Universidad Pontificia de Comillas

Ingeniería Industrial

Proyecto Fin de Carrera

Energy Efficient Optimisation of Energy Flows within the Ships Engineering Systems

Autor: Marta García Sansigre

Director: Professor Richard Bucknall

Madrid, Mayo 2015

UNIVERSIDAD PONTIFICIA ICAI ICADE COMILLAS MADRID

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Energy Efficient Optimisation of Energy Flows within the Ships Engineering Systems

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Director: Bucknall, Richard.

Entidad colaboradora: UCL - University College of London

RESUMEN DEL PROYECTO

1. *Introducción*

El objetivo del presente proyecto es la comparación de los distintos tipos de sistemas de propulsión marítimos para obtener la máxima eficiencia energética desde el punto de vista de las emisiones. Mientras que la eficiencia energética se suele definir como la producción de un mismo bien o servicio con el mínimo coste de energía, cuando se habla de transporte la eficiencia energética está íntimamente ligada al consumo de combustible y consecuentemente a las emisiones.

Como el transporte marítimo es un sector amplio y muy diverso, el proyecto se centra en el estudio de los barcos costeros, también conocidos como SSS (Short Sea Shipping).Aunque el transporte marítimo es responsable del 2,5% del total de CO_2 emitido a la atmósfera por parte del transporte (22,6% del total de CO_2), debe reducir sus emisiones aún más. Esta reducción se debe al reciente interés de la Unión Europea por el cambio en el modo de transporte de la carretera al mar, para así aliviar el tráfico y reducir las emisiones al medioambiente. El transporte marítimo de corta distancia es capaz de competir con el transporte por carretera cubriendo el 42% t-km dentro de la UE mientras que el transporte por carretera cubre el 44%.

Además, la normativa para el transporte marítimo es cada vez más restrictiva, no solo para las emisiones de CO_2, sino también para las de NO_X, SO_X y PM. (MARPOL anexo VI, 2011). Actualmente el nitrógeno y el contenido de sulfuro de los combustibles marinos está regulado dentro las zonas de emisiones controladas ECAs y SECAs respectivamente.

Por todo ello, la optimización de las fuentes energéticas y de su uso es una necesidad actualmente y objeto central de investigación y el desarrollo del transporte marítimo en la actualidad.

2. *Metodología*

Para la realización del este proyecto ha sido necesario dividir el estudio en diferentes pasos, así como establecer unos márgenes para alcanzar los objetivos propuestos.

- Lectura y compresión de la regulación referente a emisiones presentada en el Anexo VI (IMO, 2014).
- Establecimiento de los criterios para clasificar los barcos dentro del sector de barcos costeros.

- Análisis de las características técnicas de los cinco tipos de barcos costeros de carga. El resultado permite la identificación de los sistemas de propulsión más extendidos para estos tipos de barcos costeros.

- Análisis de los principales sistemas de propulsión y la evaluación de un posible cambio en la propulsión de un motor diésel a una turbina de gas o vapor.

- La comparación de los anteriores sistemas se ha realizado en términos económicos, energéticos y medioambientales. El volumen y peso de los sistemas se ha tenido también en consideración.

- Para hacer el estudio más cuantitativo se ha utilizado un barco específico como modelo de estudio. De este barco se ha utilizado la potencia, y medidas para la comparación. También se ha realizado el perfil operacional del mismo.

- Estudio del impacto en las emisiones usando una tecnología en desarrollo como son las células de combustible.

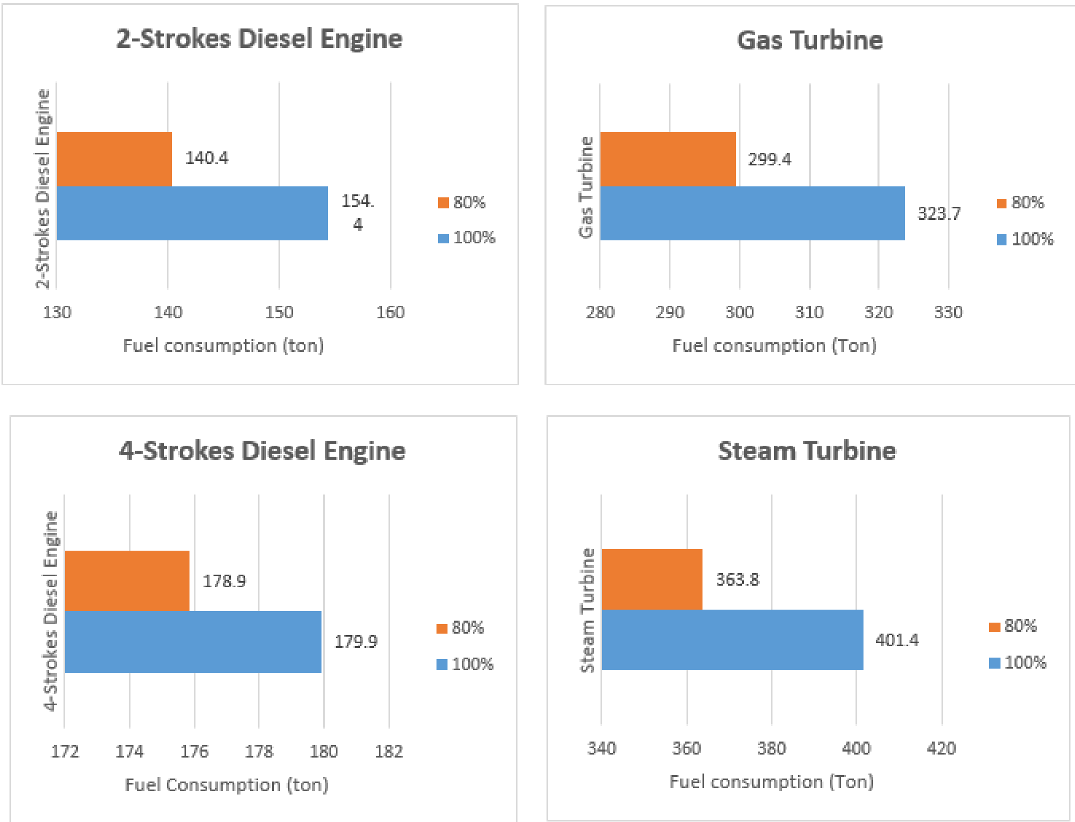
3. *Resultados*

En términos de consumo y ahorro de combustible, hoy en día la mejor tecnología son los motores diésel. En referencia a las emisiones, las de CO_2 están directamente relacionadas con el consumo de combustible, son menores en los motores diésel, pero por el contrario, las emisiones de NO_X, que son una preocupación real en la actualidad dentro de las zonas ECA, son casi inexistentes en las turbinas.

El coste de inversión de las turbinas es significativamente más alto que el coste de la instalación del motor diésel equivalente. Esto también es debido al estado de desarrollo de las tecnologías, mientras que los motores diésel están ampliamente extendidos y se usan muy comúnmente en embarcaciones de pequeño tamaño, las otras tecnologías se encuentran menos desarrolladas.

En cuanto a volumen, el motor diésel de cuatro tiempos es el más adecuado. El espacio ocupado por todo el sistema de propulsión en el caso estudiado es de 161.312 m^3. La tecnología más ligera es la turbina de gas, pero el coste de la inversión unido a los índices estudiados previamente hacen que la turbina de gas sea una tecnología muy costosa de implementar, y que no pueda considerarse como una opción realista para buques de carga de pequeñas proporciones.

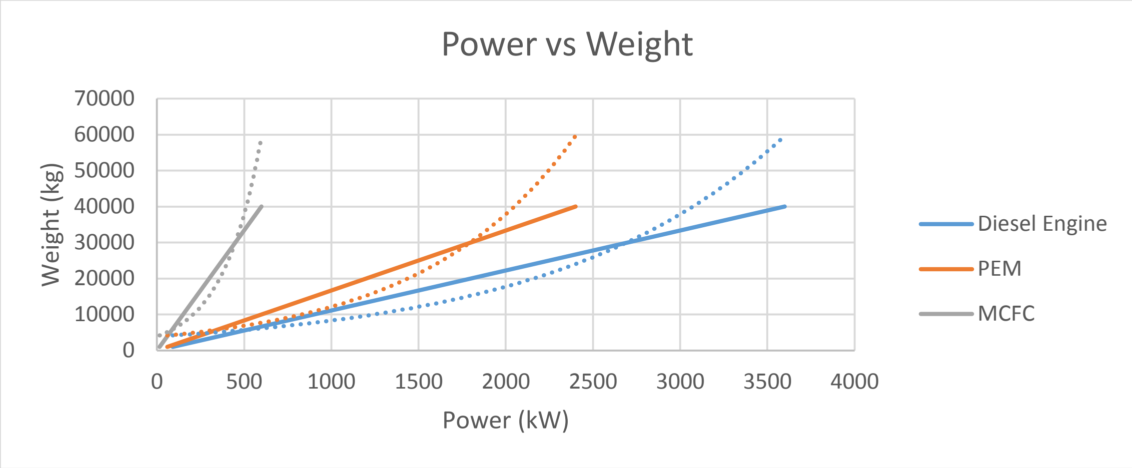
	GAS TURBINE	STEAM TURBINE	DIESEL ENGINE
Efficiency	✗	✗	✓✓
Consumption	✗	✗	✓
Emissions			
CO_2	✗	✗	✓
NOx	✓	✓	✗
SOx	✓	✓	✗
Cost	✗	✗	✓✓
Size	✓	✗	✓
Weight	✓	✗	✗



El gráfico anterior presenta las diferencias entre los consumos totales de acuerdo con el perfil operativo estudiado. El buque estudiado navegó 5068,06 millas náuticas en dos meses. El consumo real se representa en la gráfica del motor de 4 tiempos, mientras que los otros consumos hacen referencia al consumo presentado al cambiar el tipo de propulsión principal del buque específico.

Investigaciones recientes han demostrado que hay otras tecnologías que podrían llegar a ser una alternativa real en la propulsión de barcos, como son las células de combustible. Esta tecnología es una realidad en los autobuses y además existe un ferry que las utiliza como sistema de propulsión principal.

Los principales problemas de esta tecnología son el peso y el volumen, ambos combinados hacen que la aplicación de este sistema no sea efectiva hoy en día. En la siguiente figura, se muestra que para la gama de potencias de los buques costeros (1000-4500 kW) , el uso de las MCFC es inadecuado y el peso para proporcionar una potencia de 2000 kW es un 75% más con PEM que al utilizar un motor diésel .



Finalmente, hay que tener también en cuenta el volumen y los problemas de almacenamiento del hidrógeno, que es el combustible requerido por este sistema de propulsión. Para la potencia del modelo de estudio el espacio requerido por el H_2 es 64 veces mayor que el espacio requerido por el combustible diésel, mientras que el peso de la H_2 es 3 veces menor.

