Norwegian School of Economics
Bergen, Fall 2020

Sustainable Shipping

Exploring the Feasibility of Investments in Hydrogen-Powered Vessels for the Short-Sea Sector

Harald F. Fure

Supervisor: Professor, Roar Adland

Master thesis, Economics and Business Administration, Financial Economics

NORWEGIAN SCHOOL OF ECONOMICS

Acknowledgements

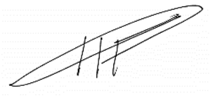
First and foremost, I would like to thank my supervisor, Roar Adland, for professional guidance, and always quick and constructive feedback! This has truly been helpful in the process of writing this thesis.

Further, I would like to thank Andreas Buskop and Karl Fredrik Vistad at Vard Engineering Brevik AS for providing me with essential information regarding the newly developed concept vessel, Vard ZeroCoaster.

I would also like to thank Eivind Dale at DNV GL, Lars Erik Marcussen at HeidelbergCement and Per-Kenneth Oye at Felleskjøpet for providing me with first-hand knowledge and information regarding their project with the aim to establish a long-term contract for a zero-emission vessel.

Finally, I would like to thank the banks, fuel cell producers, battery producer, cargo-owners, and charterers for contributing with important information.

Bergen, December 2020



Harald F. Fure

Abstract

Greenhouse gas emission from the shipping industry is increasing. At the same time there is a pressing need to reduce the anthropogenic greenhouse gas emissions. The need for alternative marine fuels is a fact. In this paper I analyze the feasibility of investments in hydrogen-powered vessels for the short-sea sector. The contributions of the paper are to investigate whether such investments are possible from a technical and operational viewpoint, if hydrogen can contribute to decarbonize the short-sea sector and if such investments can be financially viable. These are all essential topics that must be addressed to consider hydrogen as an alternative marine fuel for the short-sea sector.

A case study is built based on an announced contract for a zero-emission vessel, combined with data for a concept vessel designed to fit that contract. Through interviews with relevant stakeholders and secondary data, technical and regulatory challenges are mapped. Based on a thorough literature review of hydrogen as a marine fuel, the environmental footprint measured on well-to-propeller is mapped. These results are compared to results for common fossil fuels used today to determine if hydrogen can contribute to reduce greenhouse gas emissions for the short-sea sector, today and in the future. Based on data from the case study, combined with data from the literature, the yearly emissions related to the use of hydrogen versus fossil fuels are calculated. Lastly a thorough analysis of the financial viability is performed based on the case study. Information from interviews with cargo-owners, ship designers and financial institutions is used in combination with current and future estimated hydrogen prices to derive a qualified academic answer. The results from the case study are used in combination with a survey conducted among European cargo-owners and charterers to identify if any of the results are transferrable to the short-sea market in general.

The result from the analysis is that investment in a hydrogen-powered vessel is not a feasible option today. Technical, regulatory, and logistical challenges related to building and operating a hydrogen-powered vessel should be possible to overcome. If produced from renewable energy, hydrogen can also contribute to reduce greenhouse gas emissions on a well-to-propeller perspective. The main challenge is related to the financial viability of such investment. Given the level of freight rates, cost of fuel, cost of building such vessel and the cost of renewing the energy converter systems, it is deemed unlikely that such investment can be financially viable today. This applies both to the case study and the short-sea sector in general.

Contents

1. Introduction

Climate change and its consequences have gained increasingly attention for several years. It is broadly recognized that climate change is one of the greatest challenges for humankind and a defining issue of our time. Effort has been made to make world leaders enter into multilateral treaties to combat climate change. The most significant such treaty is the Paris Agreement. The central aim of the Paris Agreement is to reduce the global temperature rise and keep it below 2 degrees Celsius above pre-industrial levels (UNFCCC, 2020). There is a direct link between the concentration of greenhouse gases (GHG) in the earth's atmosphere and the average global temperature on earth. It is also well known that carbon dioxide (CO_2) accounts for about two-thirds of the GHGs and this is mainly the product of burning fossil fuels. (United Nations, 2020)

In UNCTADs (2020) annual Review of Maritime Transport 2019 it is estimated that 80 per cent of the volume of world trade is carried by sea, hence maritime shipping is crucial for global trade and access to global markets. Transporting these volumes of cargo requires vast amounts of energy, making shipping a mass consumer of fossil fuels. However, maritime shipping is also recognized as the most energy efficient mode of transporting large volumes of cargo.

The Fourth IMO GHG Study revealed that the GHG emissions from shipping have increased from 977 million tonnes in 2012 to 1076 million tonnes in 2018, representing a 9.6% increase. Of these GHG emissions, 962 million tonnes in 2012 and 1056 million tonnes in 2018 were CO2 emissions, representing an increase of 9.3% for this period. The share of emissions from shipping in global anthropogenic emissions has also increased in this period. From 2.76% in 2012 to 2.89% in 2018, and it is estimated that the total emissions from this industry will increase in the future if no action is taken. (Faber, et al., 2020)

With this knowledge on hand, regulatory authorities, such as the International Maritime Organization (IMO) and the EU, recognize that the shipping industry needs to act and contribute to reduce GHG emissions. In 2018 IMO presented an initial strategy on reduction of GHG emissions from ships. This strategy can be summarized in three main ambitions. Firstly, a goal to decline the carbon intensity of ships through stricter Energy Efficiency Design Index (EEDI) requirements. Secondly, an ambition to reduce the CO_2 emissions per transport unit by at least 40% by 2030 and aiming for 70% reduction by 2050, relative to IMOs chosen base year of 2008. And lastly the most ambitious goal is to peak and decline GHG emissions from international shipping as fast as possible and reduce the annual GHG emissions by minimum 50% within 2050, compared to the base year of 2008. (IMO, 2020)

However, members of the European parliament are not satisfied. They want instant action and have this year voted to include CO_2 emissions from maritime transport in the EU Emission Trading System (ETS). (European Parliament, 2020)

The financial sector has also developed an interest in climate change in recent years. Financial institutions recognize that they must take climate risk into account when providing capital. Most ships are built to last for at least 25 years and some even longer, a newbuilding delivered today will sail until the year 2045 and potentially even longer. Based on the goals set by IMO in its strategy to reduce GHG emissions from ships, one should expect several environmental regulations being imposed on the shipping industry for the coming years up to 2050. The financial sector has started to emphasize this fact. After IMO released its strategy in 2018, a group of ship financiers, ship owners and industry experts gathered to explore practical approaches for integrating climate risk into financial decision-making in the maritime industry. This resulted in the Poseidon Principles being launched the 18th of June 2019. (Poseidon Principles, 2020) The Poseidon Principles are a global framework for responsible ship finance, and it builds on four principles that are used to assess and disclose the climate alignment of ship finance portfolios. (Poseidon Principles, 2020)

Like the financial sector, major cargo-owners and charterers have started to realize the consequences of climate change. Focus has increased both on emissions related to operational activities and logistical activities. Shortly after the Poseidon Principles were launched, some charterers expressed the need for a transparent process for reporting emissions related to chartering activities. Consequently, it was decided to develop a framework equivalent to the Poseidon Principles for charterers. This framework has been named Sea Cargo Charter and builds on the same four Principles as the Poseidon Principles. (Sea Cargo Charter, 2020) Some may argue that the Sea Cargo Charter do not directly lead to cut in emissions, but rather reporting on emissions. However, two cargo-owners have taken focus on reduction of GHG emissions one step further. The Norwegian cargo-owners HeidelbergCement Norway AS and Felleskjøpet Agri SA are aiming to combine opposite cargo flows, enabling minimized ballast legs, with a long-term contract in return for a shipowner who can offer a zero-emission vessel

(DNV GL, 2020). The hypothesis is that the additional costs related to a zero-emission vessel will be covered by improved utilization of the vessel.

With pressure to reduce GHG emissions from regulatory authorities, financial institutions and cargo owners, the shipowners find themselves in a difficult position. Zero-emission solutions are needed today, but the technology is still in its early phase.

From a shipowner's perspective, enablers and drivers are needed to accelerate the shift towards a more sustainable business. Regulators, financial institutions, and cargo-owners/charterers can be described as the drivers, while the ship supply chain and land-based supply chain can be described as enablers. (Eriksen, et al., 2020) Until today, there has not been built any commercially operated zero-emission vessels for transporting goods over long distances. Some examples of zero-emission vessels exist, however the common feature for these is that they sail over *very* short distances. Examples of this type of ships are ferries in Norway, Yara Birkeland and the Asahi Tankers order of two battery powered coastal tankers. However, technology is evolving and this year the Norwegian ship design company Vard Engineering Brevik AS launched a zero-emission concept vessel for the short-sea sector, named Vard ZeroCoaster. This vessel is designed to enable sailing over longer distances than existing zero-emission vessels operating today, and one of the fuel options is hydrogen.

The short-sea sector is a broad definition, which do not have any firm rules on the exact vessel type and size (Stopford, 2009). Research done in this paper is based on defining the short-sea sector as general cargo/multipurpose/dry bulk/self-discharging vessels in the size range 2000-7000 deadweight tonnage (DWT) trading in Europe.

Maritime industry experts point at the short-sea sector to be a good starting point for testing and developing new and more environmentally friendly solutions (DNV GL, 2019). The argument mainly builds on the nature of the trade, where one sail relatively short distances compared to deep-sea shipping. In addition, the vessels in the short-sea sector are generally smaller than in the deep-sea sector, hence the required energy to propel the vessels are lower. These characteristics are preferable for testing out zero-emission fuels and technologies. The reason for that is the logistical and technical challenge related to zero-emission fuels and technologies. Zero-emission fuels require larger volumes to store than traditional fuels. Hence, to enable a sailing range of more than a few days are challenging. Therefore, a lower required energy to propel the vessels are preferable. Another argument is the high average age of the short-sea fleet. The high average age result in an upcoming need for fleet renewal.

However, even though the short-sea sector might be a good starting point for testing new and environmentally friendly solutions, there are some drawbacks. IMO, EU, and industry initiatives fail to include a large proportion of the short-sea fleet in its scope for emission reducing initiatives. Their scope only covers ships over 5000 gross tonnage, equivalent to a size of about 7000 DWT for the vessel type discussed in this paper. The reason for this is not clearly stated, however one explanation might be the competition with road transport. In some cases, it can be argued that the short-sea sector is competing with road transport. Hence, imposing carbon taxes on the smallest vessels can lead to a shift from sea- to road transport. While cargo vessels in the short-sea market have an emission of 21 grams of CO_2 per tonne-km, heavy trucks with trailer emit 50 grams CO_2 per tonne-km (Moirangthem, 2016).

The objective of this paper is to investigate the feasibility of investments in hydrogen-powered vessels for the short-sea sector. The contributions of this paper are threefold. Firstly, I analyze whether it is technically possible to build and operate a hydrogen-powered short-sea vessel today. Secondly, I analyze if a hydrogen-powered vessel will be environmentally friendly. Thirdly, I analyze if investments in hydrogen-powered vessels can be financially viable.

Chapter 2 present facts and literature on hydrogen as a marine fuel and relevant energy converters. In chapter 3 the methodology used to answer the problem of this paper is presented. A case study is built to enable precise and realistic calculations. The framework for the case study is presented in chapter 4. Chapter 5 contains analysis, results, and discussion. At the end chapter 6 concludes.

2. Hydrogen as an Alternative Marine Fuel

Hydrogen is as an energy carrier, meaning that it can be used to store, move, and deliver energy that has been produced from other sources of energy (Satyapal, 2017). A normal distinction to make when discussing hydrogen is to divide it into grey, blue and green hydrogen. The "colour" of the hydrogen is determined by the sources of energy and the method used to produce the hydrogen. Blanc, et al., (2020) describe the three different types of hydrogen as follows; Grey hydrogen is produced from fossil fuels which is a carbon intensive process. In 2019, 96% of the hydrogen produced in the world were classified as grey hydrogen. Blue hydrogen is like grey hydrogen produced using fossil fuels, but in the process of production one use carbon capture and storage (CCS) to remove some of the CO_2 that is occurring during the production process. Hence the total CO_2 emission from this production process is lower than for grey hydrogen. Green hydrogen is the environmentally friendly type of hydrogen. This is produced using electrolysis, where a zero-emission energy source such as electricity from wind, sun, hydropower, or nuclear power is making the *production* of the fuel completely free of CO_2 emissions.

To achieve a storage capacity of an acceptable amount of energy, one mainly relies on two methods of storing hydrogen today. Namely as compressed hydrogen (CH_2) or as liquefied hydrogen (LH_2). Compressed hydrogen must be stored under high pressure (300 to 700 bar) and liquefied hydrogen must be stored at a very low temperature (-253 °C). The method of storing the hydrogen will determine the volumetric- and gravimetric energy density of the hydrogen. Of the two alternatives, liquefied hydrogen is the preferred method of storage in terms of storing enough energy to power a ship. (DNV GL, 2019) This is illustrated in table 1 on next page.

It should also be mentioned that hydrogen can be stored in other forms than compressed and liquefied hydrogen. Ammonia can serve as a hydrogen carrier and from a theoretical viewpoint it is preferable compared to other means of storing hydrogen. This is mainly because it contains more energy per volume unit than LH_2, is easier available and cheaper. However, the technology for utilization of ammonia is considered more challenging and immature than for pure hydrogen, hence it is not covered in this paper. The same goes for Liquid Organic Hydrogen Carriers (LOHC), in terms of storing energy it is preferred over LH_2 and CH_2. But as for ammonia, it is at a very early stage in terms of utilizing the energy stored. (Damman, et al., 2020) Hence it is not covered in this paper.

Fuel	Compressed Hydrogen (350 bar)	Liquefied Hydrogen
Abbreviation	CH_2	LH_2
Density (kg/m^3)	23	71
LHV (kWh/kg)	33,3	33,3
MJ/m^3	2800	8500

Table 1: Properties[1] of MGO and Hydrogen (Brinks & Hektor, 2020) & (Hirth, et al., 2019)

As a marine fuel, hydrogen have the potential to be used both in combustion engines and in fuel cells. The maritime industry is trying to develop combustion engines for *ships* that can run on hydrogen, while fuel cells have already proven to work. The efficiency of combustion engines running on hydrogen is estimated to be lower than for fuel cells. In addition, the combustion process generates NOx (Guo, et al., 2020). Hence a combustion engine running on hydrogen cannot be classified as hundred percent zero-emission. Fuel cells on the other hand do not emit any GHGs when hydrogen is used, hence a vessel running on hydrogen with fuel cells to convert the energy can be classified as zero-emission during operation (Gilbert, et al., 2018).

Using hydrogen as a marine fuel will require approval from regulatory authorities. Currently there are no regulatory framework to regulate storage and the use of hydrogen as fuel for vessels, hence one would need to rely on a case-to-case process to get "alternative design" approval for a vessel fuelled by hydrogen. (Atanasiu, 2019)

The availability and cost of hydrogen are important factors when considering its potential as a marine fuel. The following sections focus on liquefied hydrogen due to preferable properties compared to compressed hydrogen in terms of storing enough energy on board a ship. Today the production capacity of liquefied hydrogen in Europe is 20 tonnes per day (Decker, 2019). However, with increasing demand, the production capacity is expected to rise to about 25 tonnes per day for 2021 (Decker, 2019). At present time, this production is carried out in three countries in Europe, namely Germany, Netherland, and France. All of them producing grey hydrogen from natural gas (Hirth, et al., 2019). While the production capacity is very low, the

[1] LHV: Lower heating value

price is very high, relative to other fuels. With such low volumes of production, there is no functional market for trade of liquefied hydrogen. Hence, to set an exact price of the product is challenging. The price of liquefied hydrogen will also depend on the place of delivery. With only three production sites in Europe today, one would in most cases rely on transporting the product from production site to the vessel. The cost for this will naturally depend on the distance of transportation. Despite the challenges of setting an exact price of liquefied hydrogen, some facts and estimates exist. Hirth, et al., (2019) state that the price of liquefied hydrogen delivered in Southern Norway have a retail price of roughly EUR 15 per kg. They also state that the retail price in Europe (unspecified location) excluding distribution is EUR 7,1. However, for the future they estimate that the price in Norway can go down to EUR 3,5-7,5 per kg. At the most optimistic price scenario for Norway, at EUR 3,5 per kg, LH_2 would still not be able to compete with fossil fuels such as marine gas oil (MGO) as table 2 shows.

Place and time of delivery	Fuel	EUR/tonne	EUR/kg	LHV(kWh/kg)	Specific Fuel consumption (g/kWh)	Efficiency of engine	Cost in EUR per kWh to shaft
Rotterdam today	MGO	339	0,339	11,97	174,0	48 %	0,0590
Norway today	LH_2	15000	15	33,3	60,06	50 %	0,9009
Europe ex distribution today	LH_2	7100	7,1	33,3	60,06	50 %	0,4264
Lowest future estimate	LH_2	3500	3,5	33,3	60,06	50 %	0,2102

Table 2[2],[3],[4]: EUR/kWh to shaft for MGO vs LH_2

The following sections contain a literature review of CO_2 equivalent (CO_2eq) emissions related to LH_2, marine diesel oil (MDO) and marine gas oil (MGO). Both MDO and MGO can be used in engines for vessels sailing in the short sea market today, however MGO is the

---

[2] MGO price USD 400 delivered in Rotterdam, December 2020. Price retrieved form bunkerindex.com. Exchange rate used: USD/EUR = 0,8479

[3] Efficiency of engine for combustion engine (MGO) from (Lindstad, 2019), LHV for MGO from (Hirth, et al., 2019)

[4] Efficiency of engine for PEMFC (LH_2) and LH_2 price from (Hirth, et al., 2019)

normal standard for vessels of the size and trading area discussed in this paper. Summarized results for comparison can be found in table 3 on page 16.

Gilbert et al., (2018) find that while LH_2 used in fuel cells have zero emission during operation, it can have significant emissions related to production of the fuel. Their study analyses the life cycle emissions, also referred to as well-to-propeller (WTP) in their paper, related to different marine fuels. For hydrogen they assume that the primary source of energy, natural gas, is extracted and processed in Europe and transported 180 km before it is liquefied and used to make hydrogen. Further on they include a scenario for production of LH_2 both with and without carbon capture and storage (CCS), including liquification of hydrogen. They use a distribution distance of 50 km for the end product, LH_2. Storage, bunkering and use in fuel cells are included before they arrive at the CO_2eq per kWh power delivered to the shaft. For LH_2 without CCS they find that the emission is 1000 grams CO_2eq/kWh delivered to shaft. For LH_2 with CCS they find the emission to be approximately 590 grams CO_2eq/kWh delivered to shaft. They have also analysed the emissions related to green liquefied hydrogen produced by electrolyse of water with renewable electricity from a wind farm in Europe. From this they find green LH_2 to have an emission of about 110 grams CO_2eq/kWh delivered to shaft. For marine diesel oil (MDO) they estimate an emission of roughly 610 grams CO_2eq/kWh where the emissions mainly are a result of using the fuel, which put the numbers for hydrogen in context. Hence grey LH_2 is less environmentally friendly than MDO in a WTP perspective according to their study.

