94,94	103,57	112,20	120,84
11,7	17,38	26,06	34,75	43,44	52,13	60,81	69,50	78,19	86,88	95,56	104,25	112,94	121,63
11,8	17,51	26,27	35,02	43,78	52,53	61,29	70,04	78,80	87,55	96,31	105,06	113,82	122,58
11,9	17,67	26,50	35,34	44,17	53,01	61,84	70,67	79,51	88,34	97,18	106,01	114,85	123,68
12	17,85	26,77	35,70	44,62	53,54	62,47	71,39	80,32	89,24	98,16	107,09	116,01	124,94
12,1	18,05	27,07	36,10	45,12	54,14	63,17	72,19	81,21	90,24	99,26	108,29	117,31	126,33
12,2	18,27	27,40	36,53	45,67	54,80	63,94	73,07	82,20	91,34	100,47	109,60	118,74	127,87
12,3	18,51	27,76	37,01	46,26	55,52	64,77	74,02	83,28	92,53	101,78	111,03	120,29	129,54
12,4	18,76	28,14	37,53	46,91	56,29	65,67	75,05	84,43	93,81	103,19	112,58	121,96	131,34
12,5	19,04	28,56	38,07	47,59	57,11	66,63	76,15	85,67	95,19	104,70	114,22	123,74	133,26
12,6	19,33	28,99	38,66	48,32	57,99	67,65	77,31	86,98	96,64	106,31	115,97	125,64	135,30
12,7	19,64	29,45	39,27	49,09	58,91	68,73	78,54	88,36	98,18	108,00	117,82	127,64	137,45
12,8	19,96	29,94	39,92	49,90	59,88	69,86	79,84	89,82	99,80	109,78	119,76	129,74	139,72
12,9	20,30	30,45	40,60	50,74	60,89	71,04	81,19	91,34	101,49	111,64	121,79	131,94	142,08
13	20,65	30,98	41,30	51,63	61,95	72,28	82,60	92,93	103,25	113,58	123,90	134,23	144,55
13,1	21,02	31,53	42,03	52,54	63,05	73,56	84,07	94,58	105,09	115,59	126,10	136,61	147,12
13,2	21,40	32,10	42,79	53,49	64,19	74,89	85,59	96,29	106,98	117,68	128,38	139,08	149,78
13,3	21,79	32,68	43,58	54,47	65,37	76,26	87,16	98,05	108,95	119,84	130,74	141,63	152,53
13,4	22,19	33,29	44,39	55,49	66,58	77,68	88,78	99,87	110,97	122,07	133,17	144,26	155,36
13,5	22,61	33,92	45,22	56,53	67,83	79,14	90,44	101,75	113,05	124,36	135,67	146,97	158,28
13,6	23,04	34,56	46,08	57,60	69,12	80,64	92,15	103,67	115,19	126,71	138,23	149,75	161,27
13,7	23,48	35,22	46,95	58,69	70,43	82,17	93,91	105,65	117,39	129,12	140,86	152,60	164,34
13,8	23,93	35,89	47,85	59,81	71,78	83,74	95,70	107,67	119,63	131,59	143,55	155,52	167,48
13,9	24,38	36,58	48,77	60,96	73,15	85,35	97,54	109,73	121,92	134,11	146,31	158,50	170,69
14	24,85	37,28	49,70	62,13	74,56	86,98	99,41	111,83	124,26	136,69	149,11	161,54	173,97

Appendix H

Range

The range matrices are interpolated from the hydrogen required matrices in G. In these matrices for ranges above 7000 nm are not calculated, therefore they just say "7000" in the matrices. This means that the range is either 7000 or above.