4. *Conclusión*

Para la propulsión de los buques de carga de corta distancia, cuyas características principales son: viajes cortos, tamaño pequeño-mediano e inversión ajustada, la solución que mejor se adapta actualmente es un motor diésel de 4 tiempos. El rendimiento y el consumo de combustible es significativamente mejor que en las turbinas (vapor y gas). Además por sus requisitos de volumen, peso e inversión los motores diésel de 4 tiempos son más adecuados que los motores de 2 tiempos. Como esta embarcación hace viajes de corta distancia, las horas de navegación son menos que en cargueros transoceánicos, y por lo tanto, el rendimiento no es la máxima prioridad.

En términos de flexibilidad, los motores diésel, por su carácter modular, se adaptan fácilmente a diferentes potencias como las que se presentan en el transporte costero (de 1000 a 4500 kW). Además el coste de la inversión en las turbinas aumenta a medida que disminuye la potencia proporcionada, por lo tanto las turbinas de gas son económicamente más rentables para los buques más grandes.

Debido a la normativa, cada vez más restrictiva en términos de emisiones, el desarrollo e implementación de nuevas tecnologías como alternativa a los motores, se hace cada vez más necesaria. Las células de combustible y las baterías como dispositivos de almacenamiento de energía electroquímica, están siendo utilizadas como parte de los sistemas auxiliares del barco. Futuros desarrollos podrían hacer que estas tecnologías sean una alternativa real dentro de la propulsión marina si se mejoran los problemas principales: el almacenamiento y el consumo de H_2, y la baja densidad de potencia. Además, el espacio requerido para su instalación hace que su uso en pequeñas embarcaciones sea actualmente imposible, puesto que su instalación implica una gran reducción del espacio disponible para el almacenamiento de la carga que se va a transportar.

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Project ABSTRACT

1. *Introduction*

The aim of this project is to compare different technologies used in ship propulsion systems, in order to achieve maximum energy efficiency, which will be understood throughout this report as the ratio between Power Output and the Emissions released into the atmosphere. The final objective is to provide recommendations to a future owner of a ship (small-medium cargo) which is going to sail inside the areas of restricted emissions.

As the Maritime transport is a wide field, the project is focused on Short Sea Shipping (SSS) which is usually defined as the movement of cargo and passengers which do not imply crossing an ocean. Energy efficiency is commonly defined as the production of the same good or service with lower energy cost. In terms of transport, energy efficiency is directly related to fuel consumption and consequently to emissions.

Although the contribution of Maritime Transport to overall CO_2 emissions from transport is 22,6% only represent a 2,5% (IEA,2014). Maritime transport must reduce its CO_2 emissions even further, due to the recent interest the EU has demonstrated in a change from road to sea transport, to alleviate road congestion and reduce emissions.

Secondly, the regulations for this type of transport are becoming more and more restrictive not only for CO_2, but also for NO_X, SO_X and PM. (MARPOL annex VI, 2011). Both the nitrogen and sulphur content in marine fuels are now regulated in the Emission Control Areas (ECAs & SECAs).

Thirdly, as a result of the new regulations and the increased of costs of crude oil, energy costs are rising in this sector. The optimization of energy resources has become a necessity today.

In terms of sustainable mobility, SSS has made a significant contribution and is evaluated in comparison to rail and lorry transport. It is able to hold on with the growth in road transport, performing the 42% t-km in Europe-15 while the share of road is 44%. (Douet M. & Cappuccilli J., 2011)

Finally, a goal of a 40-50% reduction in GHG by 2050 has been settled on by the European Commission (EU, 2011).

2. *Methodology*

This project has been divided into steps to manage the size of information available, as well as to narrow the boundaries of the study, in order to achieve the main objective of the project.

- Careful review of the regulation MARPOL Annex VI (IMO, 2014) to understand and highlight the measures that regulate the maritime transport in terms of emissions.

- Develop a criteria to classify Short Sea Shipping.

- Analysis of the technical characteristics of five types of Short Sea Shipping vessels. The result allowed an understanding of the propulsion systems used inside such vessels.

- Analysis of the main prime movers, and afterwards an evaluation of the possibility to change the propulsion system to the Steam Turbine or Gas Turbine.

- The comparison has been made in terms of the economic, energy and environmental based impacts. The volume and size of the different layouts has been also taken into consideration.

- Identification and use of a particular vessel as a case study: "King Fisher". Development of the operating profile of the vessel to achieve a better understanding of the routes, times spent sailing and on port of coastal vessels.

- The Potential impact on emissions level using developing technology: A qualitative analysis of Batteries and Fuel Cells to point out which could possibly be the future in this mode of transport.

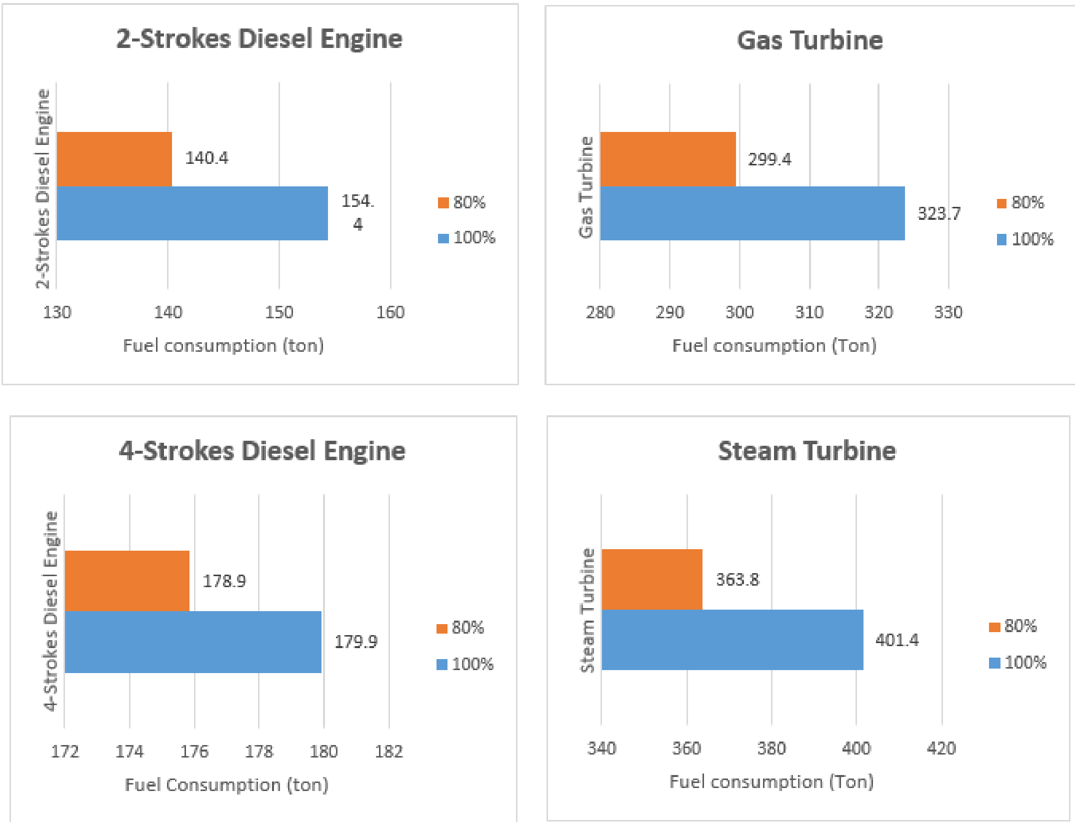
3. *Results*

In terms of fuel consumption and efficiency nowadays the best technology are Diesel Engines. Referring to the emissions, CO_2 emissions, which are directly related to fuel consumption, are less in diesel engines, but on the contrary, the NO_X emissions are a real concern nowadays inside the ECAs are hardly non-existent in turbines.

The investment cost of the turbines are significantly higher than the cost of the installation of the equivalent diesel engine. This is also because of the stage of development of the technologies, while the diesel engines are widely spread and commonly used in small size vessel the other technologies are at least one step backwards.

As for volume, the high speed 4-Strokes diesel engine is the most suitable. The space required for all the propulsion system in the studied vessel is only 161.312 m3. In terms of weight the lighter technology is the Gas Turbine, but the investment cost together with the indexes previously studied make the gas turbine a really expensive technology to implement and does not stand as a realistic option for small cargo vessels.

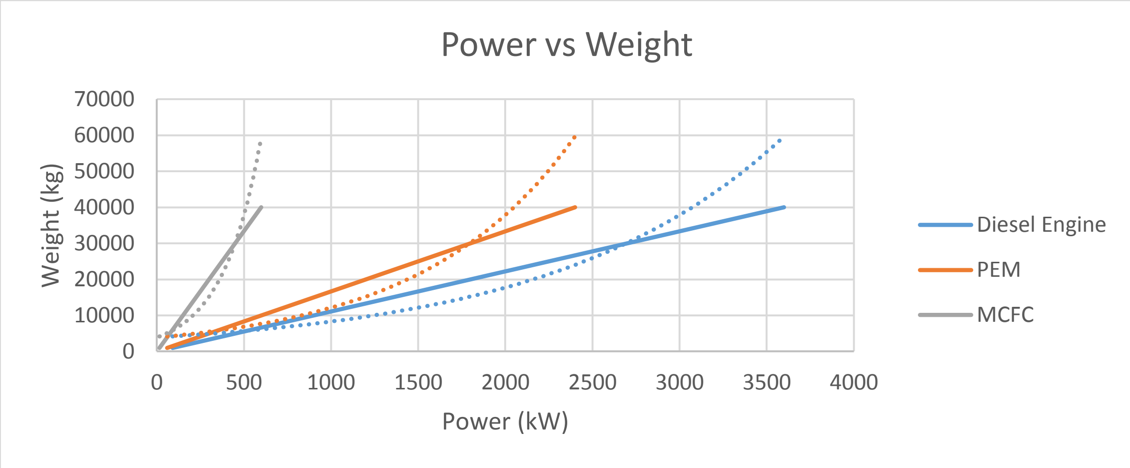
	GAS TURBINE	STEAM TURBINE	DIESEL ENGINE
Efficiency	✗	✗	✓✓
Consumption	✗	✗	✓
Emissions			
CO_2	✗	✗	✓
NOx	✓	✓	✗
SOx	✓	✓	✗
Cost	✗	✗	✓✓
Size	✓	✗	✓
Weight	✓	✗	✗



The graph above presents the differences of total fuel consumptions according to the studied operational profile. The vessel in two months sailed 5068,06 nautical miles the real consumption is represented in the 4-Strokes Diesel engine, while the other consumptions are referred to a change in the prime mover of the specific vessel.