Chryssakis et al., (2014) made a paper where they investigated emissions for different marine fuels. They investigated LH_2 produced from renewables and distributed in the area of production and they investigated LH_2 from reforming of Russian natural gas without CCS. Like Gilbert et al., (2018) they find that LH_2 have no emissions during use (tank-to-propeller: TTP) but can have significant emissions related to production and distribution (well-to-tank: WTT). Their results for LH_2 are presented in the form of grams of CO_2eq per Mega Joule of fuel (MJf) on WTT. They find that LH_2 from Russian natural gas will have an emission of 90 grams CO_2eq/MJf on a WTT basis and that LH_2 from renewables will have an emission of 1 gram CO_2eq/MJf on WTT basis. Emissions related to MDO are also analyzed in that study. They find that the emissions related to MDO is approximately 88 grams CO_2eq/MJf on a WTP basis, where approximately 85% of the emissions are related to TTP.

Recently the Texas A&M University performed a study for Trafigura where they investigated the emissions related to different alternative marine fuels. For grey LH_2 they found the emissions to be roughly 128,7 grams CO_2eq/MJ fuel, for blue LH_2 71,3 grams CO_2eq/MJ fuel and for green LH_2 5,2 g CO_2eq/MJ fuel. All the emissions are occurring on WTT basis. (Trafigura, 2020) Their results are presented with some spread due to the uncertainty of exact emissions, but the above-mentioned values are the average result.

The European Commission's science and knowledge service, Joint Research Centre has for several years been making well-to-tank reports for a wide range of fuels. Among these fuels, LH_2 is covered in detail. They present their results in grams CO_2 equivalent/MJ LH_2. For grey LH_2 they use a production path for taking the natural gas 4000 km in pipelines to Europe, producing the LH_2 by electrolysis near the market and transporting the LH_2 300 km by road to the end user. For green LH_2, their estimates are based on renewable electricity from offshore wind, electrolysis and liquification close to market and 50 km transport to the end user. For green LH_2 they find that the WTT emission is 3,6 grams CO_2eq/MJ of LH_2. For grey LH_2 produced from natural gas they find the emission to be 128,1 grams CO_2eq/MJ of LH_2. (Prussi, et al., 2020)

Lindstad et al., (2020) have analysed emissions related to different fossil fuels, among them MGO. Their results are presented in gram CO2 eq/kWh based on well-to-propeller, where they distinguish between the emissions caused by WTT and TTP. In addition, they account for the fact that different engines have different fuel consumption per kWh of power delivered. For 2-stroke MGO diesel engines they find that the emission is 644 g CO2 eq/kWh, where 84% of the emission is occurring on TTP. For 4-stroke MGO diesel engines they find that the emission is 685 g CO2 eq/kWh. Both results are presented in a 100-year timeframe global warming potential (GWP). The results from Lindstad et al., (2020) is in line with what Brinks & Hektor (2020) report for MGO. They report an emission of 88 kg CO_2/GJ for MGO. These results are also in line with what DNV GL (2019) find in their report where they investigate alternative fuels and technologies. They find that MGO have a WTP emission of 87.1 g CO_2 equivalent per MJ of fuel, where 85% of the emissions are occurring on TTP.

Gram CO_2eq/kWh delivered to shaft					
Studies	**Grey LH_2**	**Blue LH_2**	**Green LH_2**	**MDO**	**MGO**
Gilbert, et al., 2018	1000	590	110	610	-
Chryssakis, et al., 2014	648	-	7,2	660	-
Trafigura, 2020	926	513	37,4	-	-
Prussi, et al., 2020	922	-	25,9	-	-
Lindstad, et al., 2020	-	-	-	-	644-685
Brinks & Hektor, 2020	-	-	-	-	660
DNV GL, 2019	-	-	-	-	653

Table 3: Summary of results from literature review presented in same energy unit[5]for well-to-propeller

Fuel cells

Fuel cells transform chemical energy from certain compounds, such as hydrogen, into electric power. The process is done without any combustion, hence there are no emissions related to the energy conversion. (Kirstein, et al., 2018) There is a wide range of different types of fuel cells, each with their own characteristics and fuel compatibility. In 2017 DNV GL performed an analysis on behalf of the European Maritime Safety Agency where they investigated which fuel cells that were most promising for application in ships. The study concluded that Proton Exchange Membrane Fuel Cell (PEMFC), High temperature PEMFC and Solid oxide fuel cell (SOFC) were the most promising fuel cell technologies (Tronstad, et al. 2017). PEMFC is compatible with hydrogen and was the system that received the highest overall score and is considered the most promising for application in ships. PEMFC has been tested on several ships, however not in the scale investigated in this paper. (Tronstad, et al, 2017) These results are also in line with what Mestemaker et al., (2019) find. They range PEMFC to be the most mature type of fuel cell for application in ships. Different fuel cells have different characteristics that are important when performing environmental and economic analysis. The following sections elaborate on the most important characteristics for PEMFC.

The efficiency of a fuel cell is of high importance. This will determine the amount of LH_2 needed to generate the required power. Alaswad et al., (2016) and Mestemaker et al., (2019) state that PEMFC have an electrical efficiency of 40-60%. The exact efficiency of the PEMFC

[5] Facts for calculations, accounted for in Chapter 3.3: 1 MJ = 3,6 kWh. 50% efficiency for fuel cells. 48% efficiency for combustion engine.

system will however depend on the power load. The required power load is dependent on the total fuel cell system size and the energy required to maintain a given speed. (Klebanoff, et al., 2018) For fuel consumption calculations, to perform environmental and economic analysis, different studies[6] use an estimated efficiency of 50%-53%. With 50% efficiency, liquefied hydrogen containing 33.3 kWh/kg (LHV) will give an effective electrical power of 16.65 kWh/kg. However, the exact efficiency will depend on the above-mentioned factors.

The limited lifetime of fuel cells is important to highlight. While a combustion engine normally lasts the entire lifetime of a ship, provided good maintenance (Moirangthem, 2016), a fuel cell has a limited lifetime. The lifetime will depend on the type of fuel cells and operational profile of the fuel cells, however general guidelines can be obtained. Mestemaker et al., (2019) State that PEMFC for application in vessels have an expected lifetime of 500 – 20 000 operational hours. TECO 2030 ASA inform that their PEMFC system for ships will have an operational lifetime of up to 35.000 hours (C. Skajem, personal communication, November 20, 2020). PowerCell AB inform that their PEMFC have an expected lifetime of 5.000 – 35.000 hours, depending on the start stop cycling, load factor, etc (J. Burgren, personal communication, December 08, 2020).

The estimated cost for fuel cells today and in the future is of high importance when analysing if a hydrogen-powered vessel can be financially viable. This is because the fuel cells will have to be renewed during the vessel's lifetime. The International Energy Agency (2019) estimate a fuel cell cost of USD 2000/kW for ships today and aiming for USD 1000/kW for the future. Mestemaker et al., (2019) state that the current cost for PEMFC is 1000-2500 EUR/kW, and for the future without specifying "future" they have a projected cost of 50-500 EUR/kW. TECO 2030 ASA inform that a fuel cell system for ships today will be in the range 1000-1800 EUR/kW, depending on the size of the system. Five years ahead they aim for a price of 400-800 EUR/kW. (T.E. Hoftun, personal communication, November 26, 2020). PowerCell Sweden AB inform that their PEMFC cost roughly 1750 EUR/kW today (J. Burgren, personal communication, December 08, 2020). However, no estimate for the future was possible to obtain.

[6] (Klebanoff, et al., 2018), (Gilbert, et al., 2018), (Hirth, et al., 2019)

3. Methodology

This chapter presents the argumentation for choice of research method, exposition of data collection, techniques for analysis along with limitations and weaknesses are accounted for.

3.1 Research Method and Design

The paper combines qualitative and quantitative method to answer the problem. Qualitative method is used to answer the first contribution of this paper, whether it is technically possible to build and operate a hydrogen-powered short-sea vessel today. A combination of qualitative and quantitative method is used to answer the second and third contribution of this paper, whether a hydrogen-powered vessel is environmentally friendly and if it can be financially viable.

To derive a qualified academic answer to the problem of this paper it was considered advantageous and necessary to limit the scope, enabling precise and realistic answers and calculations. A case study allows for thorough analysis of a complex problem applied to a real-world situation (McCombes, 2020). Therefore, it was concluded that a case study would be an appropriate research design. Parallel to the case study, results are used to investigate whether any of the findings can be applied to the short-sea market in general.

The case study for this paper builds on an announced freight contract for a zero-emission vessel and a newly developed zero-emission concept vessel. Felleskjøpet Agri SA and HeidelbergCement Norway AS are the cargo-owners that have issued this contract. Vard Engineering Brevik AS is the company that have developed the concept vessel. A full presentation of the framework for the case study is presented in chapter 4.

3.2 Data Collection

Secondary data

DNV GLs webpage “Green Shipping Programme” was used to collect relevant documents related to the case study. Further on, academic and industry research papers related to hydrogen and fuel cells were collected through wide searches on Oria, ResearchGate, ScienceDirect, Google Scholar and Google. Wide web searches have also been conducted to collect information related to ongoing projects for zero-emission vessels. Time charter equivalent rates for this size of vessels in the short-sea sector has been collected through Maritime Strategies International (MSI) data. Lastly, shipping industry books has served as a source to support the theoretical framework.

Primary data

Related to the case study, extensive amount of primary data has been collected through a series of semi-structured interviews with multiple stakeholders. Rahim & Daud (2015) highlight semi-structured interviews as an important method for data collection when conducting a case study. This type of interviews enables the researcher to use an interview guide at the same time as it allows for contextual adoption when required. Video- and phone interviews, instead of in person interviews, has mainly been performed due to COVID-19 restrictions and to enable interviews with stakeholders in other cities. In some cases, it was not suitable to perform interviews, hence data has been collected through mail correspondence.

Among the enablers for zero-emission vessels it was deemed necessary to collect primary data from a ship design company, fuel cell producers, battery producers and a classification society. Among the drivers it was deemed necessary to collect primary data from financial institutions and cargo-owners. In addition, primary data has been collected from an anonymous shipowner.

Vard Engineering Brevik AS was contacted to collect data for a zero-emission vessel. They are a recognized ship design company and have since the start of 2019 been working on a pilot project to develop the “next generation coastal bulk carrier”. Through this pilot project they have developed a zero-emission vessel called ZeroCoaster. Primary data was collected through one initial semi-structured video interview with Andreas Buskop (General Manager) and Karl Fredrik Vistad (Naval Architect) to get a general understanding of their work and status for developing this zero-emission vessel. Thereafter follow-up mail correspondence and a phone interview were conducted to ensure the correct data was used. The interview guide and relevant questions can be found in the appendix 8.1.

To give a qualified answer to whether an investment in a hydrogen-powered vessel can be financially viable, the realistic financing structure and achievable financial terms must be established. Semi-structured interviews with three banks involved in ship finance has been conducted. Bjorn Ardal in Sparebanken Vest, Francis Birkeland in ABN AMRO and Tom Vagen in Danske Bank were interviewed. The interview guide can be found in appendix 8.2. The interviewed banks were promised that specific statements related to them should not be quoted or identified with one specific bank in this paper. Hence when information from these interviews is used, it is only referred to as “interviews with banks” or (Banks, 2020). In addition to interviews with banks, a semi-structured interview with an anonymous multinational energy company has been conducted. They investigate the opportunity to do shared investments with shipowners.

To get a better understanding of the plan and terms for the contract used in the case study semi-structured interviews with both cargo-owners has been conducted. Lars Erik Marcussen (Chartering Manager, HeidelbergCement North Europe) and Per-Kenneth Øye (Chief Logistics, Felleskjøpet Agri SA) were interviewed. With HeidelbergCement it was, due to lack of time, first sent an e-mail with relevant questions and then followed up by a phone interview. Interview guide and relevant topics discussed can be found in appendix 8.3.

TECO 2030 ASA and PowerCell Sweden AB were contacted to collect information regarding fuel cells for vessels. Expected lifetime, current and future prices for their fuel cells has been collected through e-mail correspondence. Corvus Energy Norway AS produce and sell batteries for vessels. Information regarding expected lifetime, current and future prices for the battery package suggested to use in the concept vessel has been collected through e-mail correspondence. List of questions sent can be found in appendix 8.4.

A classification society have in depth knowledge of regulatory and technical challenges related to ships. Hence it was deemed necessary to get in contact with such company. DNV GL was chosen because they are a leading classification society and because they are involved in the contract used as case study for this paper. The contact with DNV GL has mainly been via e-mail. The relevant questions and topics discussed can be found in appendix 8.5.

Data on dry-docking cost has been collected from an anonymous shipowner. The data is used to estimate the correct dry-dock costs for the type of vessel investigated in this paper. E-mail correspondence has been used to collect the data.

An online survey has been issued to 20 European cargo-owners and charterers. To ensure a good quality of the data gathered, the survey was issued directly to relevant personnel within each company. Relevant personnel are defined as chartering manager, supply chain manager and similar titles. The number of participants was kept low in order to ensure a good quality of the data. The sample is low. However, it is argued that it is a representative sample for the population. This builds on the fact that the invited cargo-owners and charterers cover different commodities and trades. It was decided to keep it anonymous to increase the likelihood of getting honest answers and increase the reply rate. The purpose of the survey was to get a general impression of cargo-owners and charterers focus on emissions in relation to their business in general and logistical activities. Further on they were asked if they are able or willing to pay more for transportation services that are more environmentally friendly than what they use today. It was also checked if they are willing or able to enter long-term contracts to facilitate for investments in low or zero-emission vessels. Only 12 of the 20 invited companies replied to the survey. Due to the low number of replies, a thorough statistical interpretation is not conducted. However, the results are used as they can be backed by previous research conducted on the topic. The survey can be found in appendix 8.6.

To a large extent, the paper is dependent on primary data. To evaluate the quality of the primary data it has, to the extent possible, been cross checked with other primary- and secondary data sources.

3.3 Techniques for Analysis

The first contribution of this paper is analysed and answered based on available literature, ongoing projects, interviews, and conversations with industry experts.

The second contribution of this paper is answered in two steps. First the data from the literature review is summarized in chapter 2 and presented in the same unit to enable comparison. To calculate from gram CO_2eq/MJ fuel to gram CO_2eq/kWh delivered to shaft the following equation is applied:

$$X \text{ MJ} * 3.6 / Y = Z$$

Where X is the gram CO_2eq per MJ of fuel. Y is the efficiency of fuel cells for LH_2 and efficiency of combustion engines for MDO and MGO. The efficiency for fuel cells is set to 50%, and the efficiency for combustion engines is set to 48%. This is accounted for in chapter 2. Z is the gram CO_2eq/kWh delivered to shaft. The summarized results from chapter 2 are again presented in chapter 5.2, however there the average value based on the literature review is used. In addition, the presentation distinguishes between where the emissions occur.

Thereafter, a calculation of yearly CO_2eq emissions related to the case study for the use of LH_2, MDO and MGO is conducted. The annual energy consumption is based on a default sailing route, a fixed sailing speed of 7 knots and a concept vessel, all presented in chapter 4. For the calculation it is assumed that all vessels can use shore power in port, hence the calculation is based exclusively on energy consumption related to sailing. The results are presented as tonnes CO_2 equivalent emissions per year. For calculations, the same yearly energy demand to shaft at 7 knots is used for LH_2, MDO and MGO. Hence the results represent the Well-To-Propeller emissions for an energy efficient newbuilt vessel, not necessarily representative for existing vessels in the market. In addition, the results are based on the default sailing route for the case study, hence a vessel with different operational profile will have a different result. To calculate the yearly CO_2eq emissions related to the case study, the average CO_2eq emissions from the literature review is used.

The third contribution consists of three different main types of calculations. First the required time charter rate is calculated. Thereafter the achievable time charter rate is calculated. Lastly a discounted cashflow analysis is performed.

The required time charter rate

The foundation for this calculation is the case study presented in chapter 5. It is assumed that the vessel will be built to sail on a fixed contract for 20 years and sold after this contract expires. Based on the estimated newbuilding price, estimated residual value, and time horizon, the *minimum* required time charter (TC) rate to cover day-to-day cost of operating the vessel is calculated for different levels of operating cost (OPEX) and weighted average capital cost (WACC).

The TC rate is the disposable income for the shipowner to cover the cost of running the ship under a TC contract. On a TC contract the cargo-owners/charterers pay a fixed amount, typically per day or month, to rent a ship. The cargo-owners/charterers have the commercial "ownership" of the vessel; hence they pay the voyage related costs. Voyage related costs are typically bunker fuel and port cost. The remaining cost elements for the shipowner to cover with the TC rate are mainly OPEX, capital cost and periodic maintenance. The OPEX mainly consists of crew wages, daily maintenance and repairs, stores and supplies and insurance. (Stopford, 2009) The minimum cost that must covered to run the ship on a day-to-day basis is OPEX and capital cost.

The required time charter rate is calculated in two steps. Based on the above-mentioned factors, the required annuity per year is calculated. Thereafter, assuming the operational cost is constant, these are added. Combined this will indicate what level the required time charter rate must be at to cover the *minimum* cost of running the ship on a day-to-day basis. Two different calculations are made. One based on the normal project cost of building such vessel and one based on receiving investment support from public support scheme, hence an adjusted project cost.

The achievable time charter rate

Thereafter the achievable time charter rate is calculated for the case study. The time charter equivalent (TCE) equation is used for this.

$$\text{TCE} = \frac{\text{Gross Revenue} - \text{Voyage Costs}}{Tripduration}$$

The concept vessel presented for the case study serves as the default vessel, in terms of cargo capacity, speed and energy consumption. The contract presented for the case study serves as the framework for the realistic freight rate per tonne of cargo, distances, and estimated time use. Estimated port costs is based on a study of the average port cost for this type of vessel in Norwegian ports. Cost of LH_2 and electricity are based on the most up to date data for this topic. Freight rates excluded vat is used for calculation as vat is normally added on top of the freight rate to easily compare freight rates in the market.

In addition, TCE rates from the general market, not directly related to the case study are presented.

The discounted cashflow analysis

At the end, two discounted cashflow analyses for the case study is performed, one based on the normal project cost of building such vessel and one based on receiving investment support. Important factors for these analyses are the expected lifetime of fuel cells and batteries, expected cost for renewal at the end of lifetime and dry-docking cost (periodical maintenance). The expected dry-docking cost for a vessel of this size have been collected through primary and secondary data. Thereafter the cost for engine maintenance/repair in dry-dock has been subtracted based on information from primary data. At the end, the cost for renewal of fuel cells and batteries has been added at relevant time intervals. The cost and relevant intervals for fuel cells and batteries are based on the system size of the components for the concept vessel and data on expected lifetime and renewal cost. The renewal intervals are based on an operating profile for the default route with a sailing speed of 7 knots. Two base cases are established for the two investment alternatives and sensitivity analyses are performed for different levels of TC rate, OPEX, newbuilding price, WACC and levels of debt.