H.1 Interpolated Range Matrices

Table H.1.1: Range in Good Weather

Speed (Knots)	**Propulsion + Hotel + Boiler**					**Propulsion + Hotel**					**Propulsion only**				
	8 Tanks	**10 Tanks**	**12 Tanks**	**14 Tanks**	**16 Tanks**	**8 Tanks**	**10 Tanks**	**12 Tanks**	**14 Tanks**	**16 Tanks**	**8 Tanks**	**10 Tanks**	**12 Tanks**	**14 Tanks**	**16 Tanks**
11	4072	5124	6505	7000	7000	4337	5421	6505	7000	7000	5193	6491	7000	7000	7000
11,1	4087	5144	6529	7000	7000	4353	5441	6529	7000	7000	5207	6508	7000	7000	7000
11,2	4097	5157	6544	7000	7000	4362	5453	6544	7000	7000	5212	6514	7000	7000	7000
11,3	4102	5164	6549	7000	7000	4366	5458	6549	7000	7000	5208	6510	7000	7000	7000
11,4	4101	5164	6546	7000	7000	4364	5455	6546	7000	7000	5196	6495	7000	7000	7000
11,5	4095	5158	6535	7000	7000	4357	5446	6535	7000	7000	5177	6471	7000	7000	7000
11,6	4084	5145	6515	7000	7000	4344	5430	6515	7000	7000	5150	6438	7000	7000	7000
11,7	4068	5125	6488	7000	7000	4326	5407	6488	7000	7000	5117	6396	7000	7000	7000
11,8	4048	5100	6454	7000	7000	4303	5379	6454	7000	7000	5077	6347	7000	7000	7000
11,9	4024	5070	6413	7000	7000	4276	5345	6413	7000	7000	5032	6290	7000	7000	7000
12	3996	5035	6367	7000	7000	4244	5305	6367	7000	7000	4981	6227	7000	7000	7000
12,1	3965	4995	6314	7000	7000	4209	5262	6314	7000	7000	4926	6158	7000	7000	7000
12,2	3931	4951	6256	7000	7000	4171	5214	6256	7000	7000	4867	6084	7000	7000	7000
12,3	3895	4903	6194	7000	7000	4130	5162	6194	7000	7000	4804	6005	7000	7000	7000
12,4	3855	4853	6128	7000	7000	4085	5107	6128	7000	7000	4738	5923	7000	7000	7000
12,5	3814	4799	6058	7000	7000	4039	5049	6058	7000	7000	4670	5838	7000	7000	7000
12,6	3770	4743	5986	6983	7000	3990	4988	5986	6983	7000	4600	5750	6900	7000	7000
12,7	3725	4685	5910	6895	7000	3940	4925	5910	6895	7000	4528	5660	6792	7000	7000
12,8	3679	4625	5833	6805	7000	3888	4860	5833	6805	7000	4454	5568	6682	7000	7000
12,9	3631	4564	5753	6712	7000	3835	4794	5753	6712	7000	4380	5475	6570	7000	7000
13	3582	4502	5672	6618	7000	3781	4727	5672	6618	7000	4305	5382	6458	7000	7000
13,1	3533	4439	5590	6522	7000	3727	4659	5590	6522	7000	4230	5288	6345	7000	7000
13,2	3483	4376	5508	6425	7000	3672	4590	5508	6425	7000	4155	5194	6233	7000	7000
13,3	3433	4312	5424	6328	6954	3616	4520	5424	6328	7000	4080	5100	6120	7000	7000
13,4	3383	4248	5341	6231	6853	3561	4451	5341	6231	7000	4006	5007	6009	7000	7000
13,5	3333	4184	5258	6134	6752	3505	4381	5258	6134	7000	3932	4915	5898	6881	7000
13,6	3283	4120	5174	6037	6651	3450	4312	5174	6037	6899	3859	4824	5789	6753	7000
13,7	3233	4057	5092	5940	6550	3394	4243	5092	5940	6789	3787	4734	5680	6627	7000
13,8	3183	3993	5010	5845	6450	3340	4175	5010	5845	6680	3716	4645	5574	6503	7000
13,9	3134	3931	4928	5750	6350	3286	4107	4928	5750	6571	3646	4558	5469	6381	7000
14	3085	3869	4848	5656	6250	3232	4040	4848	5656	6464	3577	4472	5366	6260	7000

Table H.1.2: Range in Moderate Weather

Speed (Knots)	**Propulsion + Hotel + Boiler**					**Propulsion + Hotel**					**Propulsion only**				
	8 Tanks	**10 Tanks**	**12 Tanks**	**14 Tanks**	**16 Tanks**	**8 Tanks**	**10 Tanks**	**12 Tanks**	**14 Tanks**	**16 Tanks**	**8 Tanks**	**10 Tanks**	**12 Tanks**	**14 Tanks**	**16 Tanks**
11	3565	4490	5402	6302	7000	3783	4729	5675	6621	7000	4419	5524	6629	7000	7000
11,1	3579	4507	5422	6326	7000	3797	4746	5695	6644	7000	4431	5538	6646	7000	7000
11,2	3587	4517	5435	6341	7000	3805	4756	5707	6658	7000	4435	5544	6652	7000	7000
11,3	3590	4520	5441	6348	7000	3807	4759	5711	6663	7000	4432	5540	6648	7000	7000
11,4	3589	4518	5440	6346	7000	3805	4756	5707	6658	7000	4422	5527	6633	7000	7000
11,5	3583	4509	5432	6337	7000	3797	4746	5696	6645	7000	4405	5507	6608	7000	7000
11,6	3572	4496	5417	6320	7000	3785	4731	5677	6623	7000	4383	5478	6574	7000	7000
11,7	3558	4477	5395	6295	7000	3768	4710	5652	6594	7000	4354	5443	6532	7000	7000
11,8	3539	4453	5368	6264	7000	3747	4683	5620	6557	7000	4321	5401	6481	7000	7000
11,9	3517	4425	5335	6227	7000	3722	4652	5583	6513	7000	4282	5352	6423	7000	7000
12	3492	4392	5297	6183	7000	3693	4617	5540	6463	7000	4239	5299	6358	7000	7000
12,1	3464	4356	5254	6134	7000	3661	4577	5492	6408	7000	4192	5240	6288	7000	7000
12,2	3433	4316	5206	6081	6949	3627	4533	5440	6347	7000	4142	5177	6213	7000	7000
12,3	3400	4273	5155	6023	6883	3589	4487	5384	6281	7000	4088	5110	6132	7000	7000
12,4	3364	4228	5099	5961	6812	3550	4437	5324	6212	7000	4032	5040	6048	7000	7000
12,5	3327	4180	5041	5895	6737	3508	4385	5262	6138	7000	3974	4968	5961	6955	7000
12,6	3288	4130	4980	5827	6659	3464	4330	5196	6062	7000	3914	4893	5871	6850	7000
12,7	3247	4078	4916	5755	6578	3419	4274	5129	5983	7000	3853	4816	5779	6743	7000
12,8	3206	4025	4851	5681	6494	3373	4216	5059	5902	7000	3791	4738	5686	6633	7000
12,9	3163	3970	4785	5604	6408	3325	4157	4988	5820	7000	3727	4659	5591	6523	7000
13	3119	3915	4718	5526	6320	3277	4097	4916	5735	7000	3664	4580	5496	6411	7000
13,1	3075	3859	4649	5446	6231	3229	4036	4843	5650	7000	3600	4500	5400	6300	7000
13,2	3031	3803	4580	5364	6142	3180	3975	4769	5564	7000	3536	4420	5304	6188	7000
13,3	2986	3746	4511	5282	6051	3130	3913	4696	5478	6944	3472	4340	5208	6076	6944
13,4	2941	3689	4442	5201	5960	3081	3851	4622	5392	6818	3409	4261	5113	5965	6818
13,5	2896	3632	4373	5119	5867	3032	3790	4548	5306	6692	3346	4183	5019	5856	6692
13,6	2852	3576	4304	5037	5774	2983	3728	4474	5220	6568	3284	4105	4926	5747	6568
13,7	2807	3519	4236	4957	5682	2934	3667	4401	5134	6445	3223	4028	4834	5640	6445
13,8	2763	3464	4168	4877	5590	2886	3607	4328	5050	6324	3162	3953	4743	5534	6324
13,9	2719	3408	4101	4798	5498	2838	3547	4257	4966	6205	3103	3878	4654	5430	6205
14	2676	3354	4035	4720	5408	2790	3488	4186	4883	6089	3044	3805	4566	5327	6089