Recent research has shown that there are another technologies which could possible become a real alternative for marine propulsion such as the fuel cells. Fuel cells are a reality in buses and there is a ferry which uses them as the main propulsion system.

The major problems for this systems are weight and volume, both combined make the actual implementation of this system inadequate nowadays. In the following figure, it is shown that for the range of power outputs of coastal ships (1000-4500 kW), the use of MCFC is inadequate and the weight for a 2000 kW is 75% more using PEM than using a Diesel engine.



Finally, the last concern is the volume and storage problems of the Hydrogen required in this propulsion system, in terms of volume the space required for the H_2 is 64 times the space required by the fuel, while the weight of the H_2 is 3 times less.

4. *Conclusion*

For the propulsion of Short Sea shipping cargo vessels whose main characteristics are: short trips, medium-small size and a tight budget, the actual solution is a **4-Stroke diesel engine**. Its efficiency and fuel consumption is significantly better than both steam and gas turbines, while its volume and weight requirements combined with the investment cost makes them more suitable than low speed 2-Strokes. As this vessels does short-distance trips the sailing hours are less than ocean crossing vessels, and the efficiency is not as relevant. Also the heat recovery systems used with power plant diesel engines works on lower temperatures compared to the turbines.

In terms of flexibility, diesel engines are easily adapted to the changing power outputs (1000-4500 Kw) presented in SSS because of their modular character. And the investment cost of the turbines increases as the power output decreases, because of that the gas turbines are more economically suitable for larger vessels.

The tendency of increasing regulations will shortly need a significant change in the use of this technology and due to this, there are another technologies that should be taken under consideration. Fuel cells and batteries as electrochemical energy storage devices, which are already being used as a part of the auxiliary systems, can make a significant change in marine propulsion if future research improves the two main problems: H2 storage and consumption, and low power density. In addition, the space required by this layout makes its use inside small size cargo vessels impossible, because its installation implies a great reduction of the space for cargo.

DEPARTMENT OF MECHANICAL ENGINEERING

MECH 3002 PROJECT
2014/2015

DECLARATION FINAL REPORT

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Abstract

Due to increasing regulations, in terms of NOx, SOx, CO_2 and PM (IMO, 2013), and environmental awareness, the analysis of traditional prime movers used within Short Sea Shipping Vessels is needed. This report starts with the analysis of the mature propulsion systems, which are widely used inside Maritime Transport.: Diesel Engines, Gas Turbines and Steams Turbines. A comparison is presented in terms of energy consumption, environmental impact and economic impact, always regarding to the requirements of SSS cargo vessels. To finalize with an evaluation of the potential of fuel cells and batteries as a future main propulsion system.

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Nomenclature

- BOG: Boil-off Gas
- DWT: Deadweight tones
- ECAs: Emission Controlled Areas
- EEDI: Energy Efficiency Design Index
- EEOI: Energy Efficiency Operational Index
- EPA: Environmental Protection Agency
- EU: European Union
- GHG: Greenhouse gases
- HFO: Heavy Fuel Oil
- HTPEM: High Temperature Fuel Cell
- IFO: Intermediate Fuel Oil
- IMO: International Maritime Organization
- LNG: Liquefied Natural Gas
- LPG: Liquefied Petroleum Gas
- MARPOL: International Convention for the Prevention of Pollution from Ships
- MDO: Marine Diesel Oil
- MFCF: Molten Carbonate Fuel Cell
- NOx: Sum of NO and NO_2
- MGO: Marine Gas Oil
- PEMFC: Polymer electrolyte membrane Fuel Cell
- PM: Particulates matter
- SEEMP: Ship Energy Efficiency Management Plan
- SOFC: Solid Oxide Fuel Cell
- SOx: Sum of SO_2 and SO_3
- SSS: Short Sea Shipping
- SECAs: Sulphur Emission Controlled Areas

1 Introduction

1.1 Motivation

Energy efficiency is commonly defined as the production of the same good or service with lower energy cost. In terms of transport, energy efficiency is directly related to fuel consumption and consequently to emissions.

Maritime transport is a wide field but the project is focused on Short Sea Shipping (SSS) and although there is not a general agreement regarding its definition, it is usually defined as the movement of cargo and passengers which do not cross an ocean. The reasons to focus the study on SSS are subsequently given.

Although the contribution of Maritime Transport to overall CO_2 emissions from transport is 22,6% only represent a 2,5% (IEA,2014). Maritime transport must reduce its CO_2 emissions even further, due to the recent interest the EU has demonstrated in a change from road to sea transport, to alleviate road congestion and reduce emissions.

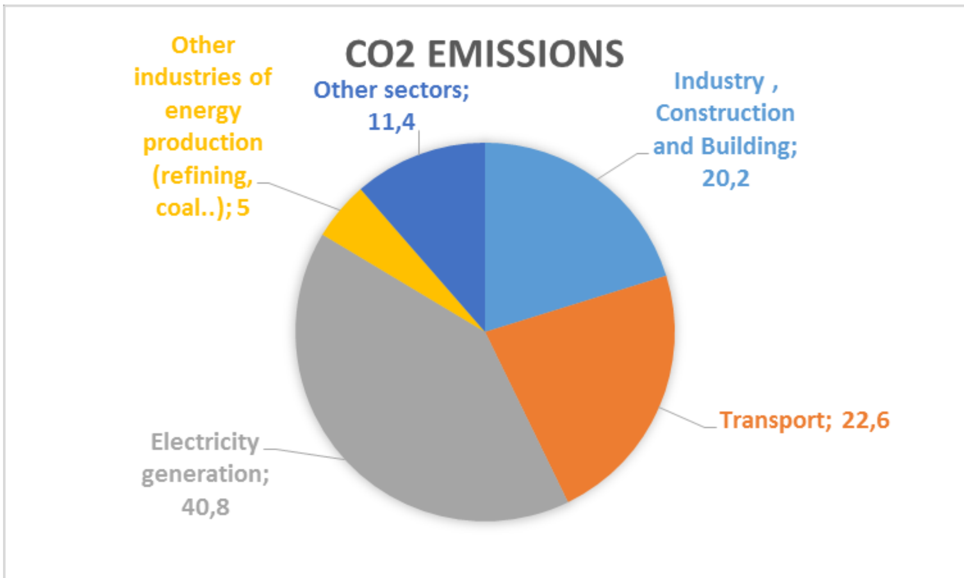


Figure 1: CO2 emissions per sector. (IEA, 2014)

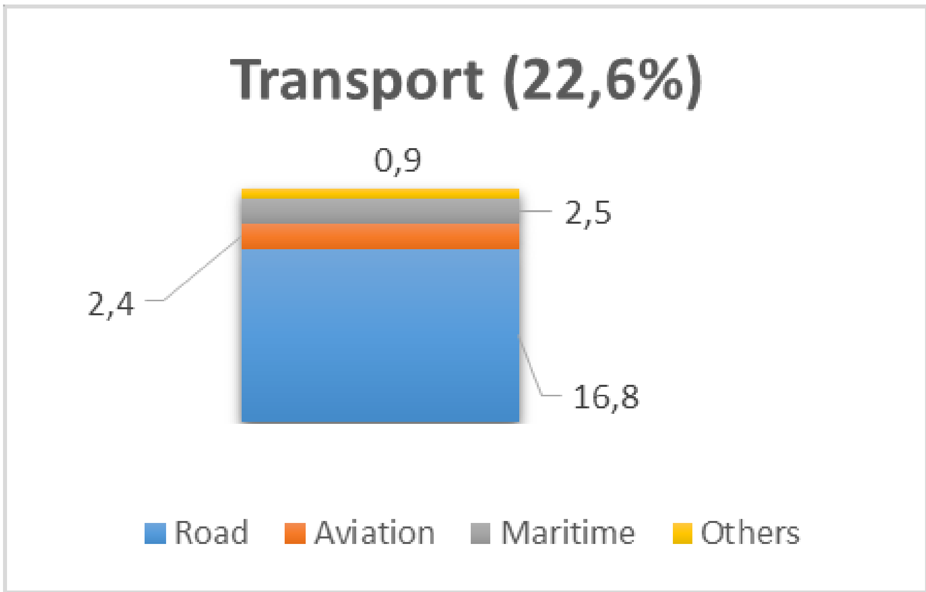


Figure 2: CO_2 emissions per sector. (IEA, 2014)

Secondly, the regulations for this type of transport are becoming more and more restrictive not only for CO_2, but also for NO_X, SO_X and PM. (MARPOL annex VI, 2011). Both the nitrogen and sulphur content in marine fuels are now regulated in the Emission Control Areas (ECAs & SECAs).

Thirdly, as a result of the new regulations and the increased of costs of crude oil, energy costs are rising in this sector. The optimization of energy resources has become a necessity today.

In terms of sustainable mobility, SSS has made a significant contribution and is evaluated in comparison to rail and lorry transport. It is able to hold on with the growth in road transport, performing the 42% t-km in Europe-15 while the share of road is 44%. (Douet M. & Cappuccilli J., 2011)

Finally, a goal of a 40-50% reduction in GHG by 2050 has been settled on by the European Commission (EU, 2011).

1.2 Objectives

The aim of this project is to compare different technologies used in ship propulsion systems, in order to achieve maximum energy efficiency, which will be understood throughout this report as the ratio between Power Output and the Emissions released into the atmosphere.

The objective is to provide recommendations to a future owner of a ship (small-medium cargo) which is going to sail inside the areas of restricted emissions. The overall project will be divided into small milestones, shown below, to achieve the main goal:

- Comprehensive analysis of the actual regulation for Maritime Transport
- Understand the performance of different types of power plants inside an SSS vessel and their actual use.
- Analysis of actual ships operating and their different characteristics in terms of the main propulsion system.
- Develop a pathway to allow comparisons between propulsion systems and to narrow the boundaries of the project.
- Comparison of the different possible types of power plants, in order to conclude which is the most suitable for the type of vessel used as a case study.
- Further evaluation of other technologies which have not yet been completely developed in terms of Maritime Transport.

1.3 Methodology

This project has been divided into steps to manage the size of information available, as well as to narrow the boundaries of the study, in order to achieve the main objective of the project.

The first step was to undertake a careful review of the regulation MARPOL Annex VI (IMO, 2014) to understand and highlight the measures that regulate the maritime transport.

Secondly, a data based analysis of five types of Short Sea Shipping vessels has been made. The result allowed an understanding of the propulsion systems used inside such vessels. A criteria to classify them in SSS was also developed.