All calculations are performed in Euro (EUR). This is because Euro is the normal currency to use for freight rates in the European short-sea sector and because major elements like OPEX, dry-docking, sale and purchase of vessel and renewal of fuel cells are normally quoted in EUR. The freight rates for the case study are currently paid in NOK, but for the contract used in the case study it is not determined if NOK or EUR will be used. Hence it was considered relevant to perform calculations in EUR. The following average exchange rates for September 2020 has been used: NOK/EUR = 0,0927 and USD/EUR = 0,8479. Freight rates for the case study and port cost has been changed from NOK to EUR and cost for renewal of batteries have been changed from USD to EUR.

3.4 Limitations and Weaknesses

Due to the novelty of the topic and the fact that nobody has ever built a hydrogen-powered vessel of this type, the exact price of the vessel is somewhat uncertain. This is both a limitation and weakness of the paper. However, at present time the collected *estimates* are the best one can work with. Price estimates have been gathered from qualified companies and sensitivity analysis have been performed to compensate for the uncertainty.

There are limited data on well-to-propeller and well-to-tank CO_2eq emissions for LH_2. Several studies exist for compressed hydrogen (CH_2), but these are not directly comparable to LH_2. LH_2 is more energy demanding to produce (liquification process) than CH_2, hence one cannot directly compare the results. This is both a limitation and weakness.

The thesis uses one specific concept vessel to give a general answer, this is a weakness. However, it has not been possible to gather information on other vessels, this limitation in available data is caused by the novelty of the topic. It might be argued that other vessels can have better specifications in terms of range, energy consumption and cargo capacity. The vessel used in the calculations is however designed by a recognised ship designer and have been developed over a longer period. This should be representative for the best one can achieve in terms of range and energy efficiency.

The calculations are based on a fixed efficiency for fuel cells. This is a weakness of the paper caused by limitation of available data.

4. Case: Freight Contract and Zero-Emission Vessel

3rd of June 2020 two Norwegian cargo owners, Felleskjøpet Agri SA (hereafter FK) and HeidelbergCement AS (hereafter HC), issued a Request for Interest (RfI) for "*Green Transport of Gravel and Grain by Sea*". HC and FK have the ambition to establish a maritime transport system that operates without the emission of GHGs. The two companies will combine their cargo flows and have a coordinated operation, enabling minimized ballast legs. FK will transport grain from the Oslofjord on the east-coast to the west-coast of Norway, while HC will use the vessel for transport of gravel from Rogaland on the west-coast to the east coast of Norway. The planned quantity of cargo for transportation will enable close to full employment of one vessel on weekly roundtrips. (Felleskjøpet Agri SA; HeidelbergCement Norway AS, 2020) The hypothesis is that improved utilization of the vessel trough minimized ballast legs will enable the total transportation cost for cargo-owners to stay at the level they are today.

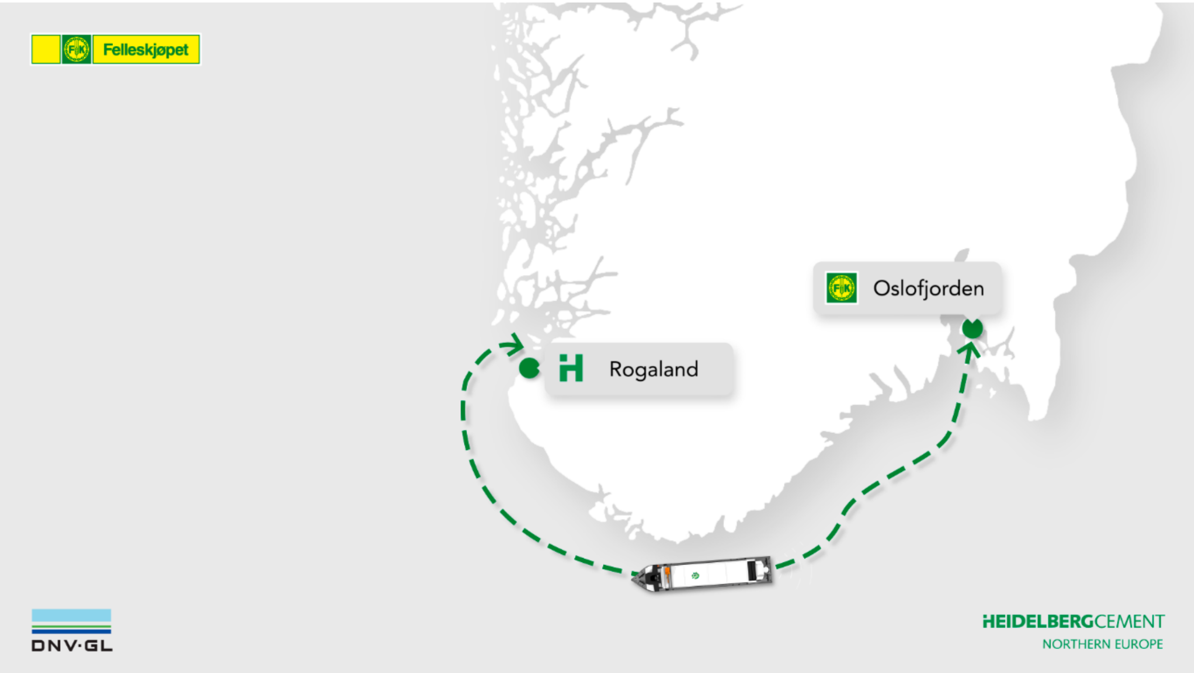


Figure 1 - Trading route (HeidelbergCement, 2020)

Grain is volume constrained, meaning that the volume of the cargo holds set the limitation to how much grain that can be loaded. Gravel is deadweight constrained, meaning that the carrying capacity of the vessel measured in tonnes set the limitation to how much gravel that can be loaded.

Cargo	Stowage factor
Wheat (Grain cargo)	0.45 mt/m3
Oat (Grain cargo)	0.63 mt/m3
Gravel	1.6-1.9 mt/m3

Table 4 – Stowage factor for different cargoes (Felleskjøpet Agri SA; HeidelbergCement Norway AS, 2020)

The contract will cover multiple ports; however, the default route set by the cargo-owners consists of the following ports: Tau, Oslo, Kambo and Stavanger. This will work as the default route for calculation of annual CO_2 equivalent emissions from different fuels and to calculate the achievable time charter rate for the contract.

Port	Cargo operation	Operating rate	Operating hours	Distance to next port, nm
Kambo	Load grain	400 mt/hr	06:00-21:00	270
Stavanger	Discharge grain	400 mt/hr	06:00-21:00	11
Tau	Load gravel	800 mt/hr	24/7	305
Oslo	Discharge gravel	500 mt/hr	06:00-21:00	29
Kambo				

Table 5 – Default route (Marcussen, 2020)

The cargo-owners will take the vessel on a long-term time charter (TC) contract and hence have responsibility for vessel utilization and fuel cost. It is announced that the cargo-owners can offer a TC contract for up to 20 years for the shipowner that can provide the best solution for a zero-emission vessel. (DNV GL, 2020b) By offering this they will give the shipowner a predictable revenue for the coming years and allow for organizing the relevant fuel infrastructure. The TC rate is planned to be adjusted according to inflation from year 1, not according to the general market situation. Parallel with the announcement of the above-mentioned contract, the cargo owners have issued a Request for Interest for fuel producers/suppliers to ensure the required fuel supply. The goal is to establish a fuel infrastructure for zero-emission fuel for the vessel that win the contract. If the vessel winning the contract will be sailing on hydrogen, it is a requirement that the production of hydrogen is according to blue or green hydrogen (Felleskjøpet Agri SA; HeidelbergCement Norway AS, 2020).

To be considered for the contract, shipowners must present a vessel that emit no GHGs during operation. The ship should be of about 5000 DWT, have minimum 6000 cubic meter(cbm) cargo hold capacity, have an electric excavator for discharging, be able to connect to shore power and have a range of minimum 500 nautical miles(nm) in normal weather conditions.

Concept vessel

A zero-emission vessel has been designed by Vard Engineering Brevik AS, see picture below.

Figure 2 – Vard ZeroCoaster, Illustration: Vard Engineering Brevik

The vessel is designed to be highly energy efficient. Because of high fuel cost, poor volumetric properties of zero-emission fuels and high cost of energy converter systems, this is considered key to succeed with zero-emission vessels. Several optimizing features have been added to the vessel to improve the efficiency. As illustrated on the picture, the vessel is fitted with a Flettner-rotor, but it is unlikely that the vessel will have this feature due to challenges with placement of the rotor. (Buskop & Vistad, 2020)

The ship is designed to have three 40 feet containers placed on the aft part of the vessel. The idea is that two of these containers will serve as fuel storage, while the last one will be fitted with an energy converter, for instance fuel cells for hydrogen. A standardized interface between the container with the energy converter and the propulsion systems will allow the shipowner to choose what type of fuel and energy converter to rely on. In addition to the containers placed on deck, a battery package of approximately 2 mWh is planned to be installed. (Buskop & Vistad, 2020) As the vessel is designed for a standardized interface for the energy converter, and the fuel storage will be in containers on deck, the vessel can in theory sail on whatever fuel is preferred by the shipowner. Liquefied hydrogen, compressed hydrogen, ammonia, battery, and diesel are all possible options for a shipowner (Buskop & Vistad, 2020). The constraint is related to the technology for utilizing and storing different fuels, range limitations and fuel availability. All relevant specifications for the vessel are presented in table 4. The vessel is still on a concept stage; hence these are indicative figures.

ZeroCoaster					
Dimensions				Speed in knots	mWh to propeller per 24 hrs
Lenght	90	m		7	10,0
Beam	15	m		8	12,0
Draft	6,5	m		9	14,7
Deadweight	5000	dwt		10	18,0
Cargo hold capacity	6000	cbm		11	21,1
Deadweight carrying capacity	4750	mt		12	25,4

Table 6 - ZeroCoaster facts (Buskop & Vistad, 2020)

5. Analysis, Results and Discussion

5.1 Is it technically possible to build and operate a hydrogen-powered short-sea vessel today?

Technical challenges related to building a hydrogen-powered short-sea vessel

A hydrogen-powered short-sea vessel mainly differs from a conventional vessel in terms of the fuel it uses and the energy converter system. Even though there are to be made energy efficiency measures to the hull of a newbuilt zero-emission vessel, ship designers conclude that the hull itself will be rather uncomplicated to build. (Buskop & Vistad, 2020)

The concept vessel will require a fuel cell system of 1600 kW. Proton Exchange Membrane Fuel Cell (PEMFC) has successfully been tested in ships (Tronstad, et al., 2017), but in a smaller scale than what will be required for the concept vessel. At present time there are therefore uncertainties related to fuel cell systems of such size for application in vessels.

LH_2 must be kept at - 253°C to remain liquid and there is little experience with storage of LH_2 on board vessels.

There is no regulatory framework for the design and approval of hydrogen-powered vessels. This creates challenges related to approval of vessel design and building the vessel.

Despite the technical challenges and related regulatory challenges, there are several pilot projects in progress which are expected to lower these barriers and increase the commercial maturity. Examples of such pilot projects are the Norwegian ferry company Norled who will be running two ferries on hydrogen, one of them on 50% CH_2 and the other one exclusively on LH_2 (Norled, 2019). End of October this year Wilhelmsen announced that they have initiated a project to build a zero-emission ro-ro vessel called “Topeka”. The vessel will sail on LH_2 and is expected to be in operation in 2024. The vessel is designed for a 3 mW PEMFC in combination with 1000 kWh battery capacity, which is expected to enable a sailing range of approximately 400 nautical miles(nm) (Wilh. Wilhelmsen, 2020).

Ship designers are also of the opinion that with increasing focus and investments, the mentioned barriers will be lowered and allow to build a hydrogen-powered vessel suitable for the short-sea sector within the next 2 years (Buskop & Vistad, 2020).

Operational challenges

The use of hydrogen as a marine fuel reduces the flexibility of a vessel. For the concept vessel, with a speed of 8 knots, a range of 650 nm is expected for LH_2, while only approximately 300 nm would be possible on CH_2 (Buskop & Vistad, 2020). A vessel of similar size sailing on fossil fuels normally has a range of more than 5000 nm[7]. Hence a vessel sailing on LH_2 will be able to sail less than 13% of the distance compared to a fossil fueled vessel. The range restriction of a LH_2 fueled vessel results in two operational challenges. Firstly, the vessel will be unable to trade on many of the common trading routes, for instance East Coast UK to North Spain, Lower Baltic to Amsterdam-Rotterdam-Antwerp-Gent (ARAG), UK/ARAG to/from West Mediterranean and Northern Norway to ARAG. The mentioned trading routes have either close to 650 nm sailing distance or more. Hence the vessel will be highly dependent on available fuel infrastructure in every port it calls. Currently there are no established infrastructure for bunkering of LH_2 as a fuel for vessels. There is a general lack of infrastructure and it is not commonly handled in ports (Clarksons Research, 2020).

With the mentioned range restrictions and lack of bunkering infrastructure, it is considered unrealistic to trade a hydrogen-powered vessel in the short-sea spot market or on contracts over the most common short sea trading routs. This means that today the concept vessel is only possible to operate under conditions as presented in the case study, with opposite cargo flows between fixed ports, short distances, and a long-term contract.

Opposite cargo flows over relative short distances, give a shipowner a predictable sailing pattern, where one knows the maximum distance required to sail. In addition, one can plan the fuel infrastructure, as the vessel will be sailing on a fixed route for several years. However, a vessel is built to last for at least 25 years, and vessels in this segment even longer. To invest in a vessel with such range limitations one should, from a shipowner's perspective, have a long-term contract to reduce the risk of owning a vessel that can only trade on a fraction of the cargoes in the market. HC and FK have also taken this into account and are offering a contract of up to 20 years. This will ensure the shipowner a predictable revenue for the vessel.

[7] IMO 9250426 & IMO 9250438 (130 mt bunker capacity or more/6,5 mt consumption per day)*(24 hours*12 knots)= 5760 nm

While HC and FK have lowered several of the major logistical barriers related to investment in zero-emission vessels, it is unlikely that European cargo-owners and charterers in general are able or willing to do the same. The survey conducted in relation to this paper confirm this. Only 25% of the respondents confirmed that they can offer contracts of 10 years or more to stimulate shipowners to invest in low/zero-emission vessels. A recent report by Fjose et al., (2020) support these findings. They find that shipowners in the short-sea sector find it challenging to obtain long-term contracts. In a 10-year perspective cargo flows may change, and commodities used in different industries may change. Hence for a cargo-owner to commit for a contract of such length is related to risk.

Several projects are in place to improve the LH_2 infrastructure. Norway is one of the countries taking a leading role in establishing hydrogen production and infrastructure. The mentioned zero-emission ro-ro vessel, planned built by Wilhelmsen, will in addition to transporting cargo also transport containerized LH_2 to bunkering hubs along the west coast of Norway (Wilh. Wilhelmsen, 2020). Another project worth mentioning is the planned production of blue hydrogen at CCB Energy Park at the west coast of Norway (Zegpower, 2019). For the case study, the cargo-owners also have the goal to establish a fuel infrastructure for the vessel that wins the contract. (Felleskjøpet Agri SA; HeidelbergCement Norway AS, 2020). For Europe in general there are several plans for establishing hydrogen infrastructure. One of the major hubs for shipping, the Port of Rotterdam, is aiming to become a hydrogen hub (Port of Rotterdam, 2020).

To sum up, from a technical viewpoint it is considered challenging to build a hydrogen-powered short-sea vessel today. Looking a few years ahead, given the substantial research and number of pilot projects that have been initiated it is likely that the technical and regulatory barriers will be lowered. From an operational viewpoint it is, for the case study, possible to operate such vessel. For the short-sea market in general it is unrealistic to operate such vessel today. This sum-up is also in line with IMOs fourth GHG study, where they define the maturity of hydrogen as a marine fuel to be “evolving” (Faber, et al., 2020).

5.2 Is it environmentally friendly?

During use in fuel cells, hydrogen do not emit any GHGs. However, to produce hydrogen one needs a primary source of energy. To determine whether hydrogen, and in this case LH_2, is an environmentally friendly marine fuel, one needs to look at the whole supply chain from primary energy source to consumption of the final energy carrier. This is also known as well-to-propeller (WTP) emissions, and the argument is supported by the Council of the European Union (2020). To investigate the WTP emissions, one combine what is commonly referred to as well-to-tank (WTT) and tank-to-propeller (TTP) emissions. Most studies identified during the work with this paper focus on the emissions on a WTP perspective *per energy unite of fuel*. However, stopping there does not give the full answer. As a fuel cell using hydrogen and a combustion engine using fossil fuels have different energy efficiency it is argued that one should focus on the emissions on a WTP perspective *per energy unit delivered to shaft*. By doing this one will get the full picture. Figure 3 illustrate the average gram CO_2eq emission per kWh delivered to shaft for LH_2, MDO and MGO based on the literature presented in chapter 3[8]. It also presents the yearly tonnes CO_2eq emission related to the case study.

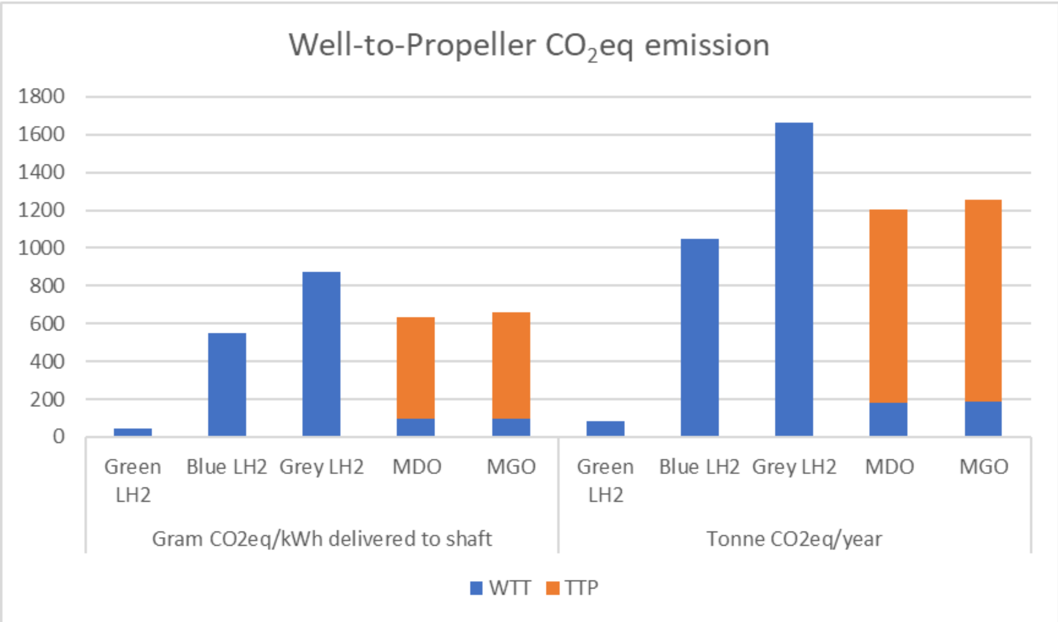


Figure 3: WTP CO_2eq emission

[8] See table 3 for detailed figures related to each study presented in the literature review.