Table H.1.3: Range in Bad Weather

Speed (Knots)	**Propulsion + Hotel + Boiler**					**Propulsion + Hotel**					**Propulsion only**				
	8 Tanks	**10 Tanks**	**12 Tanks**	**14 Tanks**	**16 Tanks**	**8 Tanks**	**10 Tanks**	**12 Tanks**	**14 Tanks**	**16 Tanks**	**8 Tanks**	**10 Tanks**	**12 Tanks**	**14 Tanks**	**16 Tanks**
11	3098	3895	4698	5487	6271	3273	4091	4909	5728	6546	3738	4673	5607	6542	7000
11,1	3110	3909	4715	5508	6294	3284	4105	4926	5747	6568	3748	4685	5622	6559	7000
11,2	3116	3917	4725	5520	6308	3291	4113	4936	5758	6581	3752	4689	5627	6565	7000
11,3	3119	3920	4728	5524	6314	3292	4115	4938	5761	6584	3749	4686	5624	6561	7000
11,4	3117	3917	4725	5522	6310	3289	4112	4934	5756	6578	3741	4676	5611	6546	7000
11,5	3111	3909	4716	5512	6299	3282	4102	4923	5743	6564	3727	4658	5590	6522	7000
11,6	3101	3896	4700	5495	6280	3270	4088	4905	5723	6541	3708	4634	5561	6488	7000
11,7	3088	3879	4678	5472	6254	3255	4069	4882	5696	6510	3683	4604	5525	6446	7000
11,8	3071	3858	4652	5442	6220	3236	4045	4854	5662	6471	3655	4569	5482	6396	7000
11,9	3051	3832	4620	5407	6181	3213	4016	4820	5623	6426	3622	4528	5433	6339	7000
12	3028	3803	4584	5366	6135	3187	3984	4781	5578	6375	3586	4482	5379	6275	7000
12,1	3003	3771	4544	5321	6084	3159	3949	4738	5528	6318	3546	4433	5319	6206	7000
12,2	2975	3735	4501	5271	6028	3128	3910	4692	5474	6256	3504	4379	5255	6131	7000
12,3	2945	3697	4454	5217	5968	3094	3868	4642	5415	6189	3458	4323	5188	6052	6917
12,4	2914	3656	4405	5159	5904	3059	3824	4589	5353	6118	3411	4264	5117	5969	6822
12,5	2880	3614	4353	5098	5836	3022	3777	4533	5288	6044	3362	4202	5043	5883	6724
12,6	2845	3569	4299	5034	5766	2983	3729	4475	5221	5967	3311	4139	4967	5795	6622
12,7	2809	3523	4243	4968	5692	2943	3679	4415	5151	5887	3259	4074	4889	5704	6519
12,8	2772	3476	4186	4900	5616	2902	3628	4354	5079	5805	3207	4008	4810	5611	6413
12,9	2734	3428	4127	4831	5538	2861	3576	4291	5006	5721	3153	3941	4730	5518	6306
13	2696	3380	4068	4761	5457	2818	3523	4227	4932	5636	3099	3874	4649	5424	6198
13,1	2657	3330	4008	4690	5375	2775	3469	4163	4857	5551	3045	3806	4568	5329	6090
13,2	2617	3280	3947	4618	5293	2732	3415	4098	4781	5464	2991	3739	4487	5234	5982
13,3	2577	3230	3887	4547	5210	2689	3361	4033	4705	5378	2937	3671	4406	5140	5874
13,4	2538	3180	3826	4475	5128	2645	3307	3968	4630	5291	2884	3605	4325	5046	5767
13,5	2498	3130	3765	4404	5045	2602	3253	3903	4554	5205	2830	3538	4246	4953	5661
13,6	2459	3080	3705	4333	4963	2559	3199	3839	4479	5119	2778	3472	4167	4861	5556
13,7	2420	3031	3645	4262	4882	2517	3146	3775	4404	5033	2726	3408	4089	4771	5452
13,8	2381	2982	3586	4192	4801	2474	3093	3711	4330	4949	2675	3344	4012	4681	5350
13,9	2342	2933	3527	4123	4722	2433	3041	3649	4257	4865	2625	3281	3937	4593	5249
14	2304	2885	3469	4055	4643	2391	2989	3587	4185	4782	2575	3219	3863	4507	5150

H.2 Range Curves

The range curves are drawn from the range matrices H.1. The range curves are marked with one line representing the longest trans-Atlantic leg referred to as "all" in the graphs, meaning values above this line can complete all legs. There is also a line for the shortest trans-Atlantic leg, labeled as "none, meaning that values below this line will not be able to complete any trans-Atlantic routes. Lastly, there is a line at 7000 nm labeled as "no data", meaning that values above this line have not been calculated as this is far above the distance of the longest trans-Atlantic leg.