Thirdly, an analysis of the main prime movers, and afterwards an evaluation of the possibility to change the propulsion system to the Steam Turbine or Gas Turbine. The comparison has been made in terms of the economic, energy and environmental based impacts. The volume and size of the different layouts has been also taken into consideration. In order to make this analysis quantitative and more specific, the use of a "King Fisher" as a case study has been required.

Finally, the research illustrates that there are a lot of other different technologies that could represent the future of the Short Sea Shipping, making it more environmental-friendly and helping the owners to cope with the increasing regulations. A qualitative analysis of Batteries and Fuel Cells, is shown in the final chapters of the project to point out which could possibly be the future in this mode of transport.

2 Literature review

2.1 Regulation

The International Maritime Organization (IMO) is the first international institution exclusively focused on maritime transport. It was created by the United Nations in 1948, and its headquarters are located in the United Kingdom (London). It is currently formed of 170 member states and 3 associated states, and the general governing body, called the “Assembly” chooses the 40 members of the “Council”, which has the executive role inside IMO.

The main objectives of the organization are summarized in the IMO slogan: “Safe, Secure and Efficient Shipping on clean Oceans”. As a result, IMO has developed and stablished 50 conventions, and over 1000 codes and recommendations inside its main three operational areas: safety, security, and pollution’s prevention.

Within the area of the prevention of the pollution the convention of interest for the project is the **International Convention for the Prevention of Pollution from ships (MARPOL)**, which took place in 1973, and whose first protocol entered into force in 1983. Within the protocol the most relevant part for this project is Annex VI that details air pollution and emissions from ships. This has been revised several times and with significantly tightened emissions limits, this process will continue to make maritime transport as environmental-friendly as possible (IMO,2013).

The MARPOL protocol annex VI establishes measures and regulations regarding the following:

- Ozone depleting substances-Regulation 12
- Nitrogen oxides form the combustion of diesel engines- Regulation 13
- Sulphur oxides and particulate matter- Regulation 14
- Volatile organic compounds-Regulation 15
- Shipboard incineration-Regulation 16
- Fuel oil availability and quality-Regulation 18

The concern for this project are emissions of NOx, SOx, PM and GHG (CO_2). A summary of the regulations relating to these is presented below:

- **NOx**

Regulation 13 of MARPOL Annex VI limits the NOx emissions from diesel engines (excluding emergency engines and exploration or exploitation machinery), it is applied to:

- Diesel engines with power outputs of more than 130 kW installed or that have undergone transformations from 1st January 2000.
- Diesel engines with power outputs of more than 5000 kW and per cylinder displacement at/above 90 litres built between 1st January 1990 and 1st January 2000.

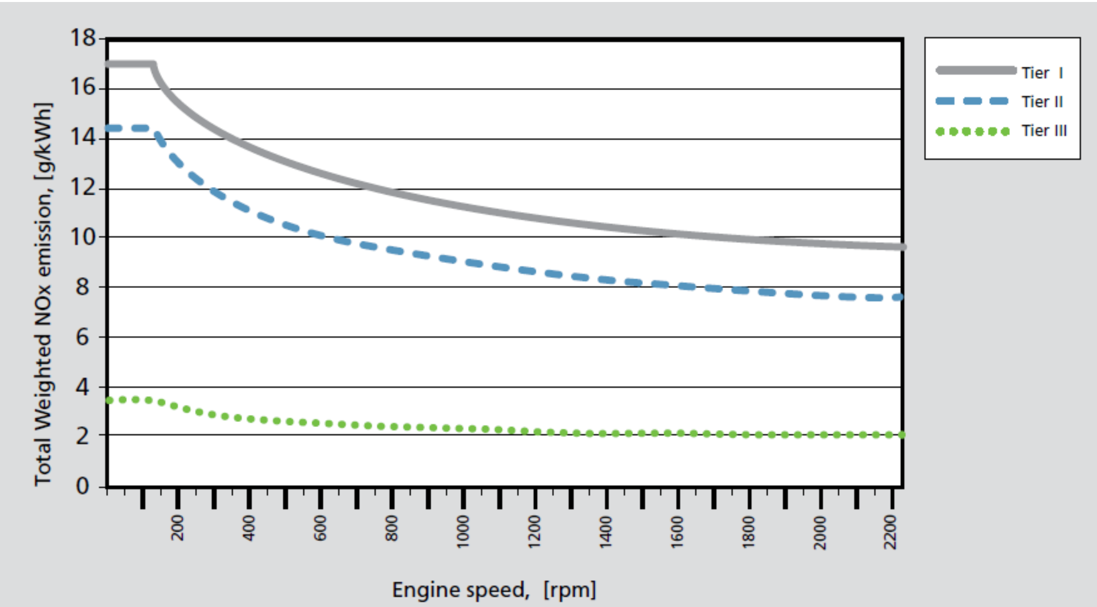


Figure 3: Limits for the NOx emissions from diesel engines (MARPOL 73/78)

Tier I	
Limits [g/KWh]	n [rpm]
17	<130
45*n^(-0,2)	130<n<2000
9,8	>2000

Table 1: NOx limits Tier I

Application:

Diesel engines from ships constructed between 1st January 2000 and 1st January

Tier II (Current Limits)	
Limits [g/KWh]	n [rpm]
14.4	<130
44*n^(-0,23)	130<n<2000
7.7	>2000

Table 2: NOx limits Tier II

Application:

Diesel engines from ships constructed from 1st January 2011

Tier III (Expected)	
Limits [g/KWh]	n [rpm]
3.4	<130
9*n^(-0,2)	130<n<2000
2.0	>2000

Table 3: NOx limits Tier III

Application:

Diesel engines from ships constructed from 1st January 2016 and which operate in the

**Tier III regulations do not concern ships with lengths of less than 24 m or purely used for recreational purposes (5.1.1. Regulation 13). The IMO emission standards are defined as Tier I...III standards.*

- **SOx**

Regulation 14 of MARPOL Annex VI limits fuel's sulphur content, which is responsible for the acid rain. In general these limitations are detailed in the following table:

Sulphur content [m/m]	Date
4.5%	Until 1 January 2012
3.5%	Present
0.50%	From 1 January 2020 (expected)

Table 4: SOx limits

For Sulphur Emission Control Areas (whose explanation is detailed below):

Sulphur content [m/m]	Date
1.50%	Until 1 March 2010
1.00%	After 1 March 2010
0.10%	From 1 January 2015

Table 5: SOx limits inside the SECAs

- **PMs** have a harmful effect on health, specifically causing respiratory problems.

With the new regulation the reduction in the emission of particles is expected to present an 80-85% reduction. The reduction of big particulates (PM>10) will have a local impact, while the reduction of small size particulates (<PM 2.5 and <PM 1.0) will have an impact on respiratory problems and blood circulation. The EPA (US Environmental Protection Agency) expects a reduction in the number of premature deaths caused by the PM 2.5.

The European Union established a limit on sulphur in marine fuels, in EU 1999/32/EC, 4 and the revision of regulation EU 2012/33/EC. The sulphur content in marine fuels inside the territorial waters of a member of the EU, cannot exceed 0,1%. This is applicable to all ships, no matter the nationality, the only exception being if ships stays in port for less than 2 hours.

- **Emission Control Areas**

MARPOL also defines some sea areas as "Special Areas" where the emission of certain pollutants are more restricted because it has been proved that maritime transport's emissions have a negative impact on the environment and public health. The areas, detailed below, have higher standards of protection than other areas due to ecological conditions or because they are located close to urban areas. The ECAs or SECAs established are:

- Baltic Sea area –defined in Annex I of MARPOL (SOx);
- North Sea area – defined in Annex V of MARPOL (SOx);
- North American area (entered into effect 1 August 2012) and United States Caribbean Sea area (entered into effect 1 January 2014) –defined in Appendix VII of Annex VI of MARPOL (SOx, NOx & PM);

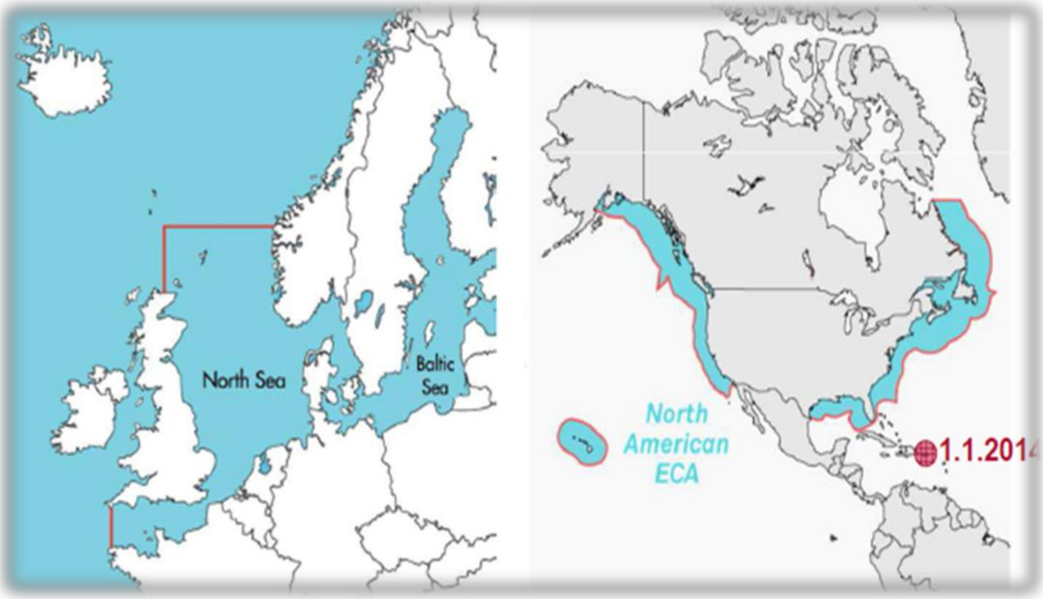


Figure 4: Emission Controlled Areas (IMO, 2013)

- **GHG:**

CO_2 as a greenhouse gas contributes to global warming. From 2011 (MEPC 57/4) two indexes have been established, which became mandatory from the 1st of January of 2013:

- ✓ **EEDI (Energy Efficiency Design Index)**:

The EEDI provides a specific figure for an individual ship design, expressed in grams of carbon dioxide (CO2) per ship's capacity-mile [g/t*nm] (the smaller the EEDI the more energy efficient the ship design) and is calculated by a formula based on the technical design parameters for a given ship (RESOLUTION MEPC. 203(62)).

The aim is to achieve CO2 reduction levels (grams of CO_2 per tonne mile) for the first phase is of 10% and these will be tightened every five years to keep pace with technological developments in efficiency and reduction measures. The more restrictive measures are an incentive to continuously improve in energy optimization.