The average emission from the different fuels display some interesting results. In fact, grey LH_2 is emitting 37.6% more than MDO and 32.6% more than MGO, measured in gram CO_2eq/kWh delivered to shaft on a WTP basis. However, both blue and green LH_2 emit less than MDO and MGO, measured in gram CO_2eq/kWh delivered to shaft on a WTP basis. Hence, LH_2 *can* be an environmentally friendly marine fuel, also when considering the emissions on a WTP basis. 2, 96% of the hydrogen production today is classified as grey hydrogen, and *all* the LH_2 production in Europe today is classified as grey hydrogen, see chapter 2. This means that a vessel propelled by $LH_{2,}$ sailing in Europe today would contribute to higher emissions than fossil fuels, measured in gram CO_2eq/kWh delivered to shaft on a WTP basis. This fact is important to emphasize in the discussion of zero-emission fuels. As LH_2 does not emit any GHGs during use in fuel cells it will save the local area where the vessel is operating for significant emissions relative to a vessel sailing on MDO or MGO. However, it would make the emission of GHGs to the global anthropogenic emissions greater, which arguably is the relevant measure to stop climate change and achieve the goals of the Paris Agreement. However, with multiple ongoing projects for green and blue hydrogen production the result will be different for the future. And in contrast to fossil fuels, one has the *ability* to produce LH_2 exclusively by zero-emission energy resources.

Related to the case study, the yearly emissions caused by the concept vessel trading on the announced contract are calculated. The vessel is planned to perform one roundtrip per week, equivalent to a total of 615 nm of sailing for the default route. Assuming the vessel operate during all weeks of a year, this will yield 52 roundtrips equivalent to 31.980 nm. With a speed of 7 knots, the vessel will manage to perform one roundtrip per week including port time. During one year of operation the vessel will then be at sea for 190 days with a daily energy delivery to shaft of 10 mWh. The yearly emissions related to the use of grey-, blue- and green LH_2, MDO and MGO are presented in figure 3 on the previous page.

For the case study the relevant fuels are blue- and green LH_2, as the cargo-owners have a goal to establish a local production of one of these types of fuel. Hence, as figure 3 illustrate, the yearly emissions will be reduced if a hydrogen-powered vessel win the contract. For blue LH_2 the reduction potential is 16.3%, measured based on WTP, relative to MGO. For green LH_2 the reduction potential is 93.2%, and potentially even more with local production, measured on WTP, relative to MGO. Hence for the case study, a hydrogen-powered vessel will be more environmentally friendly than a fossil fueled vessel in a WTP perspective.

5.3 Is it financially viable?

The case study, presented in chapter 5, is the foundation for the calculations. The investment horizon is set to 20 years, equal to the longest period the cargo-owners are willing to commit for a contract. Two different investment alternatives are outlined, one based on investment support for all the additional costs related to building a hydrogen-powered vessel and one without investment support. Three main calculations are performed. First the required time charter (TC) rate to cover OPEX and capital cost is calculated. Thereafter the achievable TC rate is calculated using the time charter equivalent (TCE) equation. At the end, results from the discounted cashflow analysis are presented.

The required time charter rate

The cost of the concept vessel has not been possible to obtain from ship designers. No comparable vessel is ever built, hence there are no historical database to find newbuilding costs. However, DNV GL has given an estimated building cost for a vessel with similar features as the concept vessel, sailing on hydrogen with fuel cells. The building cost is derived by DNV GL in connection with the contract presented in chapter 4. A fossil fuelled vessel of this type typically cost 90-100 million NOK to build in Asia and 100-120 million NOK to build in Europe (E. Dale, personal communication, September 28, 2020). For a vessel built to sail on hydrogen there will be additional costs related to fuel cells, storage tanks for hydrogen, piping system, batteries, and electrical systems. The additional building cost is estimated to be 50-60 million NOK. (E. Dale, personal communication, September 28, 2020) Due to the spread in estimates, a default price is set to EUR 15 million and sensitivity analysis from EUR 13 to EUR 17 million has been performed.

To accelerate and enable investments in new and environmentally friendly technology, several public support schemes, such as Enova and Horizon 2020, has been established in recent years. Enova is a governmental enterprise owned by the Norwegian Ministry of Climate and Environment, with the goal to reduce GHG emissions trough support of new technology (ENOVA, 2020b). Horizon 2020 is a research and innovation program launched by EU with EUR 77 billion in funding, aiming to contribute to smart, inclusive, and sustainable economic growth (European Commission, 2020). The exact investment support from different schemes will be subject to an individual application. However, based on what previous projects have received one can potentially get the additional cost, relative to a fossil fuelled vessel, covered by investment support. This is the assumption used for investment alternative 2. The price for a newbuilt conventional vessel is set to EUR 10 million, in line with what MSI estimate for this size of vessel for the coming years (MSI, 2020).

For calculations, the residual value of the vessel after 20 years must be determined. This will be influenced by the quality of maintenance the vessel has had over the lifetime, future potential emission regulations, new technology, and supply and demand in the market. To derive an exact price is close to impossible due to the long-time horizon and the number of unknown and unpredictable factors. Hence the benchmark price of a 20-year-old conventional vessel is used. According to industry reports, the most optimistic price for the coming years is EUR 2.1 million (MSI, 2020). It might be argued that the secondhand value of the vessel shall be lower than for a fossil fueled vessel due to the operational limitations for a hydrogen-powered vessel. However, looking 20 years ahead it is reasonable to assume that technology and infrastructure for alternative fuels have been improved and hence eliminated some the operational challenges.

For fossil fueled vessels of this type and size, shipowners calculate with an OPEX at the start of the vessel's lifetime of EUR 1525 per day (Newshore Invest, 2020). MSI report the average OPEX to be EUR[9] 1780 per day (D. David, personal communication, December 10, 2020). Ship designers argue that the OPEX for a zero-emission vessel with fuel cells will be lower than for a fossil fueled vessel. The argument is that with no combustion engine, there will be no need for a chief engineer and engine maintenance. However, fuel cells also need maintenance and with new technology there will likely be a need for some new competence for the crew. With few vessels currently having this technology, one might expect the cost for crew to go up as they will possess a rare competence. In addition, for the case study, the vessel should ideally have navigators possessing Pilot Exemption Certificate (PEC) allowing the vessel to enter and leave ports without pilot. For the case study, cargo-owners confirm that they would like the navigators to have this as it will save a substantial amount in piloting fees. Navigators with PEC will normally lead to increased crew cost. Maintenance cost for fuel cells is in general lower than for combustion engines. However, it is argued that the service of fuel cells will require special competence with few available service companies, at least for

[9] USD 2100 * 0,8479 = EUR 1780

the first vessels. This will in turn drive the price up for service. Hence it is argued that the total OPEX per day is likely to stay at the same level as for fossil fueled vessels. The default level used for further calculations is therefore sat to EUR 1525 per day, which is at the lower end of OPEX for fossil fueled vessels.

Table 7 summarizes the key input to calculate the required time charter rate for the base case.

	Alternative 1	**Alternative 2**
Vessel type	5000 dwt Self-discharger	5000 dwt Self-discharger
Project duration	20 years	20 years
Fuel	LH_2	LH_2
Fuel cell system	PEMFC	PEMFC
Price of vessel	€ 15 000 000	€ 15 000 000
Eligible to investment support	No	Yes
Investment support	-	€ 5 000 000
Adjusted project cost	-	€ 10 000 000
Residual value end of project	€ 2 100 000	€ 2 100 000

Table 7 – Investment alternative 1 & 2

Results for the minimum required TC rate to cover WACC and OPEX is presented in table 8 and 9 for investment alternative 1 and in table 10 for investment alternative 2. The sensitivity analysis uses 360 days per year to calculate the daily required TC rate. The cost of capital is covered more detailed under the discounted cashflow analysis. Calculations in table 8-10 are based on the assumption that OPEX is constant for the entire lifetime of the project.

		WACC						
		4 %	**5 %**	**6 %**	**7 %**	**8 %**	**9 %**	**10 %**
OPEX	**€ 1 275**	€ 4 676	€ 4 716	€ 4 749	€ 4 776	€ 4 799	€ 4 817	€ 4 832
	€ 1 400	€ 4 801	€ 4 841	€ 4 874	€ 4 901	€ 4 924	€ 4 942	€ 4 957
	€ 1 525	€ 4 926	€ 4 966	€ 4 999	€ 5 026	€ 5 049	€ 5 067	€ 5 082
	€ 1 650	€ 5 051	€ 5 091	€ 5 124	€ 5 151	€ 5 174	€ 5 192	€ 5 207
	€ 1 775	€ 5 176	€ 5 216	€ 5 249	€ 5 276	€ 5 299	€ 5 317	€ 5 332

Table 8 – Required TC rate per day for Investment Alternative 1

		WACC						
		4 %	**5 %**	**6 %**	**7 %**	**8 %**	**9 %**	**10 %**
Price of ship	**€ 13 000 000**	€ 4 441	€ 4 482	€ 4 515	€ 4 542	€ 4 564	€ 4 583	€ 4 598
	€ 14 000 000	€ 4 683	€ 4 724	€ 4 757	€ 4 784	€ 4 806	€ 4 825	€ 4 840
	€ 15 000 000	€ 4 926	€ 4 966	€ 4 999	€ 5 026	€ 5 049	€ 5 067	€ 5 082
	€ 16 000 000	€ 5 168	€ 5 208	€ 5 241	€ 5 268	€ 5 291	€ 5 309	€ 5 324
	€ 17 000 000	€ 5 410	€ 5 450	€ 5 483	€ 5 511	€ 5 533	€ 5 551	€ 5 566

Table 9: Required TC rate per day for Investment Alternative 1 for different vessel prices. Based on OPEX of EUR 1525 per day.

		WACC						
		4 %	5 %	6 %	7 %	8 %	9 %	10 %
OPEX	€ 1 275	€ 3 465	€ 3 505	€ 3 538	€ 3 565	€ 3 588	€ 3 606	€ 3 621
	€ 1 400	€ 3 590	€ 3 630	€ 3 663	€ 3 690	€ 3 713	€ 3 731	€ 3 746
	€ 1 525	€ 3 715	€ 3 755	€ 3 788	€ 3 815	€ 3 838	€ 3 856	€ 3 871
	€ 1 650	€ 3 840	€ 3 880	€ 3 913	€ 3 940	€ 3 963	€ 3 981	€ 3 996
	€ 1 775	€ 3 965	€ 4 005	€ 4 038	€ 4 065	€ 4 088	€ 4 106	€ 4 121

Table 10 – Required TC rate per day for Investment Alternative 2

An interesting question is whether any of these TC rates are achievable for the contract in the case study and for the short-sea market in general.

The achievable time charter rate

Relevant factors to calculate the achievable TC rate are discussed and defined in the following sections, before the achievable TC rates for different scenarios are presented in table 11.

The cargo-owners in the case study are not willing to *increase* the total transportation cost from the level they have today. Hence there will be no premium on the freight rate, relative to the todays level, for a zero-emission vessel. However, by combining cargo flows they could potentially lower their total transportation cost by using a fossil fueled vessel. Therefore, it can be argued that they are willing to take some extra cost for realizing a zero-emission vessel. The highest level of freight rate per tonne of cargo that is realistic for the default route is equivalent to EUR 5.1 per tonne for gravel (Marcussen, 2020). For grain cargoes the freight rate per tonne will depend on the type of grain due to different stowage factors. However, per volume unit different types of grain cargoes shall give the approximate same payment. Oat is used for calculations. From the interview with FK it was only possible to obtain an approximate level of the freight rate shipowners can expect for the default route. However, NOK 60 or more per tonne of oat was indicated. The rate used for calculations is set to EUR 6,4 per tonne, which will give approximately the same TCE as a voyage with gravel. Normally, a commission is deducted from the freight, either by a broker or by the cargo-owner. For this contract there will be no commission, according to cargo-owners.

The concept vessel will have a cargo capacity of roughly 4750 tonnes and 6000 cbm (Buskop & Vistad, 2020). This means the vessel will be able to carry 4750 tonnes of gravel and 3780 tonnes[10] of oat.

The port cost for the case study is expected to be very low. It is assumed that the vessel will be able to enter and leave port without pilot, subject to navigators with PEC. As the vessel will sail on fixed routes, no agent is planned to be used in ports. The remaining port cost will then be related to quay fee, International Ship and Port Security (ISPS) fee and terminal costs. For this type and size of vessel the average total cost for these elements is estimated to be roughly EUR[11] 2300 per port call for private ports (Dale, et al., 2018). In addition to the normal port cost, there will also be a cost related to electricity for charging of batteries and operating the electric excavator for discharging. The cost of shore power is set to EUR 0,26/kWh (Plug, 2020). The excavator is expected to be approximately 400 kW.

The daily fuel consumption is dependent on the sailing speed. The optimal speed is determined by multiple factors, such as the price of fuel, the freight rate, the sailing distance, and the optimal arrival time to next port. The price of fuel will vary based on place of delivery, for delivery in Southern Norway the latest available reported price for LH_2 was EUR 15 per kg (Hirth, et al., 2019). However, the price is expected to come down to EUR 3,5-7,5 within few years. Much of the cost today is related to transportation of the fuel, hence with local production of LH_2 one can assume the price to go down.

The theoretical optimal speed, for the above-mentioned freight rates and fuel cost, is calculated and presented in figure 6. However, this does not account for an optimal arrival time or the fact that the vessel will be sailing on weekly roundtrips and should adjust according to this. The battery capacity is assumed used for hotel power, maintaining speed in case bad weather and bow thruster in and out of port. For TCE calculations the battery is charged to full capacity two times per roundtrip.

---

[10] 6000 cbm * 0,63 cbm/mt = 3780 mt

[11] NOK 24 800 * 0,0927

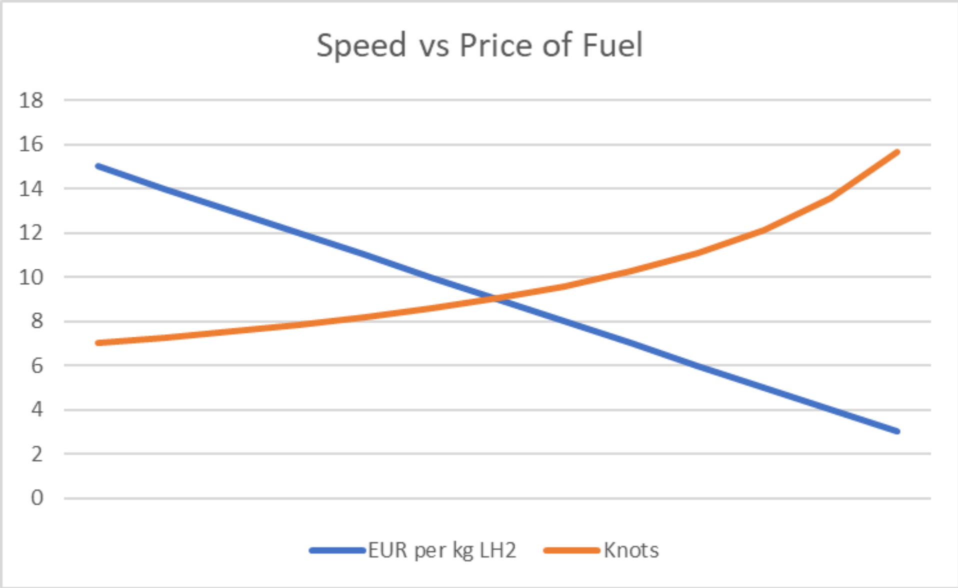


Figure 4: Theoretical optimal speed for different levels of fuel cost, based on constant freight rate and constant efficiency of 50% for fuel cells

Because the vessel will be sailing on weekly roundtrips, each voyage for the two cargo-owners cannot be analyzed separately. One needs to analyze the optimal sailing pattern for the whole weekly roundtrip. For the case study, the optimal sailing pattern will be to load grain on a Monday and complete discharging in Oslo during the weekend. By doing this, the vessel will have sufficient time to prepare the cargo hold for loading grain again on the next Monday. The ballast distance between Oslo and Kambo is too short to manage washing and drying of cargo holds before arrival in Kambo for loading of grain. In addition, one should expect the vessel to need painting in the cargo holds at certain intervals. Hence it is favorable to have some extra time before loading grain. With a fuel price of EUR 15/kg LH_2, the energy consumption must be low to reduce the total fuel cost. At 7 knots the vessel will manage to perform a weekly roundtrip according to the above plan and this is the speed with the lowest fuel cost per nautical mile.

Three different scenarios are outlined and corresponding achievable TCE rates for different fuel prices are presented in table 11. Scenario 1 is considered the realistic, the rest is hypothetic scenarios to illustrate the impact of change of sailing speed and time used. Calculation for a vessel sailing on MGO has also been done to put the economical challenge with the LH_2 price in context. The calculations for MGO are based on a typical vessel sailing in the market today, hence less energy efficient than the concept vessel[12].

Scenario 1: One roundtrip per week at 7 knots sailing speed.

Scenario 2: One roundtrip per week at 12 knots sailing speed.

Scenario 3: Sailing at 12 knots, performing more than one roundtrip per week and assuming all ports work 24/7. Average estimated total port time per roundtrip for this scenario is set to 2.75 days.

Scenario	Fuel	Fuel price	TCE per day
1	LH_2	EUR 15/kg	EUR 458
1	LH_2	EUR 3.5/kg	EUR 4072
1	MGO	EUR 343/tonne	EUR 4343
2	LH_2	EUR 15/kg	EUR 1810
2	LH_2	EUR 3.5/kg	EUR 3543
2	MGO	EUR 343/tonne	EUR 4474
3	LH_2	EUR 15/kg	EUR 2594
3	LH_2	EUR 3.5/kg	EUR 5077
3	MGO	EUR 343/tonne	EUR 6336

Table 11: TCE for different scenarios. Red text color symbolizes a negative TCE.

The results from the required freight rate analysis and the achievable time charter analysis illustrates the economical challenge for a hydrogen-powered vessel. With an LH_2 price of EUR 15/kg it is not possible to obtain a TC rate that covers the minimum cost of running a vessel on a day-to-day basis, neither for investment alternative number 1 nor investment alternative 2. For the scenario number 1, with an LH_2 price of EUR 3,5/kg, the TCE will be high enough to cover the minimum cost of running the vessel for investment alternative number 2, but not for investment alternative 1.

[12] Speed and consumption for 12 knots used from two vessels of similar type and size: IMO 9250426 & IMO 9250438. 12 knots = 6.5 mt MGO per 24 hrs. *Assumed* consumption at 7 knots = 4,5 mt MGO per 24 hrs. One deviation to Skaw for bunkering every fourth roundtrip (66 nm extra on the way from Tau to Oslo) is included. Deviation to Skaw in order to avoid mineral oil tax in Norway. Bunker price Skaw of EUR 343 per mt is used for calculations (retrieved 06/12/2020 from https://www.petrolbunkering.com/price-information/). NOx fee of about EUR 1040 per roundtrip.