H.2.1 Good Weather

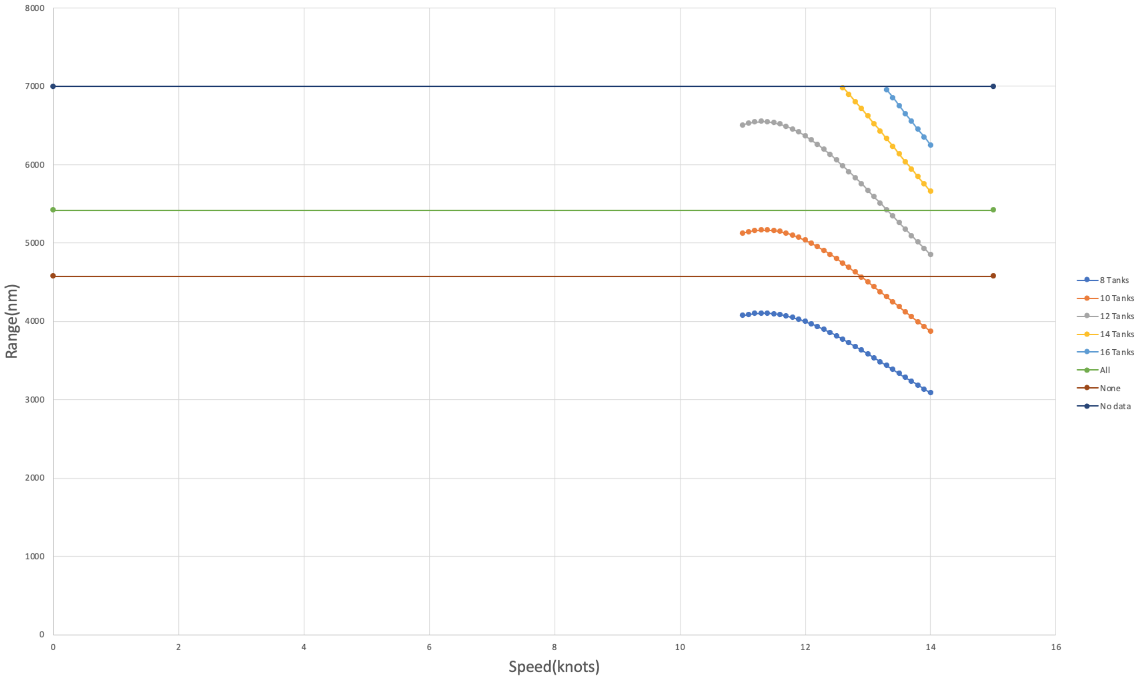

Figure H.2.1: Propulsion + Hotel Load + Boiler, Good Weather

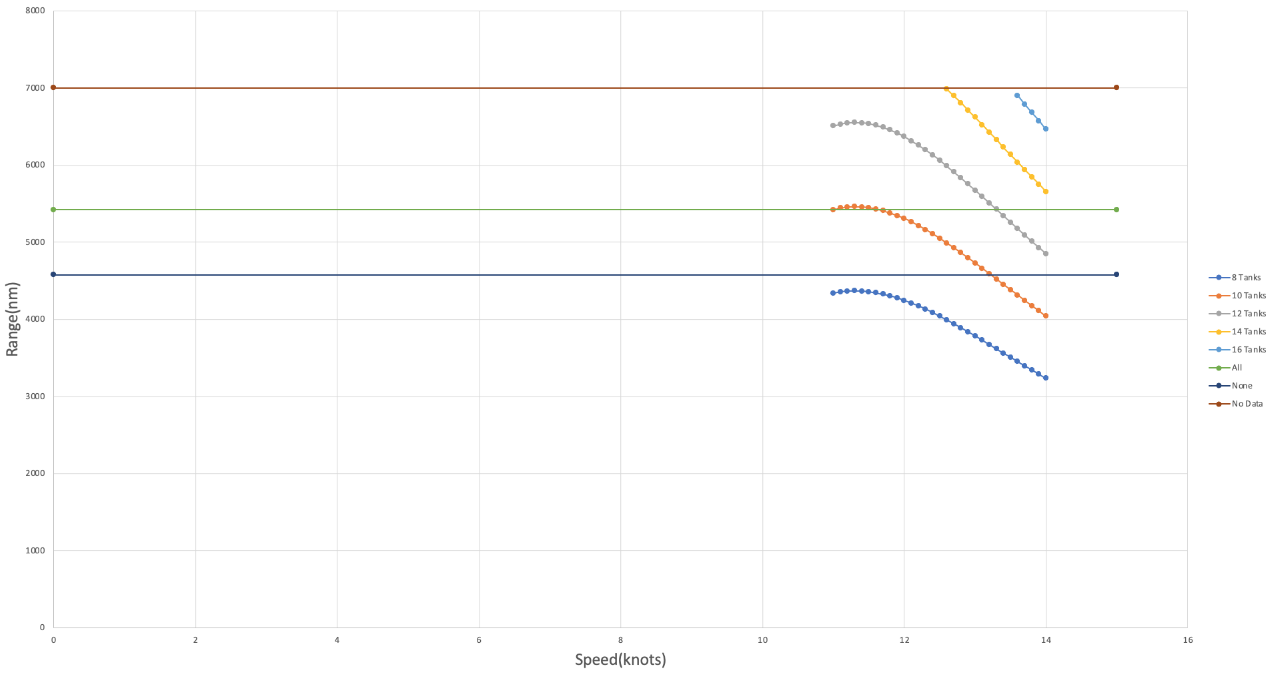

Figure H.2.2: Propulsion + Hotel Load, Good Weather

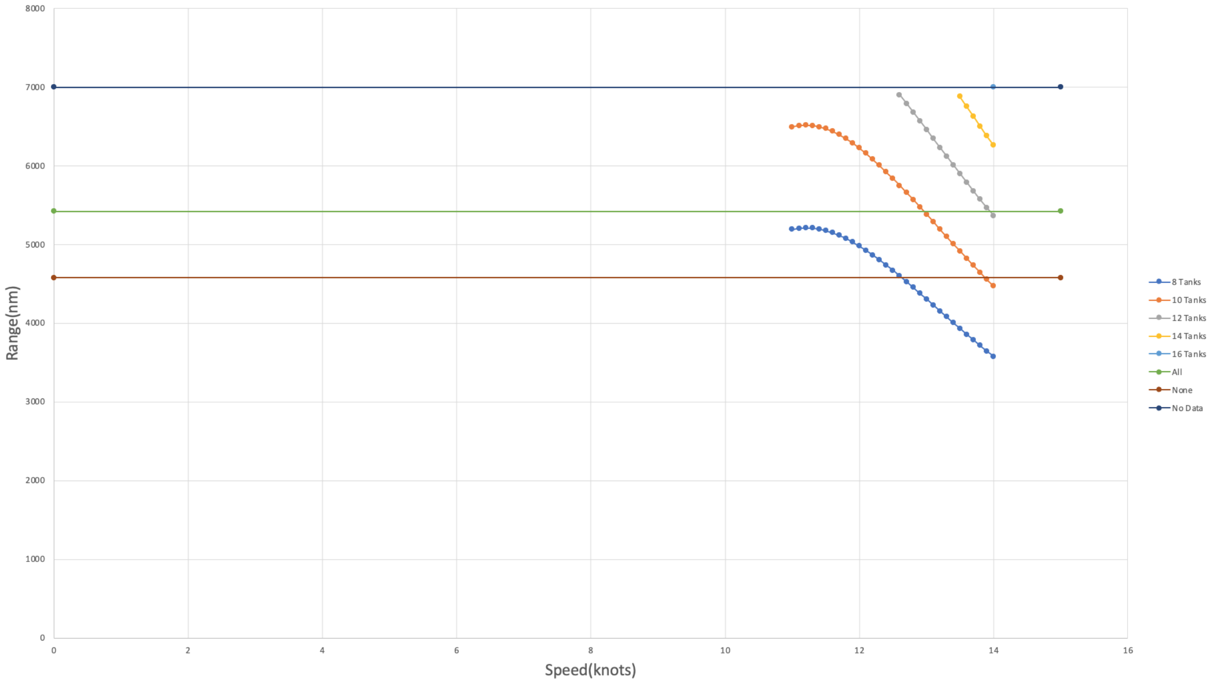

Figure H.2.3: Propulsion, Good Weather

H.2.2 Moderate Weather

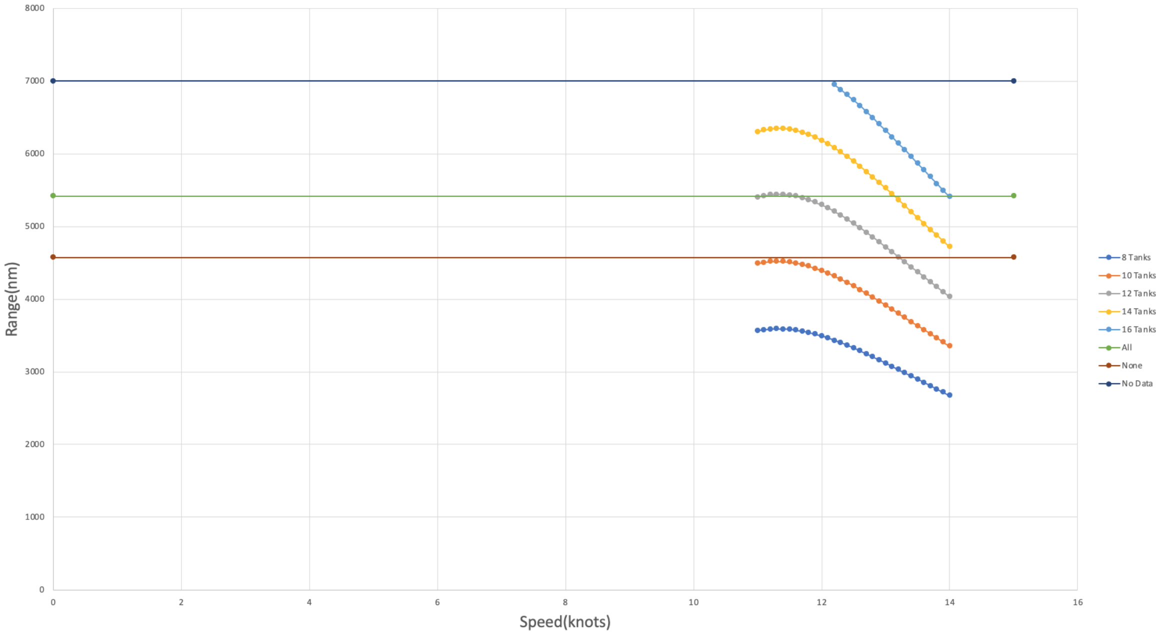

Figure H.2.4: Propulsion + Hotel Load + Boiler, Moderate Weather

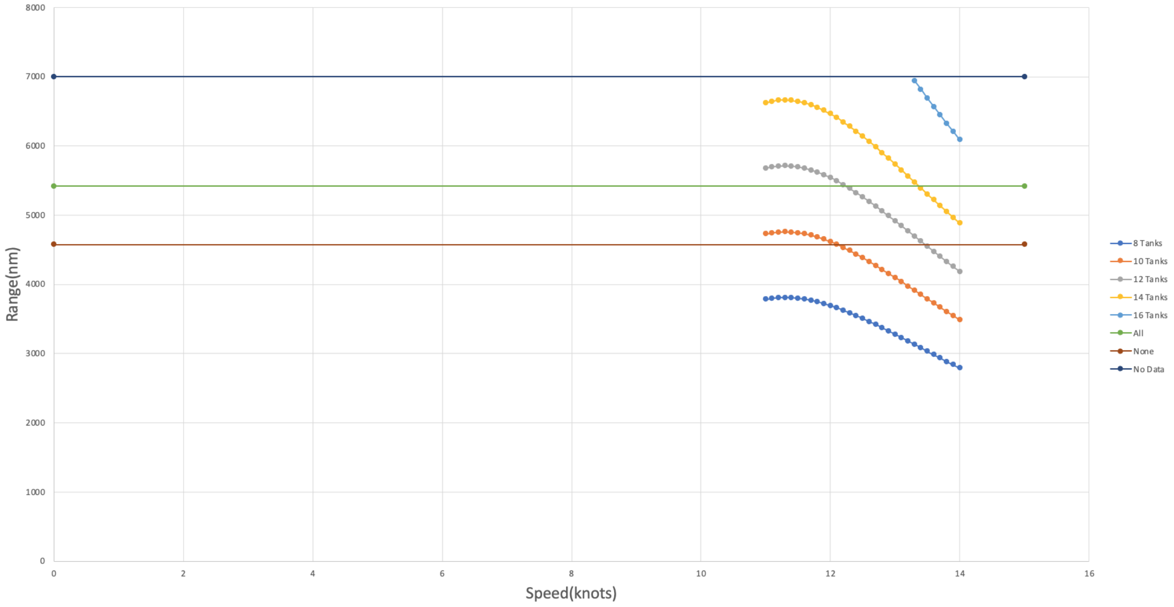

Figure H.2.5: Propulsion + Hotel Load, Moderate Weather

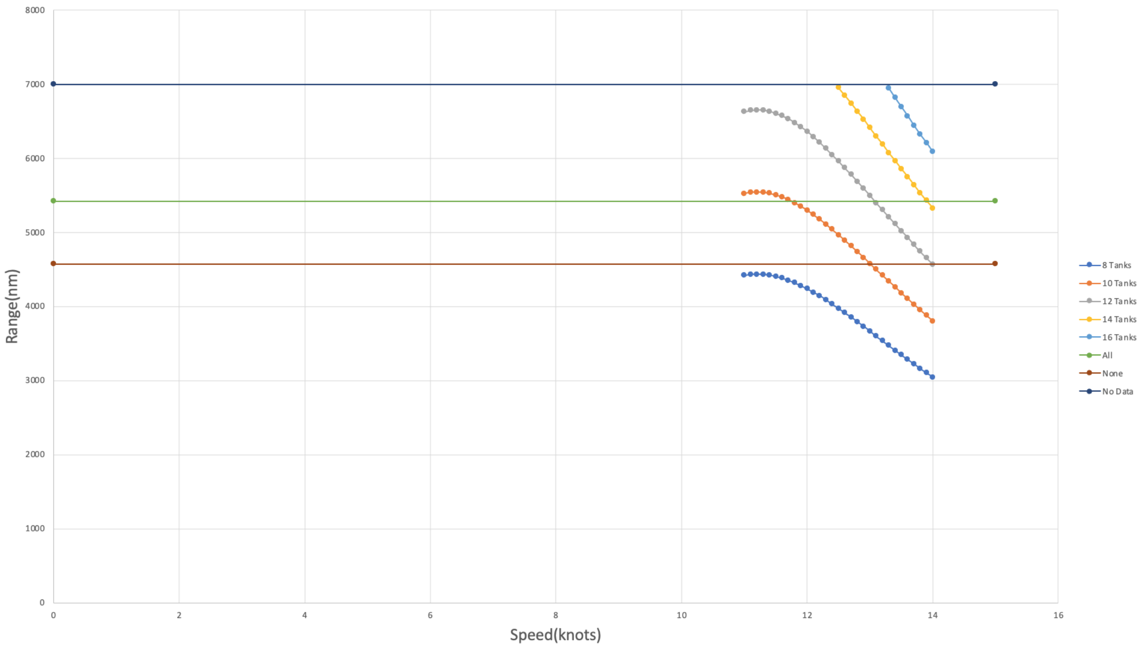

Figure H.2.6: Propulsion, Moderate Weather

H.2.3 Bad Weather

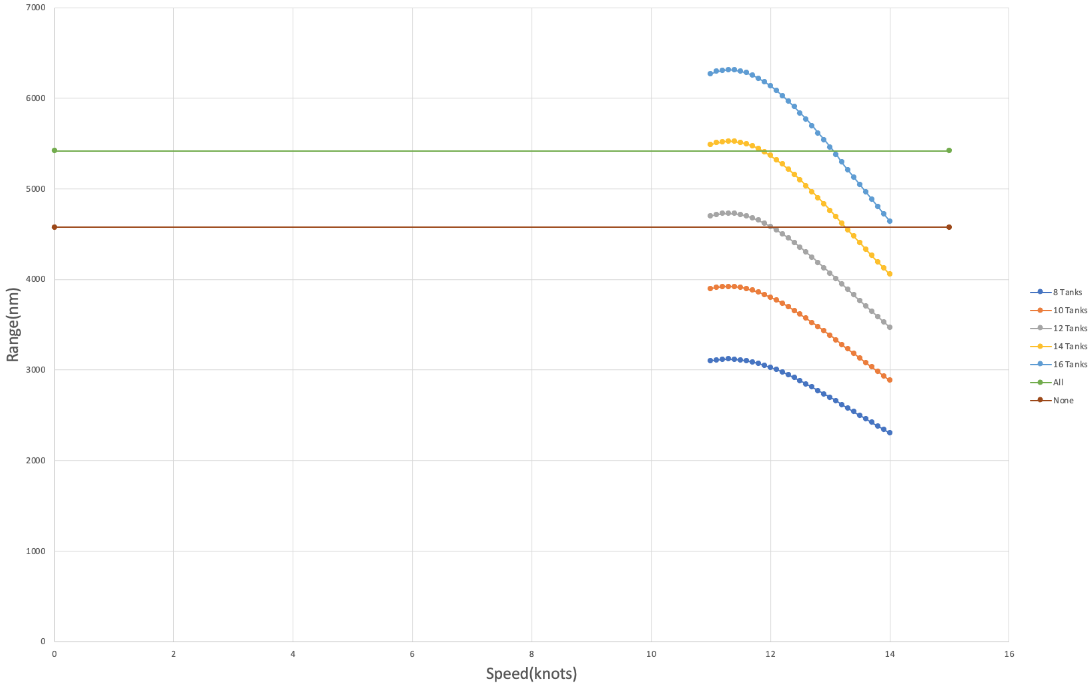

Figure H.2.7: Propulsion + Hotel Load + Boiler, Bad Weather