Application	Cargo vessels whose GT ≥ 400
	Under construction from the 1st of January of 2013 or in operation from the 1st of July of 2013
Excluded	Vessels whose main propulsion system is Hybrid, Diesel-Electric or Turbines (Steam or Gas).

Table 6: Application of the EEDI

Calculation:

The formula in general terms could be understood as:

$$EEDI = {Environmental\ Cost}/{Benefit\ for\ society}$$

$$= {C0_2\ emissions}/{[t * mile]transported}$$

The obtained EEDI must be equal or below the established EEDI:

$$EEDI\ of\ the\ project \leq EEDI\ established\ for\ the\ type\ and\ size\ of\ the\ vessel$$

$$EEDI\ established = \left({(1 - X)}/{100}\right) \times\ Reference\ value$$

**The X is defined as the reduction factor.*

✓ **SEEMP (Ship Energy Efficiency Management Plan)**:

This is an operational measure specified per vessel, where each owner company should establish an operational process to optimize the vessel's performance with the inclusion of different efficiency methods such as route optimization.

The objective is to improve energy efficiency in the operation of a vessel. The ship performance is linked both to the owner company, to the operational conditions and type of vessel.

This is mandatory for all ships, existing and new, from the 1st of January of 2013, and it is based on the following four stages:

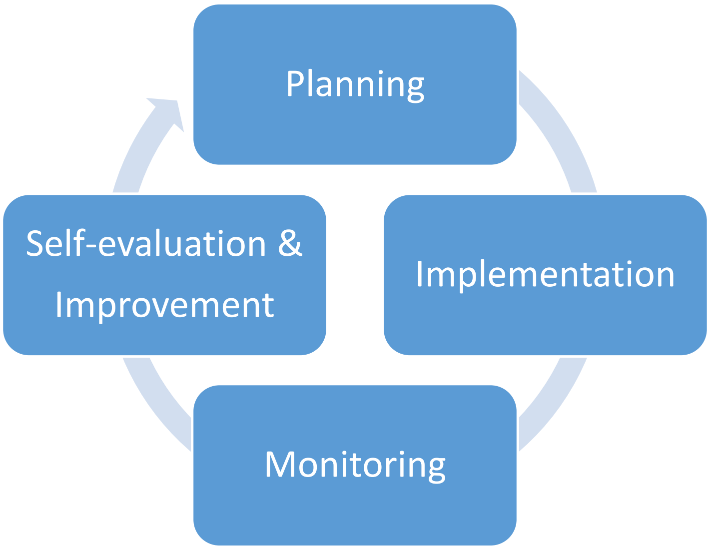


Figure 5: Stages inside the SEEMP

Planning is the first and main step. It is required to clearly identify the actual status of energy usage inside the ship and the goals towards to improvement. It is recommended that there is enough time for planning in order to succeed in the implementation of the most suitable measures. The agreement and coordination between the needs of the ships, the company requirements and the human resources are devoted to the SEEMP.

The second step, implementation, must follow defined tasks and with a clear assignation to qualified personnel. Further, a recording of the dates, problems and possible difficulties found during the process, is strongly recommended.

An important feature of the SEEMP is a quantitative monitoring of energy efficiency, and the use of a standard method such as the EEOI (Energy Efficiency Operational Index) (MEPC.1/Circ.684). This index is mainly used as a complementary tool to the SEEMP and it is useful to provide a measure of the efficiency of a specific vessel.

The final stage is the self-evaluation of the process, as a measure for continuous improvement. The aim is to learn from what has previously been done and increase the energy efficiency levels in the next cycle. In addition, in RESOLUTION MEPC 213(63) there is a summary of the main measures in terms of energy efficient optimization of fuel consumption.

2.2 Gas Emissions from Shipping

Within the energy efficient optimization of shipping whose main concern is the reduction of CO_2 emissions. There is an evident potential for reducing this specific type of emission, but without completely ruling out other types of emissions (SOx, NOx and PM) specified in the previous section.

The formation of CO_2 is directly related to the carbon content of the burnt fuel, and consequently to the fuel consumption. The measures to reduce fuel consumption often imply a rise in temperature and this high temperature in return increases the content of NOx in the exhaust gases (Smith et al. 2013).

The most effective way is reducing the fuel consumption or changing the type fuel the most promising one is the LNG. This potential for improving, in terms of CO_2 emissions, has been estimated to be in a range from 25% to 75% including different types of measures detailed in the following table:

	Saving CO2/Tonne-mile (%)	Combined (%)	Combined (%)
Design (New ships)			
Concept, speed and capability	2-50	10-50	25-75
Hull and superstructure	2-20		
Power and Propulsion systems	5-15		
Low-carbon fuels	5-15 (using LNG)		
Renewable energy	1-10		
Exhaust gas CO2 reduction	0		
Operation (all ships)			
Fleet management, logistics and incentives	5-50 (reduced operational speed)	10-50	
Voyage optimization	1-10		
Energy Management	1-10		

Table 7: Potential to reduce CO_2 emissions in Shipping (Johnson et al. ,2013)

All the energy efficiency measures previously explained are a major concern regarding SSS, because of the recent interest of the EU in a "modal change" from road to sea, the rising energy costs due to the increase in the price of crude oil, the restrictive regulations previously detailed, and because in comparison with the deep-sea shipping, SSS is competing with other means of transport for example rail or truck transport.

There is not a general agreement for a definition of SSS, but it is commonly known as the movement of cargo and passengers that does not imply crossing an ocean (Douet & Cappuccilli, 2011).

According to an EU communication, this type of transport significantly contributes to sustainable mobility, it is the only mode that could be compared to road transport, in terms of growth, covering the 39% of all t-km in Europe while road transport performed 44% between 1995 and 2005 (ibid).

The CO_2 emissions are related to the carbon content of the fuel, as well as the SO_X (the sum of SO_2 and SO_3) are produced in the combustion of any substance, in this case fuel, **containing sulphur** from the following reactions:

$$S + 0_2 \rightarrow SO_2$$

$$2SO_2 + 0_2 \rightarrow 2SO_3$$

The emission of sulphur oxides is also inherent to the content of sulphur of the fuel. While HFO contains up to 4.5% S, the light distillate contain much less sulphur: normally 0.2 to 0.5 %.

In order to decrease this type of emissions, the following technologies could be used:

- Using low sulphur fuels. But the operational cost will be highly increased.
- Scrubbers cut emissions of SO2 by 99% and considerably reduce emissions of other polluting particles, but there are still some concerns about the by-products they produce in the cleaning process.
- Gas engines or turbines can burn liquefied natural gas (LNG) which doesn't contain sulphur and subsequently SO2 emissions close to zero (Raucci, C. et al, 2013).

Finally, the last type of emissions NOx (NO, NO_2 and to a lesser extent N_2O) are mainly originated in **high temperature** combustion reactions. It is not related to the fuel.

$$N_2 + 20_2 \rightarrow NO$$

$$2NO + 0_2 \rightarrow 2NO_2$$

Forming of nitrogen oxides is related to combustion in the sense that oxygen is needed and high temperature are required (both are present locally during diesel engine combustion). The percentage of nitrogen in fuel normally is low.

The NOx abatement technologies are mainly internal engine modifications (Transport &Environment, 2015):

- Designs with Long piston stroke and large bore ratio
- Injection system design: (high) pressure independent from load and speed, shaped ignition curve and optimized control times (MAK Carterpillar, 2014).
- Water injection and exhaust gas recirculation can abate NOx emissions by 30 to 50%.
- The addition of water vapour to the combustion air, NOx emissions could be decreased by 70 to 85%.
- Selective catalytic reduction (SCR): a system to treat exhaust gases after their production but before they are actually emitted. SCR can cut NOx by up to 95%.

Electric propulsion can be used while ships are on port and decrease NOx and SOx at the same time.

2.3 Marine fuels

Fuels used in marine combustion engines and oil-fired boilers are fossil fuels. A fossil fuel is a mixture of many hydrocarbons, i.e structures of carbon (C) with hydrogen (H) attached to it. Besides carbon and hydrogen, fossil fuels may contain some sulphur (S), nitrogen (N), oxygen (O), vanadium (V), sodium (Na)…The properties of fossil fuels are mainly determined by their chemical structure: the carbon structure and the chemical bonds. These properties fix the ratio of carbon atoms: the so-called C/H ratio, which is important for many properties such as density, viscosity, stoichiometric ratio and heating value. They also determine the chemical stability, or more precisely, their inclination to react with oxygen.

The distillate and residual fuels that are used within the marine industry are the products of a sophisticated refinery process which crude oils undergo.

Distillate Products	
Gaseous Fuels	Methane
	Propane
	Butane
	The latter 2 make LPG
Light Fuels: Road transport and aviation	Gasoline/petrol
	kerosene
	gas oil (GO)
	Marine Gas Oil (MGO)
	Light Diesel Fuel Oil
	Marine Diesel Fuel Oil (MDO o MFO)
Lubricating Oils	
Residual Products	
Intermediate Fuel Oils (IFO)	Residual oil blended with up to 20% residual oil
Heavy Fuel Oil (HFO)	Bunker fuel oil or Marine fuel oil

Table 8: Types of Marine fuels

Fuel treatment

Before the fuel is burnt in a diesel engine, a gas turbine or a boiler the fuel needs to be treated after bunkering. Bunker tanks for storage of heavy fuel oils on board ships must be heated since otherwise pumping from those tanks to the settling tank is not possible. A temperature of 5ºC above the pour point is usually sufficient. In general the temperature will be kept about 35ºC.

The settling tank is the first step in the fuel cleaning process. Water and sediments can be segregated by gravity. The tank must be sufficiently high and preferably tapered to the bottom. The water and sediments can be drained off at the bottom of the tank. For modern heavy fuel oils the settling tank must be heated to temperatures of 50 to 100ºC, to increase the rate of separation.

After settling, fuel treatment of distillate fuels may only consist of a filter if virtually no water is present. If water is expected a centrifuge and a filter will be fitted to remove any water that is still present. In case of more stringent requirements, as for gas turbine plant, a centrifuge and a coalescer filter might have to be installed.

For residual fuels the treatment will be more extensive. If the residual fuel is burnt in a boiler, the fuel will go through cold and hot filters after the settling tank. If the residual fuel is burnt in an engine, the treatment is more complex: in addition to the settling tank and filters, centrifuges will be installed to separate particles (clarifier) and water (purifier) from the fuel.

2.4 Different technologies

2.4.1 GAS TURBINE

The Gas turbine is a rotating internal combustion machine. The chemical energy of the fuel is transformed into mechanical energy at the output shaft. The conversion process has two different steps: the first is the combustion reaction of the fuel and the working fluid and after the second is when the thermal energy obtained is converted into mechanical energy (EOI, 2008).