An interesting question is whether it is possible to obtain the required freight rate to run such vessel in the general market, not related to the contract in the case study. MSI report that vessels of similar size as the concept vessel is expected to achieve a TCE of EUR 3040 per day to EUR 3230 per day for the next four years (MSI, 2020). A TCE per day on these levels is not enough to cover the minimum cost of running the concept vessel investigated in this paper. In addition, the TCE rate is based on vessels sailing on MGO. With the use of LH_2, the fuel cost will increase and hence the achievable TCE rate be reduced. Given the current market situation and fuel regulations, the only way to achieve the required freight rate in the general market is that cargo-owners and charterers are willing to pay a premium for zero-emission vessels. The survey conducted in relation to this paper show that only 1 of the 12 respondents have the *ability* to pay a higher freight rate in return for low/zero-emission vessels. These results are somewhat supported by a report made by Fjose et al., (2020). They find that cargo-owners care most about price when they buy transport services. In addition, they find that the shipowner's general impression is that cargo owners are not willing to pay more for vessels that have lower emissions.

Discounted cashflow analysis

Important factors to consider for the discounted cashflow (DCF) analysis are discussed and defined in the following sections before the results are presented in table 14-15 and 17-19.

The TC rate for the case study is said to be constant based on year 1, only adjusted for inflation (Marcussen, 2020). Hence it will not follow the general adjustment for supply and demand in the market for the coming years. The OPEX is estimated to increase with 1.5% per year. When a vessel become older, the OPEX normally increase. For calculations all the figures are kept at nominal values. The discounted cashflow analysis assumes that the full payment for the vessel is done in year 0 and that the vessel is delivered the first day in year number 1.

The number of operational days (days with TC earnings and OPEX) is set to 360 per year for years without periodical maintenance. Hence allowing for some days with off-hire each year, in line with normal practice. For years with periodical maintenance (dry-dock, repairs, special-, intermediate- and Class renewal survey), the number of operational days is set based on information gathered trough primary and secondary data. See table 12 for detailed information.

A hydrogen-powered vessel with fuel cells and batteries will have somewhat different cost structure for periodical maintenance compared to a fossil fueled vessel with combustion engine. Instead of engine maintenance and repair, a vessel with fuel cells and batteries will have to renew the fuel cell system and batteries at certain intervals. To derive a realistic cost for periodical maintenance, analysis of multiple dry-dock operations for several fossil fueled vessels, of similar size and type, at different intervals have been conducted. The cost for engine maintenance/spare parts have been excluded to arrive at a realistic dry-docking cost for the hydrogen-powered vessel. Thereafter based on the expected lifetime of fuel cells and batteries, presented in chapter 2, and the operational profile of the vessel under the contract in the case study, the intervals for renewal of these are calculated. The refitting cost of fuel cells and batteries are based on primary and secondary data. Table 12 summarize important information for periodical maintenance together with intervals and cost for renewal of fuel cells and batteries.

Year	Description	Operational days	Cost periodical maintenance	Cost renewal of FC and Batteries	System size
3	Periodical maintenance	355	EUR 100 000		
5	Periodical maintenance	350	EUR 150 000		
8	Periodical maintenance & renewal of fuel cells	355	EUR 100 000	800 EUR/kW	1600 kW
10	Periodical maintenance & renewal of batteries	350	EUR 150 000	339 EUR/kWh	2000 kWh
13	Periodical maintenance	355	EUR 200 000		
15	Periodical maintenance	350	EUR 200 000		
16	Renewal of fuel cells	360	-	400 EUR/kW	1600 kW
18	Periodical maintenance	355	EUR 200 000		
20	Periodical maintenance & renewal of batteries	345	EUR 350 000	339 EUR/kWh	2000 kWh

Table 11: Schedule for periodical maintenance and renewal of fuel cells[13] & batteries[14]

The realistic and relevant financing option and terms are important to establish to build a realistic DCF. From information gathered through interviews with financial institutions and theory, a traditional asset backed loan, combined with equity from the shipowner, is deemed most realistic and suitable financing option for this type of ship. For the case study, the long-

[13] Lifetime of fuel cells is set to 35 000 hours according to most optimistic expected lifetime. Cost for renewal of fuel cells in year 8 is set according to high range of future expected price. For year 16 it is set according to low range for future expected price. These figures are accounted for in chapter 2.

[14] Cost and lifetime for batteries is collected from Corvus Energy. Lifetime expected to be 10 years. Renewal cost in the future is expected to be USD 400/kWh. (H. Hauso, Personal communication, September 30, 2020). USD 400*0.8479= EUR 339

term contract will provide a predictable and steady revenue for the vessel, which makes asset-backed bank debt a suitable financing option according to Kavussanos & Visvikis (2016) and interviews.

Alternative financing options that could be suggested to raise the required capital is the bond market with "green bonds", Export Credit Agencies (ECA) or shared investments. "Green bonds" have become more widespread the last years with increasing focus in "green" investments. A "green bond" is however deemed unrealistic for such project. The companies in the short-sea sector are in general small private owned companies and the cost of a short-sea vessel is low, relative to larger vessels in other segments. Small companies will typically have difficulties raising money in the bond market and the size of the bond should typically be above 40-50 million Euro (Kavussanos & Visvikis, 2016). Additionally, it is worth mentioning that "green bonds" only provide a marginal discount of just a few basis points below traditional bonds (Banks, 2020). The use of ECA could also be suggested. However, due to the relative low amount of capital needed to finance such project and the fact that export credit agencies normally have restrictions on the repayment profile of a loan, it is deemed unsuitable for such project. Normally the repayment profile is maximum 12 years for export credit financing (Birkeland, 2020). Shared investments are a financing alternative that has been suggested for such project analysed in this paper. Through the work with this paper I have been in contact with a multinational power company that seeks to make "green" investments. They have lined out an alternative owner and investment strategy for such a project. The idea is that they will invest, own, and maintain the new technology and propulsion system, while the shipowner will invest in and own the hull. Further on, the shipowner must rent the technology and propulsion system on board the vessel. Intuitively this seems like a good solution, as the total capital required to be raised by each party will be lower and the risk will be distributed on two companies. This implies that the project will be easier to realize. However, for the project to be more financially viable, the capital cost and payback time for the technology owner must be lower than for the shipowner. Trough the interview with this company it was clear that they did not expect to have cheaper capital cost than what a shipowner could expect. Hence with such financing structure one would need the same amount of revenue to serve the project. It is an interesting suggestion for alternative method of financing, but in terms of making such project more financially viable it is deemed irrelevant.

Based on the above discussion, the terms for an asset-backed loan must be established. General guidelines for realistic terms have been collected through interviews with financial institutions. If the shipowner has a long-term contract with strong counterparties, one could be able to finance such project with up to 70-80% debt. This is also in line with theory (Kavussanos & Visvikis, 2016). To exploit leverage effect on equity return one would, looking at that isolated, want as high leverage as possible. However, this will increase the interest and debt payments and lower the break-even level. For a zero-emission vessel the payback time can potentially be stretched up to 17 years, which is longer than what normally can be achieved for fossil fuelled vessels (Banks, 2020). With regards to interest rate, this will likely be in line with the general terms for the market. Banks do currently not have access to cheaper capital for "green" investments, hence there is no discount to pass on to the borrower. Therefore, the achievable interest rate for the debt for such project will be approximately 3% p.a. This is in line with theory and banks indicate that this is a realistic level for such project. A cost of debt of 3% p.a. is also in line with what companies in this sector report (Wilson ASA, 2020).

To determine the cost of equity is more complex. Normally one can use the capital asset pricing model (CAPM) to derive the cost of equity for companies. However, related to this paper there are no specific company to determine the cost of equity for and there is no available nor relevant sector equity beta to use. Due to the uncertainties regarding cost of equity, the default weighted average cost of capital (WACC) is set to 5.9%, which is in line with the average industry WACC for dry bulk shipping (Enova, 2020). In simple terms one can argue that the cost of capital should be higher due to uncertainties related to new technology and limited flexibility of the vessel. However, on the other hand, one can argue that the cost of capital should be lower because a hydrogen-powered vessel will eliminate the risk of potential future environmental regulations. To compensate for the uncertainties related to the cost of equity and hence the WACC, sensitivity analysis for WACC in the interval 4%-10% is performed. However, 5.9% is used as the default WACC in calculations.

The estimated cashflows are discounted by the WACC-pre tax rate, in line with the industry average WACC, due to the tonnage tax system. In shipping, tax and tax benefits of debt are normally excluded from calculations due to the tonnage tax system (Kavussanos & Visvikis, 2016). The yearly tonnage tax is not included in the cashflow as this is only a marginal amount.

For the ship in this paper, the tonnage tax would be EUR 1830 per year[15] if under the Norwegian Tonnage Tax regime.

The following sections outline the results from the DCF analysis for the case study, first for investment alternative number 1, thereafter for investment alternative 2. The TCE rates calculated for different scenarios and LH_2 price levels under the achievable TC rate are used for the DCF analysis.

Investment Alternative 1 – No Investment Support

Newbuilding price	€ 15 000 000
Residual value of vessel end of year 20	€ 2 100 000
OPEX per day in year 1	€ 1 525
OPEX growth per year	1,5 %
Debt of newbuilding price	70 %
Tenor in years	17
Repayment profile	Linear
Interest on debt p.a.	3,0 %
WACC	5,9 %

Table 12 - Base case Investment Alternative 1

The level of the achievable TC rate will depend greatly on the price of LH_2. For freight rate scenario 1, with an LH_2 price of EUR 15/kg, the vessel will only be able to make EUR 458 per day. This is not enough to make the investment financially viable as it does not even cover the OPEX. This TC rate would give a negative net present value (NPV) of EUR 19,99 million for the base case. Hence no further analysis is performed for this freight level.

Taking an optimistic view for freight rate scenario 1, with an LH_2 price of EUR 3.5/kg, the achievable TC rate would be EUR 4072 per day. This will not be enough to cover the minimum cost of running the vessel for any of the levels of OPEX and WACC. With the absolute most optimistic price of the vessel (EUR 13m), WACC (4%) and OPEX (EUR 1275) one would need a TC rate of EUR 4191 per day to cover the *minimum* cost of running the vessel on a day-to-day basis.

[15] Calculation based on updated rules from 2018 (KPMG, 2017) and vessel size up to 3000 net tonnage.

With reference to freight rate scenario 3, with an LH_2 price of EUR 3.5/kg, one can achieve a TC rate of EUR 5077 per day. This scenario is considered somewhat unrealistic, however even with this scenario the project will not be profitable for the base case. Using the input from the base case in table 13, one would need a daily TC rate of EUR 5301 per day to get a NPV of EUR 0. A sensitivity analysis of the NPV for changes in TC rate per day and OPEX per day is presented in table 14 below.

		TC Rate Per Day				
		€ 4 750	€ 5 000	€ 5 250	€ 5 500	€ 5 750
	€ 1 225	-€ 882 570	€ 149 738	€ 1 182 047	€ 2 214 355	€ 3 246 663
	€ 1 375	-€ 1 578 782	-€ 546 473	€ 485 835	€ 1 518 143	€ 2 550 452
OPEX Year 1	€ 1 525	-€ 2 274 994	-€ 1 242 685	-€ 210 377	€ 821 932	€ 1 854 240
	€ 1 675	-€ 2 971 205	-€ 1 938 897	-€ 906 588	€ 125 720	€ 1 158 029
	€ 1 825	-€ 3 667 417	-€ 2 635 108	-€ 1 602 800	-€ 570 491	€ 461 817

Table 13: NPV sensitivity for changes in OPEX and TC rate

Due to the uncertainty of the exact price of such vessel, a sensitivity analysis has been performed for different newbuilding prices and TC rates. The results are presented in table 15.

		TC Rate Per Day				
		€ 4 750	€ 5 000	€ 5 250	€ 5 500	€ 5 750
	€ 13 000 000	-€ 535 958	€ 496 351	€ 1 528 659	€ 2 560 968	€ 3 593 276
	€ 14 000 000	-€ 1 405 476	-€ 373 167	€ 659 141	€ 1 691 450	€ 2 723 758
NB Price	€ 15 000 000	-€ 2 274 994	-€ 1 242 685	-€ 210 377	€ 821 932	€ 1 854 240
	€ 16 000 000	-€ 3 144 512	-€ 2 112 203	-€ 1 079 895	-€ 47 586	€ 984 722
	€ 17 000 000	-€ 4 014 030	-€ 2 981 721	-€ 1 949 413	-€ 917 104	€ 115 204

Table 14: NPV sensitivity for changes in newbuilding (NB) price and TC rate

Investment Alternative 2 – Investment Support

Newbuilding price	€ 15 000 000
Investment support	€ 5 000 000
Adjusted project cost	€ 10 000 000
Residual value of vessel end of year 20	€ 2 100 000
OPEX per day in year 1	€ 1 525
OPEX growth per year	1,5 %
Debt of adjusted project cost	80 %
Tenor in years	17
Repayment profile	Linear
Interest on debt p.a.	3 %
WACC	5,9 %

Table 16: Base case Investment Alternative 2

For investment alternative 2 the capital structure is changed. The adjusted project cost is EUR 10 million. A debt of 70% on the total project cost would be equivalent to 105% of the adjusted project cost. Hence the shipowner would not put any of its own equity into the project. Based on interviews with banks this is a somewhat unrealistic alternative. A bank would require the shipowner to have “skin in the game”. Hence a realistic debt level would be up to 80% of the adjusted project cost. This debt level is based on the information from interviews and analysis of the optimal debt level. The same discount rate is used for the base case for this investment alternative, however sensitivity analysis for different discount rates has been performed. As this alternative assume that all extra cost related to building a hydrogen-powered vessel is received by investment support, it is not performed any analysis for different price levels of a newbuilt vessel. All calculations in this section are therefore based on a newbuilding cost of EUR 10 million, in line with brokering reports for this type of fossil fuelled newbuilt vessel.

A TC rate of EUR 458 per day would give a negative NPV of EUR 15,39 million, given the input in table 16. No further analysis is performed at these levels of TC rate.

Taking an optimistic view for freight rate scenario 1, with an LH_2 price of EUR 3.5/kg, the achievable TC rate would be EUR 4072 per day. As shown in table 10 for the required freight rate, this will be enough to cover the cost of capital and OPEX for close to all levels analysed. However, the cost for dry docking, renewal of fuel cells and batteries should also be accounted for when analysing if such investment can be financially viable. Performing the DCF analysis based on a TC rate of 4072 per day and the input from table 16, give a negative NPV of EUR 474 897. Hence the project will not be financially viable at this level of TC rate. Assuming the input from table 16 is fixed, one would need a daily TC rate of EUR 4187 per day to get a NPV of EUR 0. A sensitivity analysis of the NPV for changes in TC rate per day and OPEX per day is presented in table 17 below. The input for table 17 is from the base case in table 16.

		TC Rate Per Day					
		€ 3 750	€ 4 000	€ 4 250	€ 4 500	€ 4 750	€ 5 000
	€ 1 225	-€ 412 087	€ 620 221	€ 1 652 530	€ 2 684 838	€ 3 717 147	€ 4 749 455
	€ 1 375	-€ 1 108 299	-€ 75 990	€ 956 318	€ 1 988 627	€ 3 020 935	€ 4 053 243
OPEX YEAR 1	€ 1 525	-€ 1 804 510	-€ 772 202	€ 260 107	€ 1 292 415	€ 2 324 723	€ 3 357 032
	€ 1 675	-€ 2 500 722	-€ 1 468 413	-€ 436 105	€ 596 203	€ 1 628 512	€ 2 660 820
	€ 1 825	-€ 3 196 934	-€ 2 164 625	-€ 1 132 317	-€ 100 008	€ 932 300	€ 1 964 609

Table 17: Sensitivity analysis of NPV for changes in OPEX and TC rate

The same type of sensitivity analysis of the NPV is performed for different levels of debt, relative to the adjusted project cost, and TC rates. Input for these calculations is also based on the base case presented in table 16. The results can be found in table 18 below.

		TC Rate Per Day					
		€ 3 750	€ 4 000	€ 4 250	€ 4 500	€ 4 750	€ 5 000
Debt level	60 %	-€ 2 177 316	-€ 1 145 008	-€ 112 699	€ 919 609	€ 1 951 918	€ 2 984 226
	70 %	-€ 1 990 913	-€ 958 605	€ 73 704	€ 1 106 012	€ 2 138 321	€ 3 170 629
	80 %	-€ 1 804 510	-€ 772 202	€ 260 107	€ 1 292 415	€ 2 324 723	€ 3 357 032
	90 %	-€ 1 618 107	-€ 585 799	€ 446 509	€ 1 478 818	€ 2 511 126	€ 3 543 435
	100 %	-€ 1 431 705	-€ 399 396	€ 632 912	€ 1 665 221	€ 2 697 529	€ 3 729 838

Table 18: Sensitivity analysis of NPV for changes in Debt level and TC rate

The same type of sensitivity analysis is performed for the NPV given changes in WACC and TC rate. Input for these calculations is based on the base case presented in table 16.

		TC Rate Per Day					
		€ 3 750	€ 4 000	€ 4 250	€ 4 500	€ 4 750	€ 5 000
WACC	4 %	-€ 1 589 084	-€ 376 191	€ 836 703	€ 2 049 597	€ 3 262 490	€ 4 475 384
	5 %	-€ 1 715 695	-€ 603 313	€ 509 068	€ 1 621 449	€ 2 733 830	€ 3 846 212
	6 %	-€ 1 813 122	-€ 789 163	€ 234 795	€ 1 258 754	€ 2 282 712	€ 3 306 671
	7 %	-€ 1 887 394	-€ 941 497	€ 4 399	€ 950 295	€ 1 896 192	€ 2 842 088
	8 %	-€ 1 943 317	-€ 1 066 576	-€ 189 835	€ 686 906	€ 1 563 647	€ 2 440 389
	9 %	-€ 1 984 728	-€ 1 169 461	-€ 354 193	€ 461 074	€ 1 276 342	€ 2 091 609
	10 %	-€ 2 014 691	-€ 1 254 252	-€ 493 812	€ 266 627	€ 1 027 067	€ 1 787 506

Table 15: Sensitivity analysis of NPV for changes in WACC and TC rate

With the TC rate that is considered realistic for the case study, given a future LH_2 price of EUR 3.5/kg, the project will not be financially viable given the base case.

Discussion

While technical, regulatory, and environmental barriers related to investments in hydrogen-powered vessels are expected to be lowered for the coming years, the main hurdle for the short-sea sector is the economical aspect.