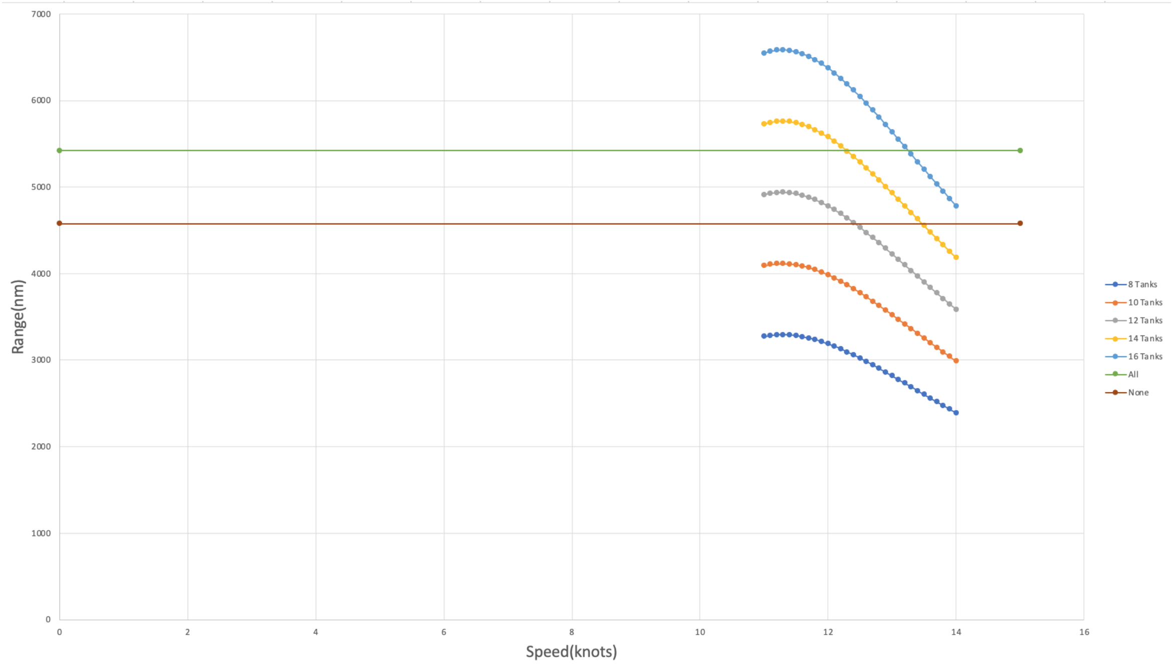

Figure H.2.8: Propulsion + Hotel Load, Bad Weather

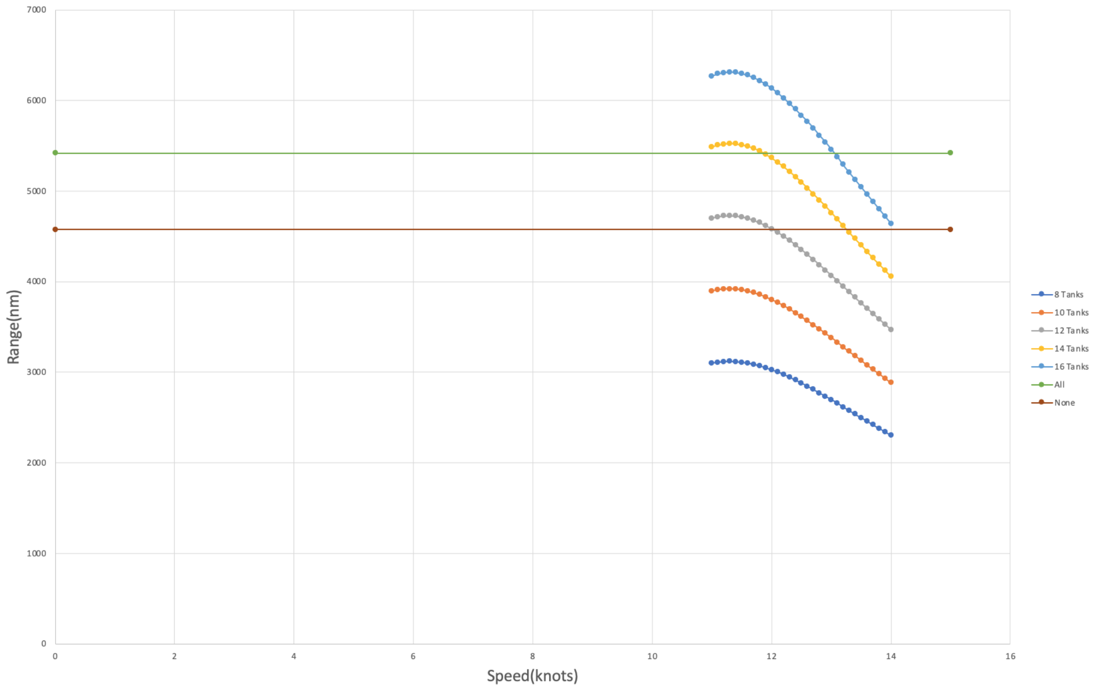

Figure H.2.9: Propulsion, Bad Weather

Appendix I

Power Requirements

Power requirements for different operational conditions.

Table I.0.1: Power Requirements

Speed (Knots)	**Shaft Power (kW)**				**Propulsion + Hotel**			**Propulsion + Hotel + Boiler**		
	Calm	**Good**	**Moderate**	**Bad**	**Good**	**Moderate**	**Bad**	**Good**	**Moderate**	**Bad**
11	2379	3315	3895	4605	3815	4395	5105	4015	4595	5305
11,1	2394	3336	3920	4634	3836	4420	5134	4036	4620	5334
11,2	2413	3363	3952	4672	3863	4452	5172	4063	4652	5372
11,3	2436	3395	3990	4717	3895	4490	5217	4095	4690	5417