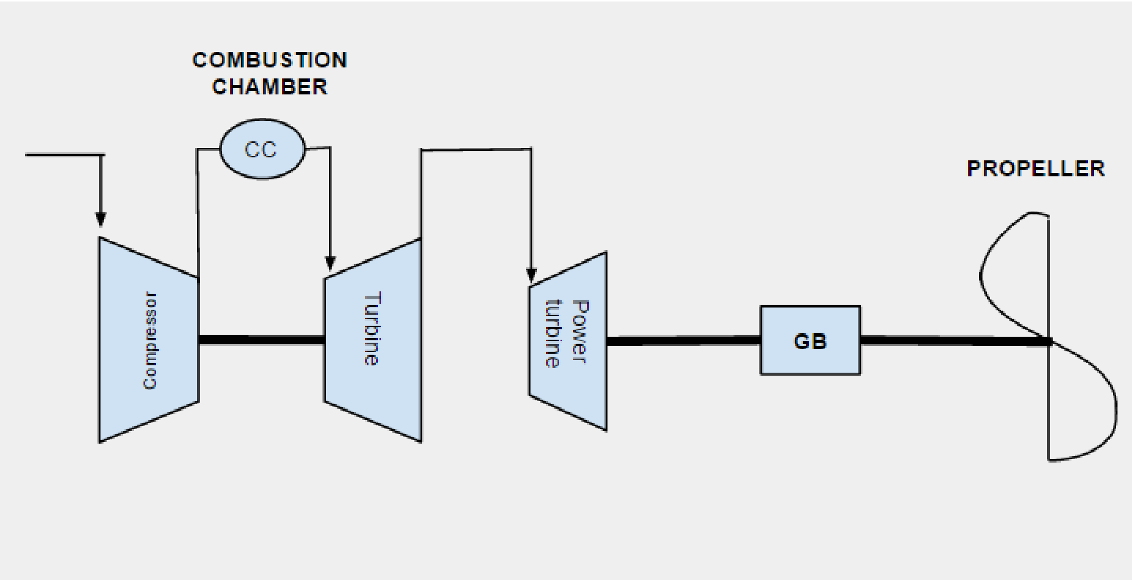


Figure 6: Gas Turbine Layout

The Gas turbine system consists of a compressor, a combustion chamber, a turbine and inlet and exhaust ducts. The output speed of the turbine is high ranged between 3000 and 7000 rpm, so a reduction gearbox is needed (Woud et al, 2002).

In general terms, the efficiency of a Marine Gas Turbine is settled between 28-34%, and its range of power outputs is between 3 and 40 MW. For lower power outputs the efficiency decreases (Fenercom, 2010). The following figure shows the electrical efficiency in ISO conditions among the existing gas turbines. The electrical efficiency is a good approximation of the mechanical efficiency which is a little higher (from 25.7% to 27.1% because of losses of the alternator).

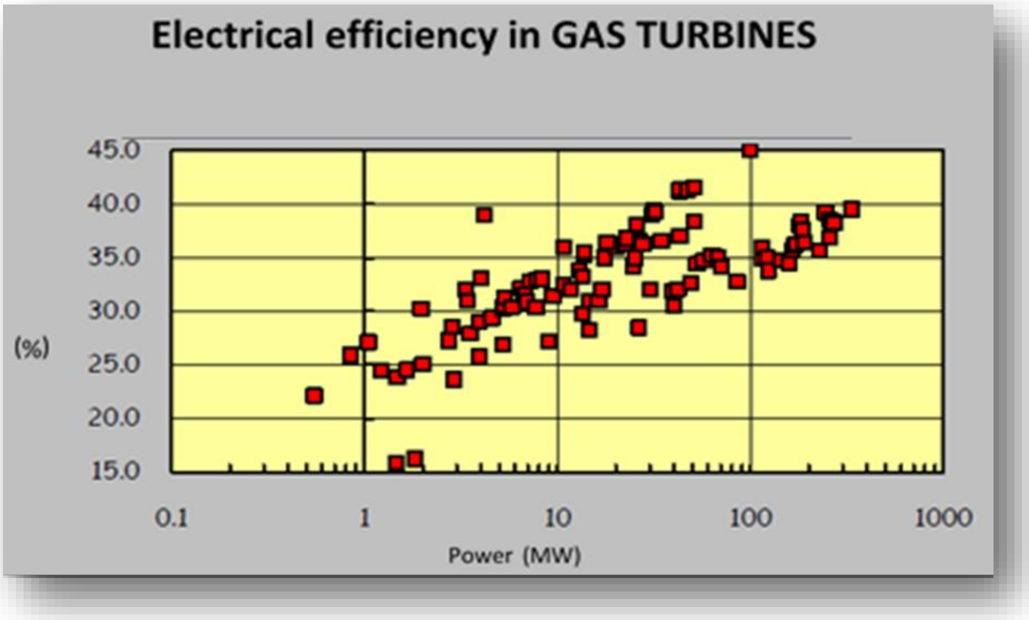


Figure 7: Gas Turbines Electrical Efficiency

<u>Thermodynamic Cycle:</u>

Gas Turbines engines use the **Brayton Cycle**, which describes the workings of a constant pressure heat engine. Table 8 describes the processes of the cycle (Woud et al, 2002):

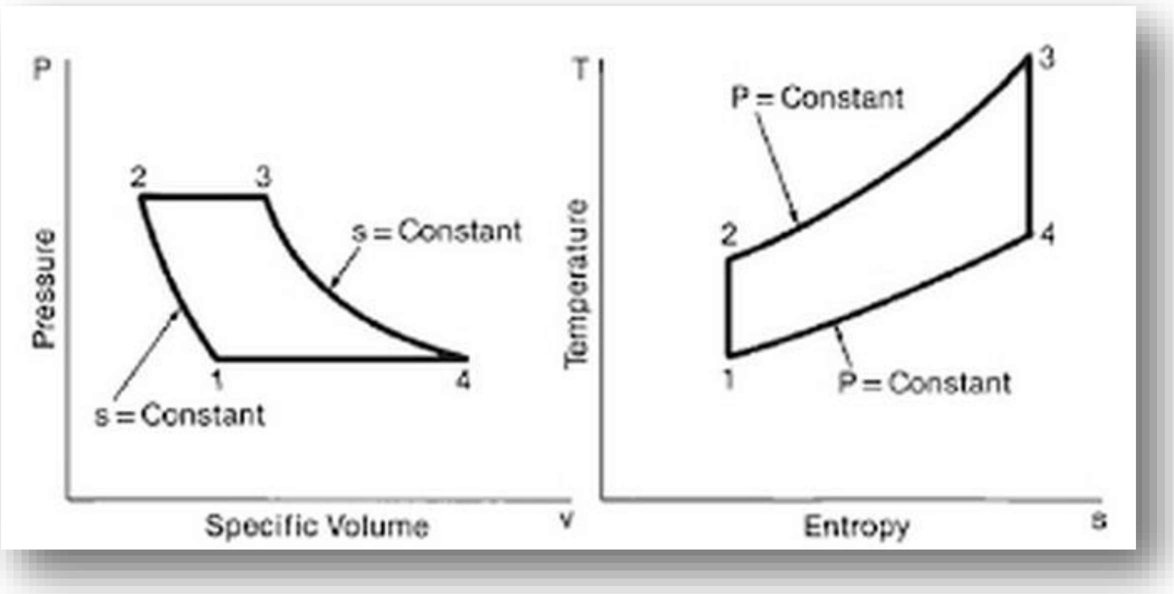


Figure 8: Brayton Cycle

Process	Description	Volume	Pressure	Temperature
1-2	Compression	↓	↑	↑
2-3	Combustion	↑	Constant	↑
3-4	Expansion	↑	↓	↓
4-1	Heat discharge	↓	Constant	↓

Table 9: Processes of the Brayton Cycle

The parameter which limits efficiency is the highest temperature in the cycle, which is reached at the end of the combustion process. Due to metallurgical requirements: the use of steel in the blades, the efficiency cannot reach higher values (EOI, 2008).

Advantages and Disadvantages:

- ✓ Gas turbines are light and compact due to the high power density.
- ✓ As a result of the absence of alternative movements and friction between solid surfaces in rotating machines, lower balancing problems and less lubricating oil consumption are required.
- ✓ Fast starting-up time, in approximately 1 minute it is directly loaded.
- ✓ Less emissions NOx, which makes this system more suitable to sailing in restricted areas.
- ✗ High fuel consumption combined with the higher quality of fuel required.
- ✗ It is not designed to be repaired on board.

Application

The use of aero-derivative turbines with high power density is common among ships such as fast ferries or frigates where space and speed are the main requirements. In addition, this type of propulsion system provides high levels of power quickly which is a necessity in naval vessels such as frigates because of necessary fast approach to other ships (Woud et al, 2002).

In basic applications the turbine that drives the compressor is also connected to the load: SINGLE-SHAFT type. This type of turbine is used for generator drive in which case the shaft speed is kept constant. For direct mechanical drive of a propeller shaft, a gas turbine invariably has a separate turbine for the load: the power turbine. With a separate power turbine the load can follow the propeller law.

The compressor, the corresponding compressor turbine and the combustion chamber from a separate unit: the gas generator.

If the gas generator is derived from an engine used in the aircraft industry the engine is an aero-derived gas turbine, which of course is light and often high-tec (High investment cost). The process of adding a power turbine and adapting the burners from kerosene to diesel fuels is called **marinising** the gas turbine.

On the contrary, the bigger gas turbines that are directly designed for stationary applications are called industrial gas turbines or heavy duty gas turbines. Apart from being generally being bigger (up to an over 100 MW), these are relatively heavy machines not designed for aeronautical purposes. In the past, heavy duty gas turbines used to be technologically more conservative (lower maximum temperatures) when compared to aero-derived gas turbines but this difference has disappeared in modern engines.

2.4.2 STEAM TURBINE

The Steam Turbine is a rotational heat engine of external combustion.