The problem is complex. A hydrogen-powered vessel is expensive, relative to a fossil fuelled vessel. It is less flexible in terms of operational range than a fossil fuelled vessel. The fuel, LH_2 is expensive, relative to fossil fuels. Even at the most optimistic future level of EUR 3,5/kg it will be more expensive than fossil fuels based on today's price and regulations. As the analysis related to the case study shows, optimizing the utilization of a vessel will help to cover some the additional costs. However, keeping freight rates and expenses constant there is a limit to how much a vessel can increase the earning per day by optimized operation. Hence it can be argued that the revenue per tonne of cargo must be increased to make hydrogen-powered vessels financially viable. Without regulation it is naive to think that cargo-owners and charterers in general are *able* or *willing* to pay more for “green” transport. The survey conducted in relation to this paper confirm this. Over 90% of the respondents in the survey confirm that reduction of GHG emissions related to their business is important. Further on, 75% of the respondents say that reduction of GHG emissions related to the vessels they use for short-sea transport is important. However, only 8% (1 respondent) of the respondents has the ability to offer higher freight rates in return for low/zero-emission vessels. The end customer must cover some of the cost. One of the respondent’s in the survey comment that “*Competition needs to be fair, and the only way achieving same is a regulatory effort that affect all market actors in a similar way*”. This is also in line with the result for the last question in the survey where 83% of the respondents ranked regulators (IMO, EU, national states and local authorities) as the most important stakeholders for a shift towards more environmentally friendly vessels and ideally zero-emission vessels.

As fuel costs, for fossil fuelled vessels, in general are passed on to cargo-owners and charterers trough freight rates, a carbon tax for fossil fuelled vessels could help to increase the freight rates and keep it at a high enough level to make zero-emission vessels profitable.

The question is then whether it is likely that regulators will impose environmental regulations on the shipping industry, including the short-sea sector. While emission reducing initiatives have been initiated for the shipping sector in general, their scope generally does not cover the vessels in the short-sea sector. This might be caused by the risk of moving cargo from sea to road, which given today’s transportation alternatives would result in higher GHG emissions. However, road transport has lower barriers for decarbonising their activities. Hence this argument will not be eternally valid.

Some sort of carbon tax for the shipping industry will most likely come, the question is just when and at what level. The short-sea sector should also expect some sort of carbon taxes for the coming years. However, until such regulations are imposed, it is difficult to make hydrogen-powered vessels profitable, even with investment support to cover the additional building cost.

6. Conclusion

Hydrogen has the potential to serve as an alternative marine fuel for the short-sea sector. Liquefied hydrogen (LH_2) is preferable to compressed hydrogen due to better properties in terms of storing the required amount of energy.

Based on current technology and regulations it is challenging to build a hydrogen-powered vessel today. The technology is in its early phase for application on vessels and there is a lack of regulations for the use and storage of hydrogen on board vessels. However, with several pilot projects that is likely to be on the water within the next years, these barriers are expected to be lowered. The fuel production and infrastructure for LH_2 is also immature. The production capacity is low and there is a general lack of infrastructure. In combination with severe range limitations for a vessel sailing on LH_2 this is a challenge for those seeking to invest in such vessels. However, the paper proves that with long-term freight contracts, over a fixed geographical area one can tackle the range limitations and allow for establishing the required fuel infrastructure. Liquefied hydrogen has the potential to be a zero-emission fuel in a well-to-propeller perspective if the production and distribution are done exclusively by renewable energy. The current production and distribution of LH_2 in Europe is however not based on renewable energy. The current production results in higher CO_2 equivalent emissions than common fossil fuels such as MGO, measured on well-to-propeller basis. The main hurdle in terms of realizing hydrogen-powered vessels for the short-sea sector is the profitability. Based on the current freight rates, building cost, fuel cost and cost for renewing the energy converter system it is not considered a financially viable investment, even if cargo-owners collaborate to minimize ballast legs and hence increase the utilization of the vessel. With investment support for the additional costs related to a hydrogen-powered vessel and the most optimistic LH_2 price scenario, such investments are still not financially viable.

Cargo-owners and charterers point at regulatory authorities as the enabler to make zero-emission vessels profitable. The fuel cost is normally passed on to the cargo-owners and charterers through the freight rates. Hence a carbon tax is likely to increase the freight rates and enable zero-emission vessels to be more competitive. The key question is whether carbon taxes of more than a symbolic amount is likely for the near future. Especially for the short-sea market, which seems to be left out of most incentives to reduce greenhouse gas emissions.

7. References

Alaswad, A., Palumbo, A., Dassisti, M., & Olabi, A. G. (2016). Fuel Cell Technologies, Applications, and State of the Art. A Reference Guide. *Reference Module in Materials Science and Materials Engineering*. Retrieved from http://www.sciencedirect.com/science/article/pii/B9780128035818040091

Atanasiu, M. (2019, September 10). EU support to maritime activities. San Francisco. Retrieved from https://www.energy.gov/sites/prod/files/2019/10/f68/fcto-h2-at-ports-workshop-2019-ii2-atanasiu.pdf

Banks. (2020, October). Financing a zero-emission short sea vessel. (H. F. Fure, Interviewer)

Birkeland, F. (2020, September 02). L6: EXPORT CREDIT. *FIE460 SHIP FINANCE AND MARINE INSURANCE*. Norwegian School of Economics.

Blanc, P., Zafar, M., Martino, F. D., Fargere, A., Carton, J., & Kolodziejczyk, B. (2020, November 08). *World Energy Council.* Retrieved from Publications: https://www.worldenergy.org/assets/downloads/WEInnovation-Insights-Brief-New-Hydrogen-Economy-Hype-or-Hope.pdf

Brinks, H., & Hektor, E. A. (2020). *DNV GL.* Retrieved from Ammonia as a marine fuel: https://www.dnvgl.com/publications/ammonia-as-a-marine-fuel-191385

Buskop, A., & Vistad, K. F. (2020, October 01). Interview Vard ZeroCoaster. (F. F. Harald, Interviewer)

Chryssakis, C., Balland, O., Tvete, H. A., & Brandsæter, A. (2014). *DNV GL.* Retrieved from Alternative fuels for shipping: https://www.dnvgl.com/publications/alternative-fuels-for-shipping-12404

Clarksons Research. (2020). *Fuelling Transition: Tracking the Economic Impact of Emission Reductions & Fuel Changes.* London: Clarkson Research Services LTD.

Council of the European Union. (2020, January 31). 5606/20. Brussels. Retrieved from https://data.consilium.europa.eu/doc/document/ST-5606-2020-INIT/en/pdf

Dale, E., Seeberg, A. R., Laugen, L., Hagen, L., & Basso, M. N. (2018). *Kostnadskomponenter og -størrelser ved skipsanløp.* Høvik: DNV GL.

Damman, S., Sandberg, E., Rosenberg, E., Pisciella, P., & Johansen, U. (2020). *Largescale hydrogen production in Norway - possible transition pathways towards 2050.* Trondheim: SINTEF.

Decker, L. (2019, December 10). *Sintef.* Retrieved from Global assets: https://www.sintef.no/globalassets/project/hyper/presentations-day-1/day1_1430_decker_latest-global-trend-in-liquid-hydrogen-production_linde.pdf

DNV GL. (2019, June 01). *DNV GL.* Retrieved from Assessment of selected alternative fuels and technologies in shipping: https://www.dnvgl.com/maritime/publications/alternative-fuel-assessment-download.html

DNV GL. (2020, October 13). *DNV GL.* Retrieved from Grønt Skipsfartsprogram: https://www.dnvgl.no/maritime/gront-skipsfartsprogram/pilotprosjekter.html

DNV GL. (2020b, September 08). *DNV GL.* Retrieved from Announcements and FQAs: https://www.dnvgl.no/maritime/gront-skipsfartsprogram/HC-FKgreenbulk/Announcements-and-FAQs.html

Enova. (2020). *Normalavkastning i lønnsomhetsberegninger.* Retrieved from Enova: https://www.enova.no/om-enova/drift/normalavkastning/

ENOVA. (2020b, November 11). *ENOVA.* Retrieved from Sammendrag av strategien: https://www.enova.no/om-enova/om-organisasjonen/strategiske-veivalg-mot-2050/sammendrag-av-strategien/

Eriksen, R., Engel, D., Haugen, U., Hodne, T., Hovem, L., Longva, T., . . . Sekkesæter, Ø. (2020). *Maritime Forecast to 2050.* Hamburg: DNV GL.

European Commission. (2020, November 12). *European Commission*. Retrieved from Horizon 2020: https://ec.europa.eu/programmes/horizon2020/en/background-material

European Parliament. (2020, September 16). *European Parliament*. Retrieved from Press room: https://www.europarl.europa.eu/news/en/press-room/20200910IPR86825/parliament-says-shipping-industry-must-contribute-to-climate-neutrality

Faber, J., Hanayama, S., Zhang, S., Pereda, P., Comer, B., Hauerhof, E., . . . Kosaka, H. (2020). *Fourth IMO GHG Study 2020.* London: International Maritime Organization.

Felleskjøpet Agri SA; HeidelbergCement Norway AS. (2020, September 11). *DNV GL.* Retrieved from Request of Interest - Hydrogen: https://www.dnvgl.no/maritime/gront-skipsfartsprogram/HC-FKgreenbulk/request-of-interest-hydrogen-download.html

Felleskjøpet Agri SA; HeidelbergCement Norway AS. (2020, July 03). *DNV GL.* Retrieved from Request of Interest: https://www.dnvgl.no/maritime/gront-skipsfartsprogram/HC-FKgreenbulk/request-of-interest-download.html

Fjose, S., Basso, M. N., Aamo, A., Pedersen, S., & Jacobsen, E. (2020). *Kartlegging av nærskipsfart - Sammensetning, alder, lønnsomhet og utfordringer med flåtefornyelse.* Oslo: Menon Economics.

Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., & Murphy, A. (2018, January 20). Assessment of full life-cycle air emissions of alternative shipping fuels. *Journal of Cleaner Production*, pp. 855-866. Retrieved from http://www.sciencedirect.com/science/article/pii/S0959652617324721

Guo, H., Zhou, S., Zou, J., & Shreka, M. (2020, September 17). A Numerical Investigation on De-NOx Technology and Abnormal Combustion Control for a Hydrogen Engine with EGR System. *Processes*, p. 1178.

HeidelbergCement. (2020, July 06). *HeidelbergCement og Felleskjøpet Agri går sammen – vil ha verdens første utslippsfrie bulkskip*. Retrieved from HeidelbergCement: https://www.heidelbergcement.no/no/Utslippsfritt%20lasteskip

Hirth, M. L., Hove, K. U., Janzen, D., Eide, P. G., Helland, P., Østvik, I., . . . Ødegård, J. (2019, April 11). *Future demand for hydrogen.* Retrieved from NCE Maritime CleanTech: https://maritimecleantech.no/wp-content/uploads/2016/11/Report-liquid-hydrogen.pdf

IEA. (2019). *International Energy Agency*. Retrieved from Data and assumptions: https://iea.blob.core.windows.net/assets/a02a0c80-77b2-462e-a9d5-1099e0e572ce/IEA-The-Future-of-Hydrogen-Assumptions-Annex.pdf

IMO. (2020, October 11). *International Maritime Organization*. Retrieved from Air Pollution: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Air-Pollution.aspx

IMO. (2020, October 11). *International Maritime Organization*. Retrieved from Greenhouse Gas Emissions: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/GHG-Emissions.aspx

Kavussanos, M., & Visvikis, I. (2016). *The International Handbook of Shipping Finance.* London: Springer Nature.

Kirstein, L., Halim, R., & Olaf, M. (2018). *Decarbonising Maritime Transport.* Paris: International Transport Forum. Retrieved from https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport-2035.pdf

Klebanoff, L. E., Pratt, J. W., Madsen, R. T., Caughlan, S. A., Leach, T. S., Appelgate, B. T., . . . Teo, A. T. (2018). *Feasibility of the Zero-V: A Zero-Emission, Hydrogen Fuel-Cell, Coastal Research Vessel.* Livermore: Sandia National Laboratories.

KPMG. (2017, February 28). *Rederiskatteordningen*. Retrieved from KPMG: https://verdtavite.kpmg.no/rederiskatteordningen

Lindstad, E. (2019, July 10). *Dr Elizabeth Lindstad on why increased use of LNG might not reduce maritime GHG emissions at all.* Retrieved from Transport & Environment: https://www.transportenvironment.org/sites/te/files/publications/2019_06_Dr_Elizabeth_Lindstad_commentary_LNG_maritime_GHG_emissions.pdf

Lindstad, E., Eskeland, G. S., Rialland, A., & Valland, A. (2020, October 20). Decarbonizing Maritime Transport: The Importance of Engine Technology and Regulations for LNG to Serve as a Transition Fuel. *Sustainability, 12*(21), 21. doi:https://doi.org/10.3390/su12218793

Marcussen, L. E. (2020, November 19). Interview with HeidelbergCement. (H. F. Fure, Interviewer)

McCombes, S. (2020, June 19). *How to do a case study*. Retrieved from Scribbr: https://www.scribbr.com/methodology/case-study/

Mestemaker, B., Castro, B., van der Blom, E., Cornege, H., & Visser, K. (2019, July). Zero emission vessels from a shipbuilders perspective. Retrieved from https://www.researchgate.net/publication/334480164_Zero_emission_vessels_from_a_shipbuilders_perspective/citations

Mestemaker, B., van den Heuvel, H., & Castro, B. G. (2020, April 21). Designing the zero emission vessels of the future: Technologic, economic and environmental aspects. *International Shipbuilding Progress*, ss. 5-31.

Moirangthem, K. (2016). *Alternative Fuels for Marine and Inland Waterways.* Petten: European Commission JRC. Retrieved from http://gasnam.es/wp-content/uploads/2016/07/inland-and-marine-waterways-exploratory-work-on-alternative-fuels_kamaljit-moirangthem_final.pdf

MSI. (2020). *Short Sea Market Report.* London: Maritime Strategies International Ltd.

Newshore Invest. (2020, September 08). *Zahlen & Fakten*. Retrieved from Newshore Invest: https://new-shore-invest.de/de/projekte/rhas-5/zahlen-fakten/

Norled. (2019, May 13). *NORLED*. Retrieved from Norled deltar i konsortiet FLAGSHIPS som mottar EU-støtte til hydrogenprosjekt: https://www.norled.no/nyheter/norled-deltar-i-konsortiet-flagships-som-mottar-eu-stotte-til-hydrogenprosjekt/

Plug. (2020, December 01). *Plug Port*. Retrieved from For rederiene: https://www.plugport.no/for-rederier

Port of Rotterdam. (2020, October 23). *News*. Retrieved from Port of Rotterdam: https://www.portofrotterdam.com/en/news-and-press-releases/an-agreement-made-to-explore-the-possibilities-of-green-hydrogen-export-from

Poseidon Principles. (2020, October 11). *Poseidon Principles*. Retrieved from How did we get there: https://www.poseidonprinciples.org/about/how-did-we-get-there/

Poseidon Principles. (2020, October 11). *Poseidon Principles*. Retrieved from FAQs: https://www.poseidonprinciples.org/faqs/

Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, R., & Lonza, L. (2020). *JEC Well-to-Tank report v5*. Luxembourg: Publications Office of the European Union. Retrieved from https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/jec-well-tank-report-v5

Rahim, M. A., & Daud, W. N. (2015). The Case Study Method in Business. *Scholars Journal of Arts, Humanities and Social Sciences*, 105-109.

Satyapal, S. (2017, February 21). *Office of Energy Efficiency & Renewable Energy*. Retrieved from Hydrogen: A Clean, Flexible Energy Carrier: https://www.energy.gov/eere/articles/hydrogen-clean-flexible-energy-carrier

Sea Cargo Charter. (2020, October 13). *Sea Cargo Charter*. Retrieved from How Did We Get There: https://www.seacargocharter.org/about/how-did-we-get-there/

Stopford, M. (2009). *Maritime Economics.* New York: Routledge.

Trafigura. (2020, September). *Resource Centre.* Retrieved from Trafigura: https://www.trafigura.com/brochure/a-proposal-for-an-imo-led-global-shipping-industry-decarbonisation-programme

Tronstad, T., Åstrand , H. H., Haugom, G. P., & Langfeldt, L. (2017). *Study on the use of Fuel Cells in Shipping.* Hamburg: DNV GL - Maritime.

UNFCCC. (2020, October 03). *United Nations Framework Convention on Climate Change*. Retrieved from What is the Paris Agreement?: https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement

United Nations. (2020, October 03). *United Nations*. Retrieved from Climate Change: https://www.un.org/en/sections/issues-depth/climate-change/

UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT (UNCTAD). (2020). *Review of Maritime Transport 2019.* New York: United Nations Publications.

Wilh. Wilhelmsen. (2020, October 22). *Wilhelmsen*. Retrieved from HySHIP project clinches EUR 8M funding award: https://www.wilhelmsen.com/media-news-and-events/press-releases/2020/hyship-project-clinches-eur-8m-funding-award/

Wilson ASA. (2020). *Årsrapport 2019.* Bergen: Wilson ASA.

Zegpower. (2019, September 19). *ZEG Power and CCB enters into strategic cooperation to establish cost efficient, clean hydrogen production from gas at Kollsnes*. Retrieved from ZEG Power: https://www.zegpower.no/zeg-power-and-ccb-enters-into-strategic-cooperation-to-establish-cost-efficient-clean-hydrogen-production-from-gas-at-kollsnes/?lang=en

8. Appendix

8.1 Interwiev Guide Vard Engineering Brevik

The following questions are intended to work as a starting point for conversation and discussion.

Introduction:

- A brief introduction of myself and the master's thesis
- Give a definition short-sea shipping covered in this thesis
- Statement of how the interview will be used
- Give the interview object the chance to be anonymous and withdraw the statements

Questions:

- Can you please share some of the key features of Vard ZeroCoaster?
- What fuel is the vessel designed for?
- If the vessel will be sailing on hydrogen, what size and type of fuel cell system and batteries are planned?
- What is the estimated sailing range for the vessel based on service speed and different fuels?
- What is the estimated daily energy consumption at different speeds?
- Is it realistic to build the vessel within 1-2 years? What fuels are you considering as most realistic to use in that case?
- Is the vessel/hull expected to be more energy efficient than vessels sailing in the market today?
- What is the estimated building cost for this vessel based on different fuels and energy converters?
- What is the estimated cost for the hull and what is the estimated additional cost for energy converter, fuel storage, etc?
- Do you expect an increase or decrease of the OPEX?
- What is the planned dimensions of the vessel? LOA, beam, draft, cargo capacity in tonnes and cbm?

8.2 Interwiev Guide Banks

The following questions are intended to work as a starting point for conversation and discussion.

Introduction:

- A brief introduction of myself and the master's thesis
- Give a definition short-sea shipping covered in this thesis
- Statement of how the interview will be used
- Give the interview object the chance to be anonymous and withdraw the statements

Questions:

- Do your company finance any short-sea shipping companies?
- What type of financing method is the most common for the short-sea shipping companies you finance and in the market in general?
- For zero-emission vessels, do you see any alternative financing options?
- Do you see it as likely that "green bonds" will be used to finance zero-emission vessels in the short-sea sector?
- What terms can one expect to get from a "green bond" for such an investment as described here? Better or equal as for "non green investments"?
- What is the typical minimum required equity when financing a newbuilding in the short-sea segment?
- Will the minimum required equity be lower, higher or the same for "green" investments, e.g. a zero-emission short-sea vessel?
- Is it normal to use export credit when financing a newbuilding in the short-sea segment?
- Is it possible to give an indication of the typical cost of debt and payback period for asset-backed loans in the short-sea segment?
- Will a shipowner be able to offer better terms for "green" investments than for investment in fossil fueled vessels?
- Do banks care about well-to-propeller emissions or only tank-to-propeller when financing "green" ships?