11,4	2463	3433	4034	4769	3933	4534	5269	4133	4734	5469
11,5	2494	3476	4085	4829	3976	4585	5329	4176	4785	5529
11,6	2529	3525	4142	4896	4025	4642	5396	4225	4842	5596
11,7	2568	3578	4205	4971	4078	4705	5471	4278	4905	5671
11,8	2610	3637	4274	5052	4137	4774	5552	4337	4974	5752
11,9	2656	3701	4349	5141	4201	4849	5641	4401	5049	5841
12	2705	3770	4430	5237	4270	4930	5737	4470	5130	5937
12,1	2758	3844	4517	5340	4344	5017	5840	4544	5217	6040
12,2	2815	3923	4610	5449	4423	5110	5949	4623	5310	6149
12,3	2875	4007	4708	5566	4507	5208	6066	4707	5408	6266
12,4	2938	4095	4812	5689	4595	5312	6189	4795	5512	6389
12,5	3005	4189	4922	5819	4689	5422	6319	4889	5622	6519
12,6	3076	4287	5037	5955	4787	5537	6455	4987	5737	6655
12,7	3150	4389	5158	6098	4889	5658	6598	5089	5858	6798
12,8	3227	4497	5284	6247	4997	5784	6747	5197	5984	6947
12,9	3307	4609	5416	6402	5109	5916	6902	5309	6116	7102
13	3391	4725	5553	6564	5225	6053	7064	5425	6253	7264
13,1	3477	4846	5695	6732	5346	6195	7232	5546	6395	7432
13,2	3567	4971	5842	6906	5471	6342	7406	5671	6542	7606
13,3	3660	5101	5994	7086	5601	6494	7586	5801	6694	7786
13,4	3756	5235	6151	7272	5735	6651	7772	5935	6851	7972
13,5	3855	5373	6314	7464	5873	6814	7964	6073	7014	8164
13,6	3957	5515	6481	7661	6015	6981	8161	6215	7181	8361
13,7	4062	5661	6653	7864	6161	7153	8364	6361	7353	8564
13,8	4170	5812	6829	8073	6312	7329	8573	6512	7529	8773
13,9	4281	5966	7011	8288	6466	7511	8788	6666	7711	8988
14	4394	6124	7197	8507	6624	7697	9007	6824	7897	9207

Appendix J

Bunkering

The energy required to complete each leg and energy required at port for the trans-Atlantic route is presented. The name of the departure port is linked to the leg.

Table J.0.1: Energy Required

Port	Leg	Total Energy, Sea (GW)	Total Energy, Port (GW)
BEANR	1	6119	1291
USHOU	2	6920	566
BEANR	3	126	538
NLRTM	4	2029	522
RUULU	5	577	137
LVRIX	6	180	444
LVVNT	7	140	476
LTKLJ	8	6610	397
PRGUY	9	272	35
PRSJU	10	2619	992
USHOU	11	1	106
USTXT	12	480	544
USBTR	13	6404	628
BEANR	14	595	920
NLRTM	15	359	130
FRLEH	16	6846	177
USHOU	17	511	174
USHOU	18	888	575
USHOU	19	415	716
USHOU	20	7167	671
BEANR	21	821	376
NLRTM	22	6807	516
USHOU	23	180	570
USFPO	24	6989	516

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