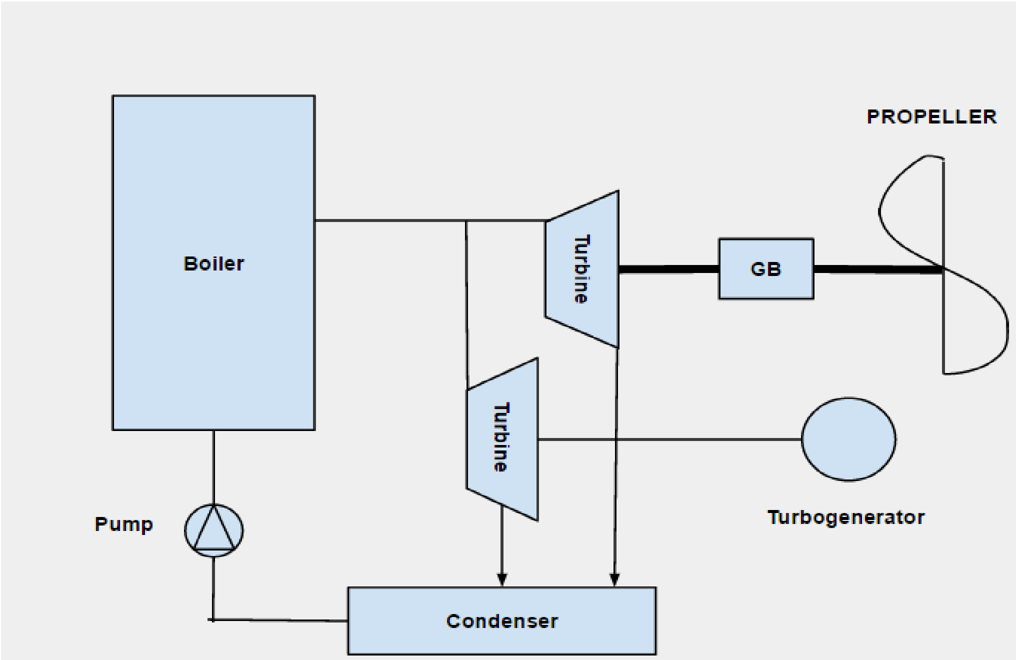


Figure 9: Steam Turbine Layout

The Steam turbine plant consists of a boiler, turbine(s) connected to a gearbox for propulsion, a sea water cooled condenser and a pump to feed the water into the boiler. The major problem with this layout is the large boiler causes leakage from the piping required (Fenercom,2010).

<u>Thermodynamic Cycle:</u>

Steam Turbines power plant systems are explained by the Rankine Cycle.

Process	Description	Location
1-2	Compression	Pump
2-3	Heating to saturation	Boiler
	Superheating	
3-4	Real Expansion	Turbine
3-4'	Expansion (Constant enthalpy)	Turbine
4-1	Rejection of heat	Condenser

Table 10: Processes of the Rankine cycle

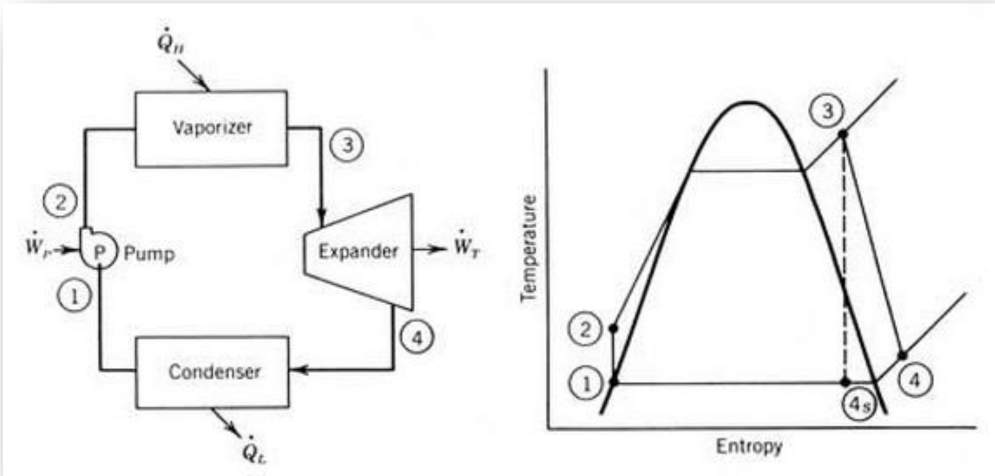


Figure 10: Rankine Cycle

The major concern is the boiler, the size and maintenance combined with the piping required and the leakage caused makes this part of plant the largest source of problems. Further, in marine applications the pressure is around 40 bar and the corresponding Temperature is 250ºC, so the efficiencies are low; at; 30% (Woud et al, 2002).

<u>Advantages and Disadvantages:</u>

- ✓ Burns most fuel oils or can use a nuclear reactor
- ✓ Low maintenance cost
- ✓ Low vibration and noise level
- × Low power density, the engines room is larger compared to compact diesel engines. In addition, the entire system is heavy and complex.
- × Slow fasting-up, several hours are required to heat up the boilers.
- × High initial cost
- × Low efficiency of 25-30% (ibid)

<u>Application</u>

The use of steam turbines is currently suitable for LNG carriers, because this power plant can use boil-off gas (BOG) generated from the cargo tank combined with other fuels. 10% of the LNG vessels included in the research presented in chapter 3 have this system as their main propulsion (crls.com, 2014) for instance "Sun Arrows". Another application of the steam turbine power plant is in nuclear propulsion. Some examples of this propulsion are: "Shapir" submarine and the icebreaker "Artika class NS 50" (marinetraffic.com, 2015).

The steam turbine has lost ground in the propulsion application because it has low power density, lower fuel economy than the diesel engines and high initial costs. However, a steam turbine plant can burn most fuels in the boilers or use a nuclear reaction as a heat source.

Sometimes a steam turbine is used in combination with a gas turbine this combined power generation is sometimes referred to as COGEN but also as COGAS (combined gas and steam turbine plant). A gas turbine produces exhaust gases, which contain a large amount of thermal energy. This thermal energy can be used to generate steam for a steam turbine. This increases the overall efficiency of the power plant, but it also increases initial costs.

2.4.3 DIESEL ENGINE

Diesel Engines are reciprocating internal combustion machines and are the most commonly used prime mover in maritime transport. Their efficiency is related to the compression ratio (Ayub, 2010).

Advantages and Disadvantages:

- ✓ Small sensibility to fuel quality
- ✓ High reliability and due to their simple and well-known technology, maintenance is easy.
- ✓ High efficiency, the intermittent character of their combustion makes their efficiency good at the design point but also at part loads, where the ship is usually operating (80% load)
- ✓ Small investment cost compared to turbines
- × Low power density compared to gas turbines
- × Pollutant emissions: SOx, PM and high levels of NOx emissions because of the temporary very high temperatures after ignition.

	2-STROKES DIESEL ENGINE "LOW SPEED"	**4-STROKES DIESEL ENGINE "MEDIUM-HIGH SPEED"**
Efficiency	10% more	-
Working Principle	2-strokes to complete one working cycle	4-strokes to complete one working cycle
Power outputs	High Power (>5MW)	Low Power (500-10000 kW)
Necessities	Extensive lubrication	Exhaust valves
Speed	85-120 rpm	300-1000 rpm
Gearbox	Not required	required
Size [m^3]	50% more	-
Weight [kg]	30% more	-
Cost	High	Medium (in comparison)
Application	Large deep sea ships: Bulker containers, large fishing vessels,	Coastal, Small size cargo vessels

Table 11: Comparison of main characteristics 2-Strokes and 4-Strokes Diesel Engines

In larger applications (MW) 2-Strokes is about two times better in terms of the Power/weight ratio but regarding smaller applications the ratio decrease and the effectiveness is very similar(ibid). In general terms, the large low-speed 2-stroke diesel engine can only be installed in relatively big ships, which have power outputs of 30 to 80 MW a figure that is still growing, particularly for containerships.

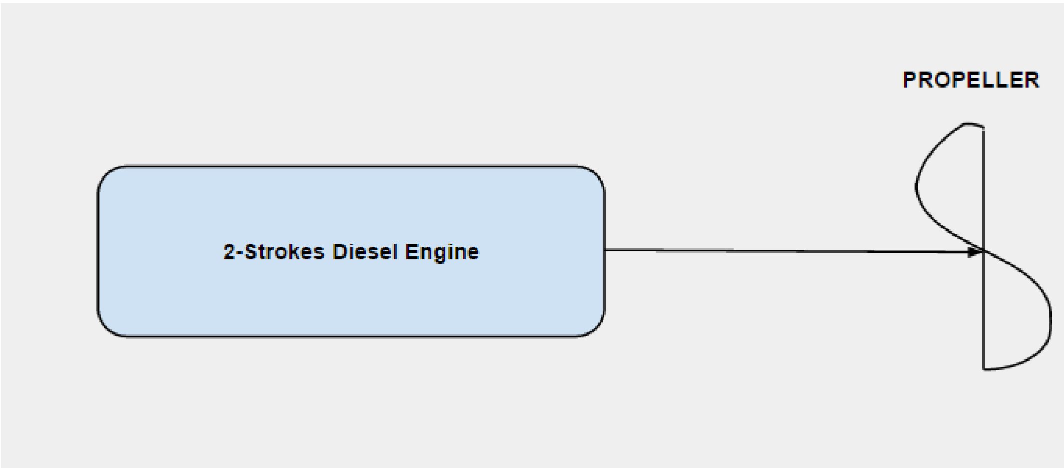


Figure 11: 2-Strokes Marine Diesel Engine Layout

Probably the most common propulsion set up in deep sea large vessels such as Bulkers, container ships, OBO, large fishing vessels, and tankers.

The engine is generally a slow speed two stroke engine, whose main manufacturers are B&W Sulzer Mak or Wartsila. It is directly connected to the propeller shaft. This set up is simple, efficient and "easy" to operate and maintain.

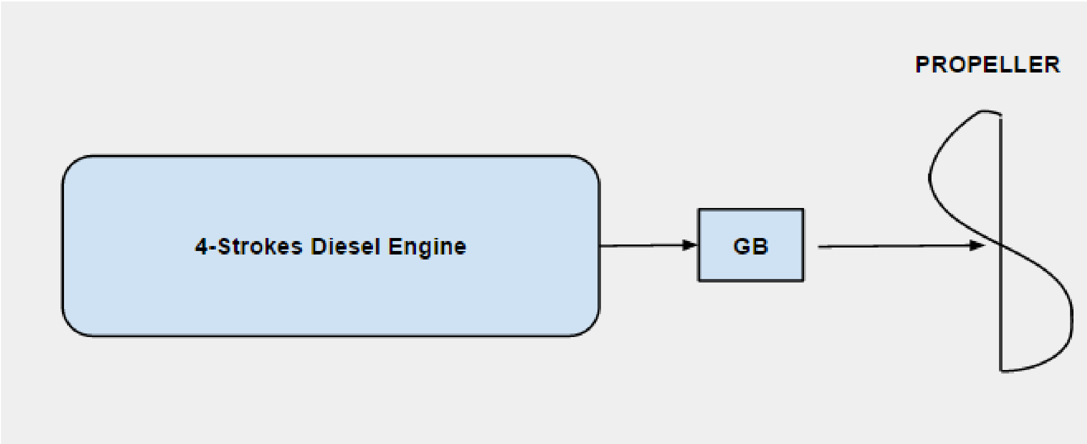


Figure 12: 4-Strokes Marine Diesel Engine Layout

This set up is common on larger fishing boats, coastal freighter, some medium size tugs (~4000 hp), it is without doubt the most common type of power plant, as a result of the analysis of the current SSS vessels operating in the world. The parts are easily serviceable because there usually "off the shelf".