8.3 Interwiew Guide Cargo Owners

Interview guide HC & FK:

The following questions are intended to work as a starting point for conversation and discussion.

Introduction:

- A brief introduction of myself and the master's thesis
- Give a definition short-sea shipping covered in this thesis
- Statement of how the interview will be used
- Give the interview object the chance to be anonymous and withdraw the statements

Questions:

- What are the most used sailing routes?
- What are the freight rates for these routes today?
- Is the cargo mainly transported on COA, TC contracts or in the spot market today?
- Will there be commission on the TC rate on this contract?
- What currency will the freight be paid in?
- Is it possible to share historical data for freight rates and port cost for the most used transport legs?
- What is the expectation for freight levels? Over, under or in line with today's levels?
- Will the TC rate be adjusted in line with the general market or be adjusted for inflation based on year 1?
- Will there be one fixed TC rate to the shipowner, or will it be paid from each of the cargo-owners?
- Do you as cargo-owners have preferences to the exact fuel the vessel will use? This will have impact on the fuel cost and hence the transportation cost under a TC contract.
- Will the vessel have priority in all ports in order to avoid congestion and ensure full utilization?

- A TC contract place the technical risk related to new technology at the shipowner. Will there be some sort of flexibility in connection to off-hire due to new technology or will it remain as it is today?
- Are the ports mostly private or publicly owned?
- Are you planning to use agents in ports?
- Will you request the navigators to have PEC?

8.4 Questions to Fuel Cell and Battery Producers

Fuel Cell

- What is the expected lifetime for the fuel cells you deliver?
- What is the expected service intervals, cost and time for the fuel cells?
- What is the expected cost today and for the future when fuel cells must be renewed?

Battery

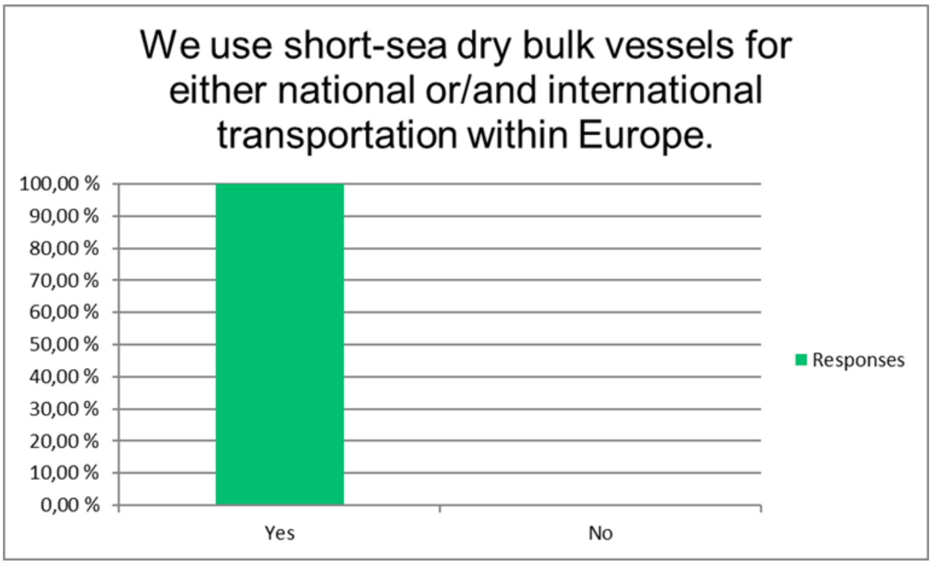
- What is the approximate price for such battery with capacity of 2 mWh?
- Do you have any guideline of expected service life for such battery?
- Do you have any indication of expected price in the future?
- Are there any yearly service costs related to the use of such batteries?

8.5 Questions DNV GL

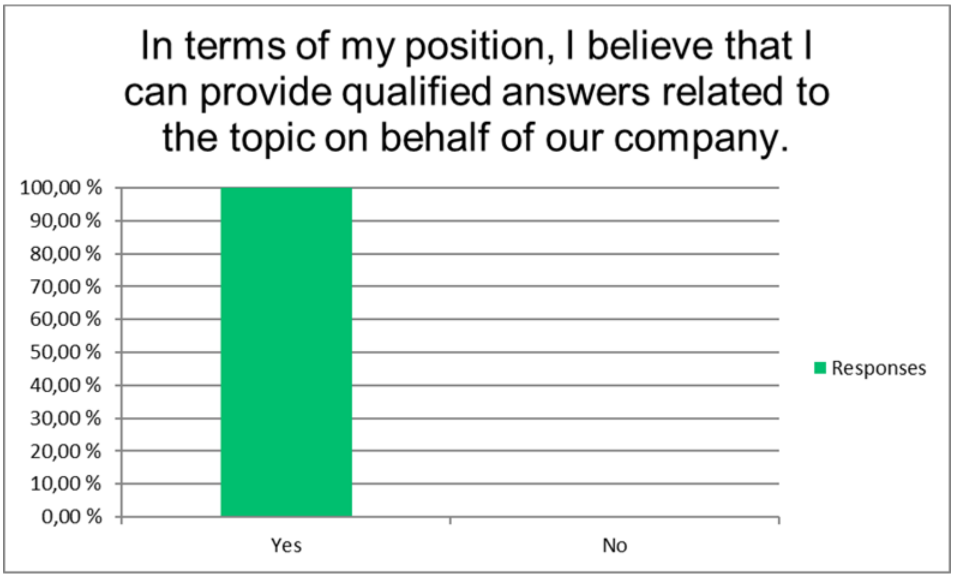
- Based on the technical solutions that exist today, is it realistic to build a zero-emission ship that can sail the distance required in short sea shipping?
- If yes to question 1, which fuel / technical solutions are considered most realistic?
- If yes to question 1, are there any cost estimates for what it will cost to build such a ship?
- Is an increase or decrease in "running costs" (maintenance, spare parts, dry dock, crew competence) expected in connection with the operation of such a ship?
- Is it expected more or fewer operational days for such vessel compared to a conventional vessel?

8.6 Survey

Reduction of Greenhouse Gas Emissions Related to Short-sea Shipping

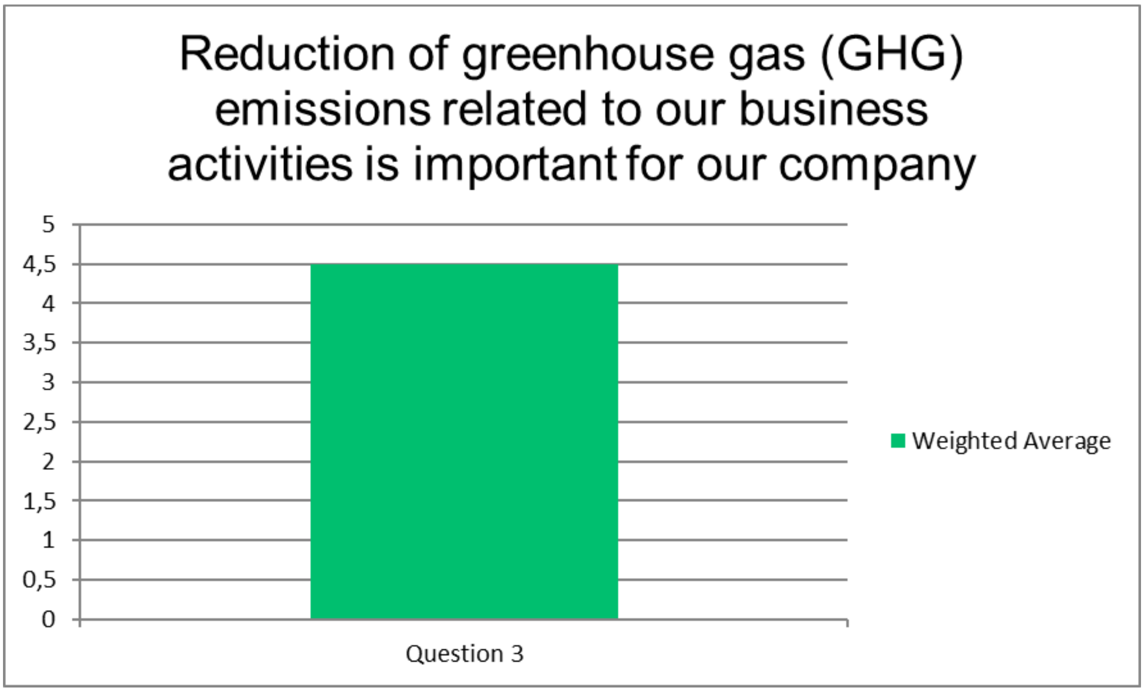


Answer Choices	Responses	
Yes	100,00 %	12
No	0,00 %	0
	Answered	**12**
	Skipped	**0**

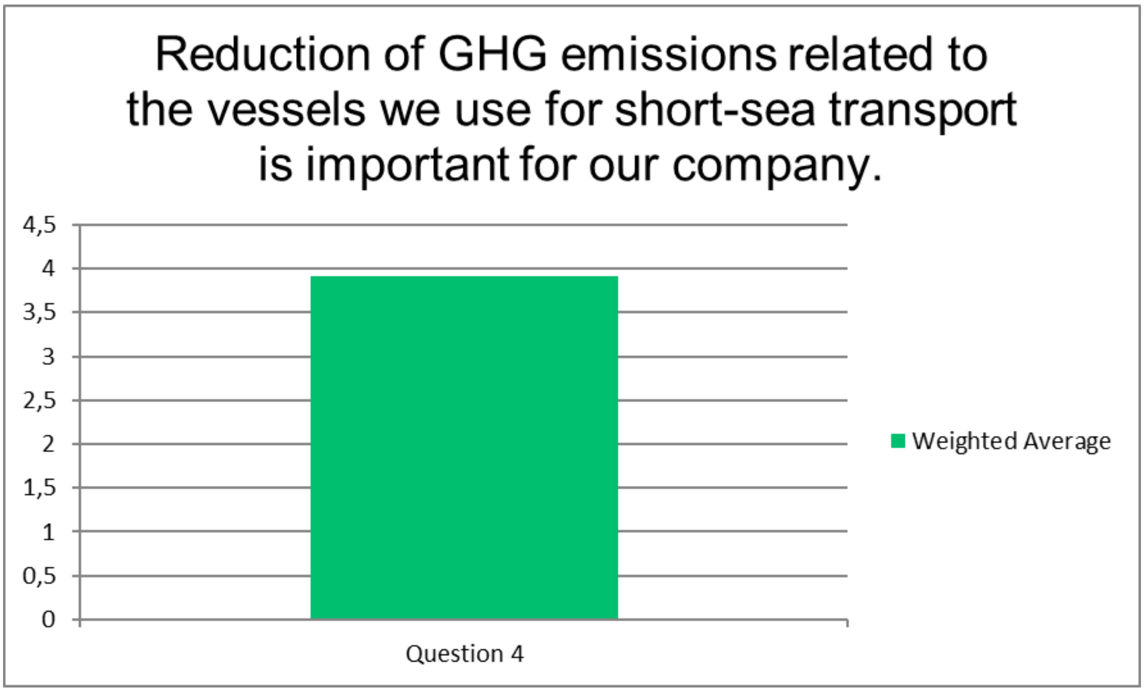


Answer Choices	Responses	
Yes	100,00 %	12
No	0,00 %	0
	Answered	**12**
	Skipped	**0**

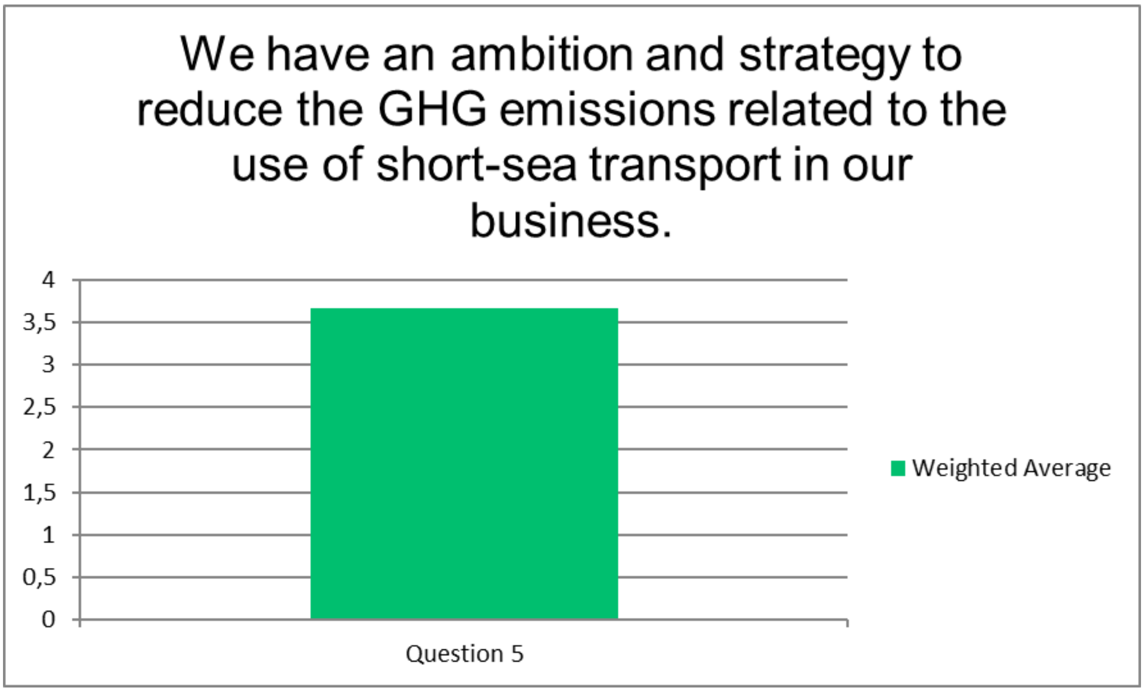
Scale from 1 to 5, where 1 = Strongly Disagree and 5 = Strongly Agree



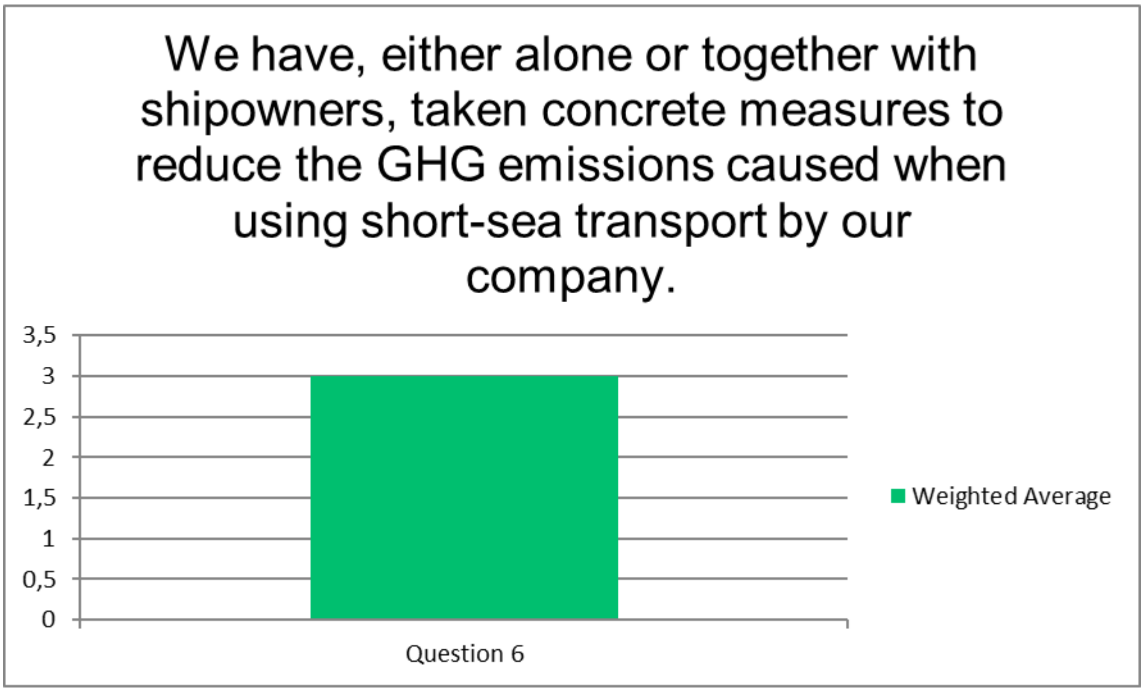
	Strongly Disagree		Disagree		Neither Agree Nor Disagree		Agree		Strongly Agree		Total	Weighted Average
Question 3	0,00 %	0	8,33 %	1	0,00 %	0	25,00 %	3	66,67 %	8	12	4,5
											Answered	**12**
											Skipped	**0**



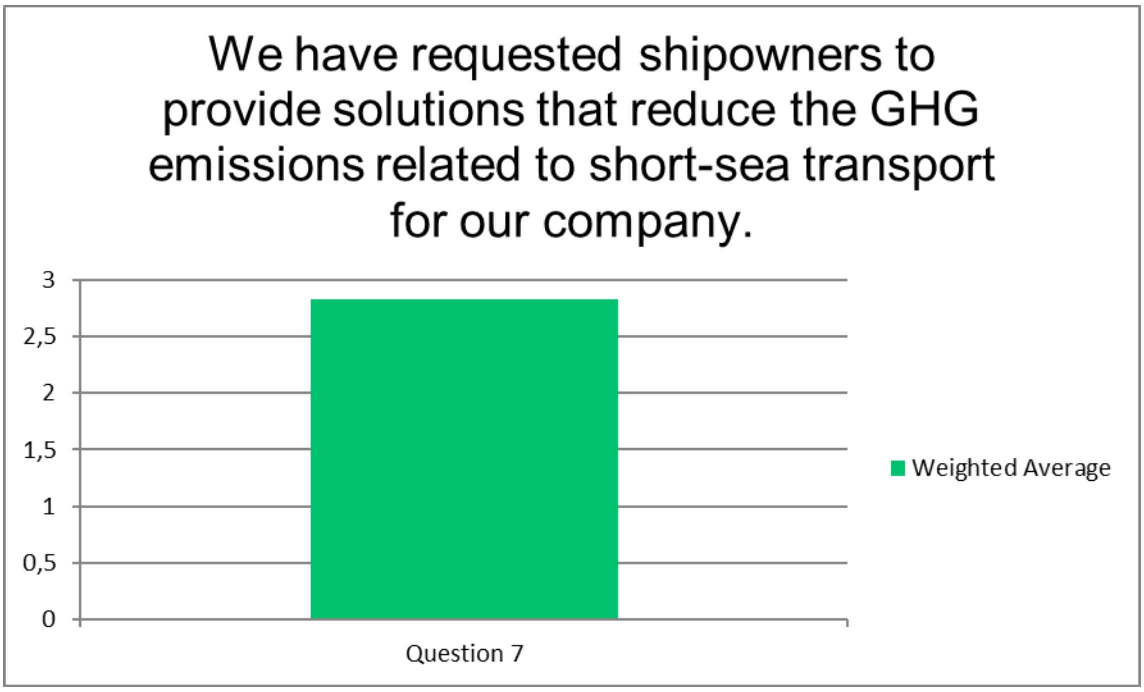
	Strongly Disagree		Disagree		Neither Agree Nor Disagree		Agree		Strongly Agree		Total	Weighted Average
Question 4	8,33 %	1	0,00 %	0	16,67 %	2	41,67 %	5	33,33 %	4	12	3,92
											Answered	**12**
											Skipped	**0**



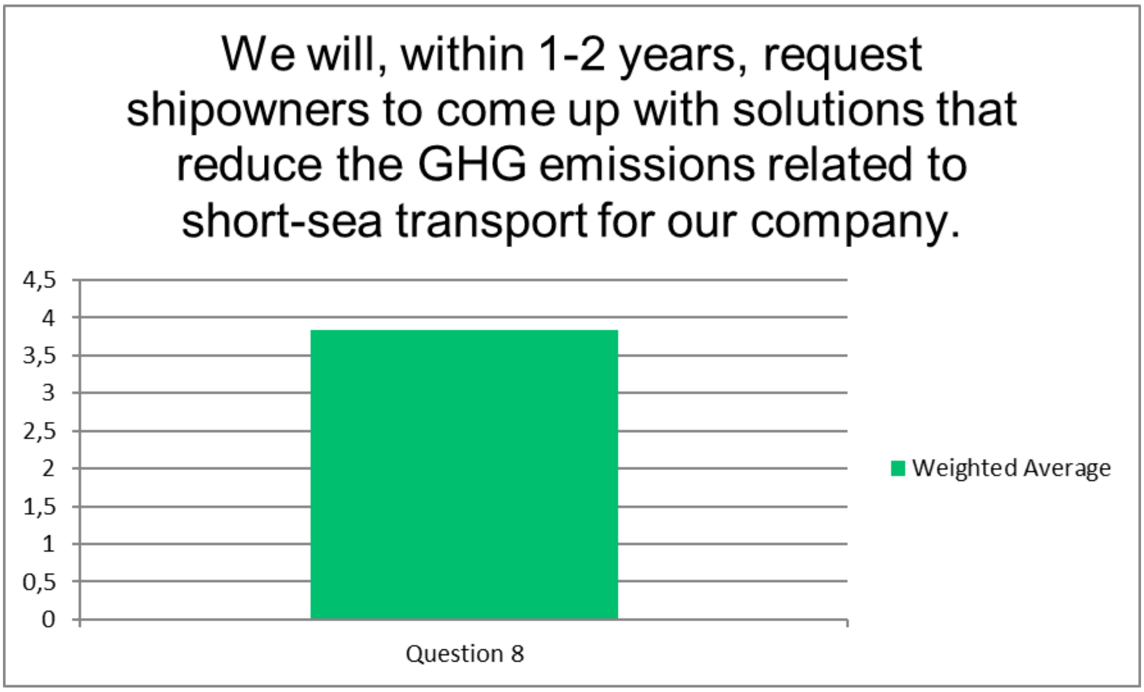
	Strongly Disagree		Disagree		Neither Agree Nor Disagree		Agree		Strongly Agree		Total	Weighted Average
Question 5	8,33 %	1	8,33 %	1	16,67 %	2	41,67 %	5	25,00 %	3	12	3,67
											Answered	**12**
											Skipped	**0**



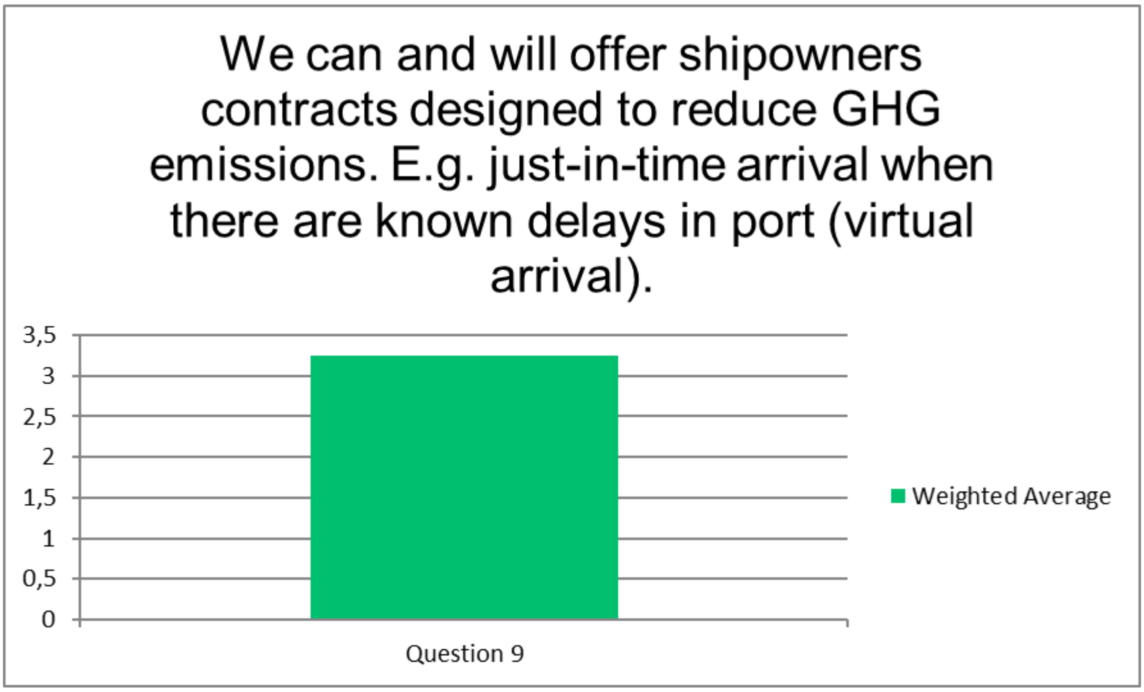
	Strongly Disagree		Disagree		Neither Agree Nor Disagree		Agree		Strongly Agree		Total	Weighted Average
Question 6	16,67 %	2	16,67 %	2	25,00 %	3	33,33 %	4	8,33 %	1	12	3
											Answered	**12**
											Skipped	**0**



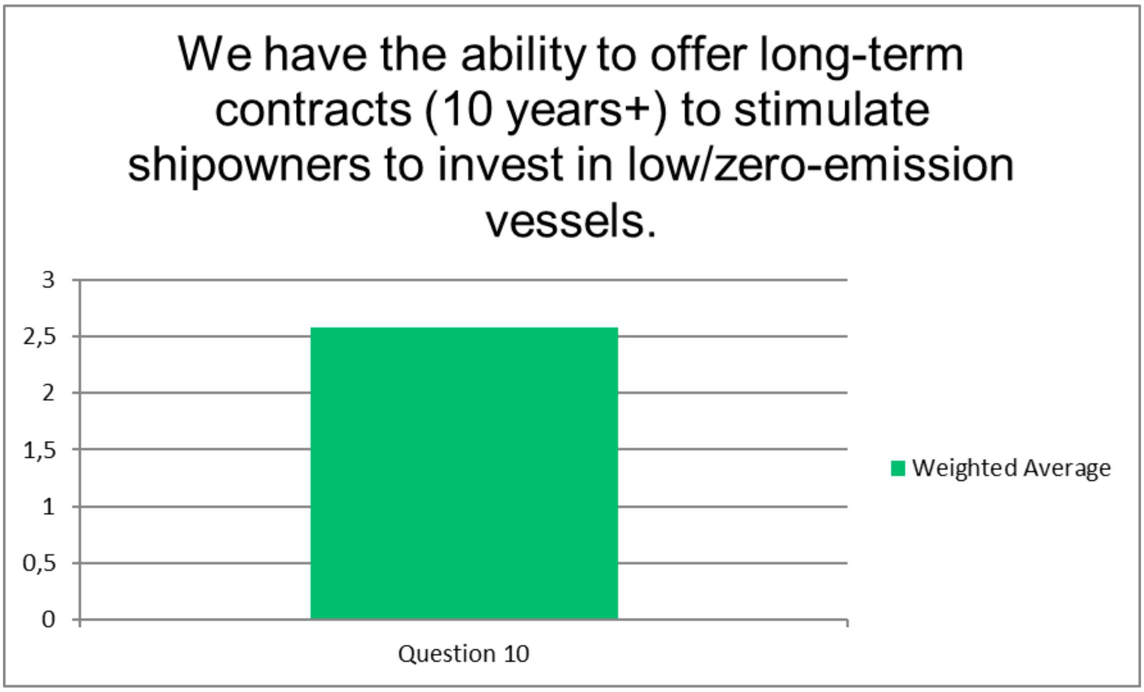
	Strongly Disagree		Disagree		Neither Agree Nor Disagree		Agree		Strongly Agree		Total	Weighted Average
Question 7	8,33 %	1	33,33 %	4	25,00 %	3	33,33 %	4	0,00 %	0	12	2,83
											Answered	**12**
											Skipped	**0**



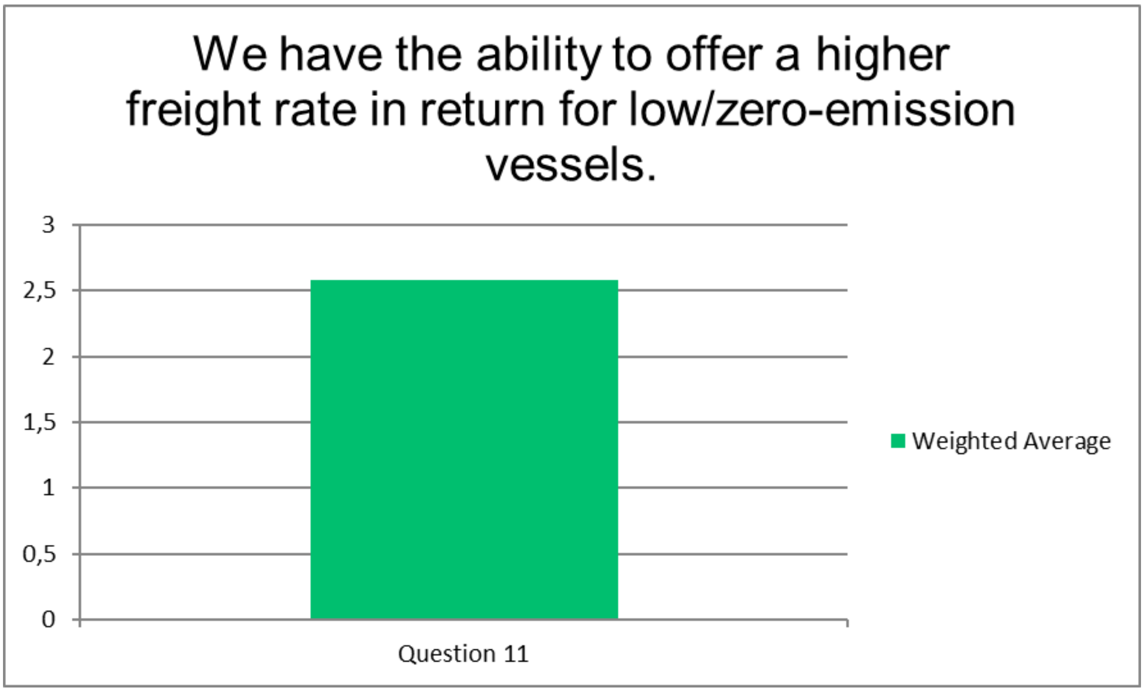
	Strongly Disagree		Disagree		Neither Agree Nor Disagree		Agree		Strongly Agree		Total	Weighted Average
Question 8	8,33 %	1	0,00 %	0	25,00 %	3	33,33 %	4	33,33 %	4	12	3,83
											Answered	**12**
											Skipped	**0**



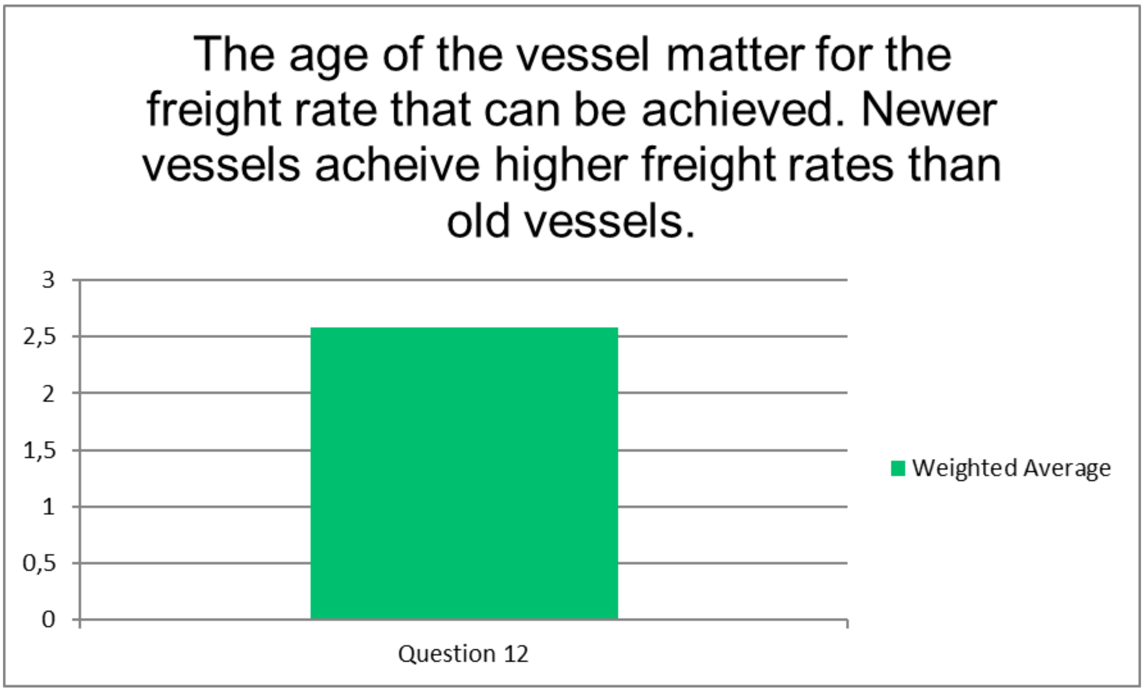
	Strongly Disagree		Disagree		Neither Agree Nor Disagree		Agree		Strongly Agree		Total	Weighted Average
Question 9	16,67 %	2	0,00 %	0	33,33 %	4	41,67 %	5	8,33 %	1	12	3,25
											Answered	**12**
											Skipped	**0**



	Strongly Disagree		Disagree		Neither Agree Nor Disagree		Agree		Strongly Agree		Total	Weighted Average
Question 10	25,00 %	3	16,67 %	2	33,33 %	4	25,00 %	3	0,00 %	0	12	2,58
											Answered	**12**
											Skipped	**0**



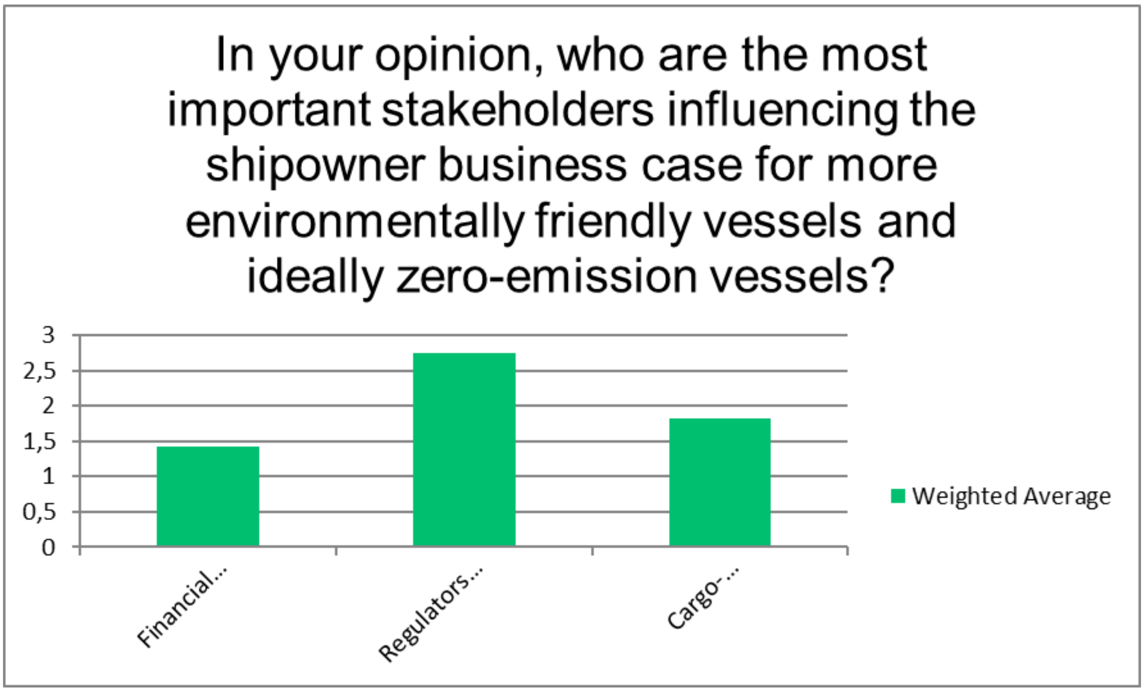
	Strongly Disagree		Disagree		Neither Agree Nor Disagree		Agree		Strongly Agree		Total	Weighted Average
Question 11	16,67 %	2	16,67 %	2	58,33 %	7	8,33 %	1	0,00 %	0	12	2,58
											Answered	**12**
											Skipped	**0**



	Strongly Disagree		Disagree		Neither Agree Nor Disagree		Agree		Strongly Agree		Total	Weighted Average
Question 12	8,33 %	1	33,33 %	4	50,00 %	6	8,33 %	1	0,00 %	0	12	2,58
											Answered	**12**
											Skipped	**0**

Question 13

Scale from 1 to 3, where 3 = Most important, 2 = Second most important and 3 = Third most important



Question 13	Most important		Second most important		Third most important		Total	Weighted Average
Financial institutions (Banks, investors, public entities etc)	0,00 %	0	41,67 %	5	58,33 %	7	12	1,42
Regulators (IMO, EU, National states and local authorities)	83,33 %	10	8,33 %	1	8,33 %	1	12	2,75
Cargo-owners/charterers	16,67 %	2	50,00 %	6	33,33 %	4	12	1,83
							Answered	**12**
							Skipped	**0**