One four stroke medium speed Diesel engines which is geared and can be run without turning the shafting because of the clutch. The set-up is straight forward and easy to maintain.

For smaller vessels, like the SSS vessels which have been considered in this project, the medium-speed 4-strokes diesel engines are popular. The power of these engines is lower: the Wartsila 64 develops a maximum of about 18 MW with 9-cylinder in-line engine and 35 MW with a 18 cylinder V-engine. The power density of a medium-speed engine is higher than the power density of a low-speed engine; this results in lower weight and volume for a required power. For small ship, the specific type regarded, the high-speed engine offers a compact solution up to 7 or 8 MW per engine.

The efficiency of a diesel engine is much better than the efficiency of a gas turbine or a steam turbine; this is true at the design point and even more so at part load. The fundamental cause of the high efficiency of diesel engines is the intermittent character of the combustion, which allows high peak temperatures in the cylinder without causing an extreme continuous thermal loading of the surrounding materials. A major disadvantage is that the harmful nitrogen oxides (NOx), previously explained, easily form at high temperatures.

As for any other machine involved in energy conversion, the power-speed characteristics, the power density and the fuel economy are important issues for a diesel engine. Other characteristics are maximum obtainable power, air consumption, emissions and cost. All of them are considered in the chapter comparison of power plants. Diesel engines can, broadly speaking, be divided into two or three categories based on engine speed: low-speed, medium-speed and high-speed.

The diesel engine with the introduction of the turbocharging become more and more popular in ships propulsion. The development of the turbocharging has result in an increase in the order of two or three for a given cylinder volume. As a result, it is now possible to power the larger ships with diesel engines, and therefore the steam turbine is nowadays a thing of the past.

3 Initial Analysis

3.1 Data Based Analysis

To achieve a general understanding of the exiting proportion of SSS vessels and their main propulsion systems, a data base analysis has been undertaken. Because there is not a general agreement on the classification of SSS vessels, the first step is to establish criteria to narrow the boundaries to filter the vessels which are going to sail inside the ECAs and SECAs.

Criteria:

- ✓ Vessels whose DWT ranges between 1000 and 15000 (DWT).
- ✓ Built between 2000 and 2015.

Types of ships evaluated:

Liquid cargo container ships:

1) Product Tanker
2) Liquefied Petroleum Gas (LPG)
3) Liquefied Natural Gas (LNG)

Dry cargo container ships:

4) Container vessel
5) Bulk cargo

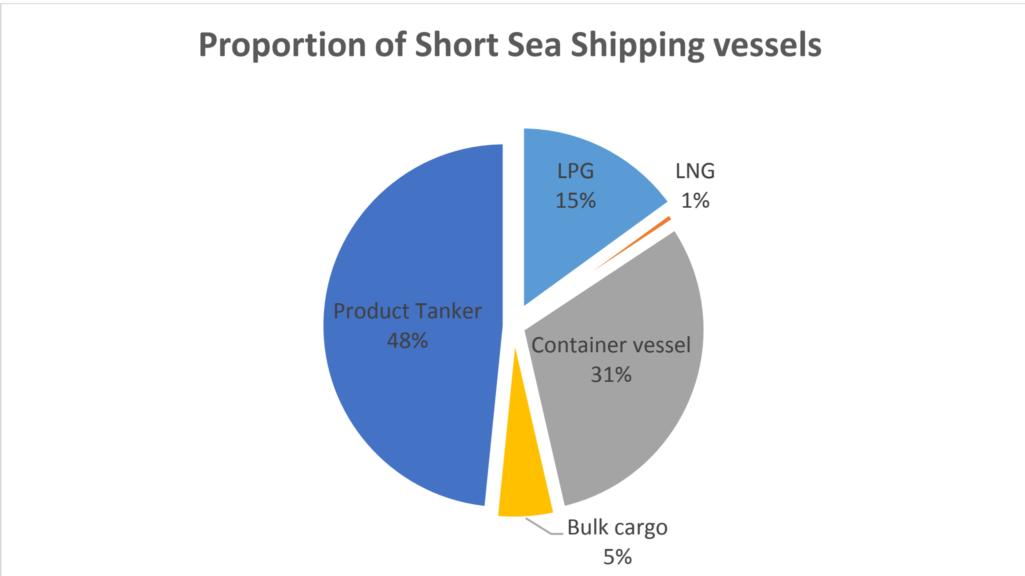


Figure 13: Proportion of Short Sea Shipping vessels (Crsl.com,2014)

Product tankers represent 48% of the total of 2522 vessels. In terms of power plant systems the table below gives the different layouts found in each type of vessel (crls.com,2014).

Type of Power Plant	LPG	LNG	Container vessel	Bulk cargo	Product tanker
Motor Ship 4-Stroke	✓	✓	✓	✓	✓
Motor Ship 2-Stroke	✓	✓	✓	✓	✓
Diesel Electric	✓	✓	×	×	✓
Steam Turbine	×	✓	×	×	×

Table 12: Types of layout per type of vessel

These layout are also found in different proportions, being the 4-Stroke Diesel engine the most commonly used. Inside each layout the number of engines is different, while regarding diesel engines the layout includes a maximum of 2 engines, while the Diesel Electric layouts go from 2 to 5 engines.

The trends over time, which are shown in the appendix, show the change from 2-Strokes to 4-Strokes on every single type of vessel, the main reason being the size and weight of the 2-Strokes, which also called “slow-speed” engines (ibid).

As the objective is to look at the most common layout, the project focuses on Product Tankers, with only one 4-Stroke diesel engine are significantly bigger than the two other options Diesel Electric and 2-Strokes.The use of only one diesel engine represents 54% of the layouts which includes 4-Strokes diesel engines.

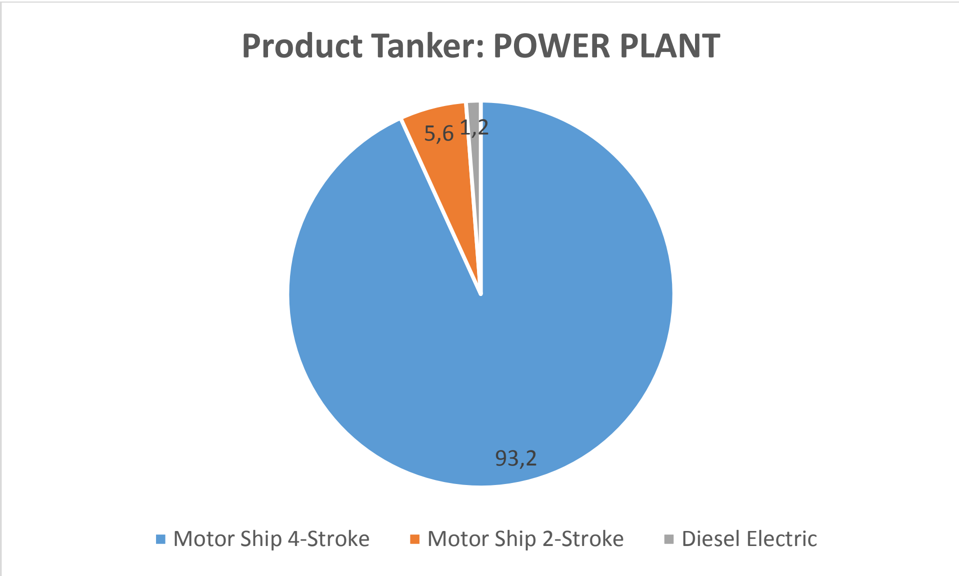


Figure 14: Proportion of each type of power plant (Crsl.com, 2014)

The power output identified ranges from 1000 to 4500 kW for the settled dimensions in this particular type of cargo vessels (ibid).

The next step was to choose a particular ship that matches the previously found characteristics to make the recommendations and the study more precise.

3.2 Vessel used as a case study: King Fisher

The King Fisher vessel is a Product carrier which travels inside the SECAs and also this vessel also matches all the necessities for the case study in terms of: power output, propulsion system, operating profile and dimensions.

Figure 15: King Fisher (Significant ships, 2013)

Vessel Name	King Fisher
Type	Product Carrier
GT	4631
Dwt	7072
Built	2013
Status	In Service
Owner Company	Damen Bergum
Builder	Damen Bergum
Speed (knots)	12,3
Power Type	Motor Ship 4-Stroke
Fuel Type	HFO
Main Engine Unit 1 RPM	750
Engine Derived Total Engine Number	1
Engine Derived Total Mechanical Propulsion Kw	2640
IMO	9556038
MMSI	244790950
Call sign	PCVY
Flag	Netherlands
AIS Type	Tanker
Gross Tonnage	4335
Deadweight	7072 t
Length x Breadth	104,52 m x 17 m

Table 13: Technical characteristics of the King Fisher (crls.com &marinetraffic.com)

3.3 Operating Profile of the vessel used as a case study

On 1st January 2013 the IMO introduced Maritime Energy Efficiency Regulations in order to benchmark the energy efficiency of new ship designs and to create a framework for the management of energy efficient ship operations for all new and existing ships. It is necessary that energy efficiency improvements for design and **operational** performance reflect an understanding of the ship's operational profile, rather than its design condition alone. A ship design is typically carried out by optimising the hull form for a limited range of operating conditions, acknowledging that in recent years there have been significant advancements in the application of ship design optimisation processes, particularly with increasing computing capabilities. However, a vessel only operates in its design conditions a small proportion of the time. To strive towards more energy efficient ship designs, it is first important to consider existing operational practices and how they have changed, and are expected to change, over the years. Furthermore current operational practices can be reviewed as part of a strategy to identify the best measures to improve operational energy efficiency. The aim of detailed operating profiles is to share average operational profile trends, and discus how the identified trends impact on design and operation considerations for energy efficiency. In summary, the operational profile of the vessels is an important issue regarding the energy efficiency in ships.

The data used to perform this analysis and details about the case ships are: voyage type distributions, speed distributions, draft distributions, fuel consumption distributions. An operating profile analyses the proportion of time spent in ballast or laden, in port, manoeuvring or sailing; operational speed ranges, mean draft ranges. Also, the operating profile provides a better understanding of the routes of the vessel and its hours on port and travelling are also found. The following table presents the typical features registered in a detailed operational profile:

Report date/time	Estimated time of arrival	Wind force	Total heavy fuel oil consumption
Duration	Location	Wind direction	Total low sulphur fuel oil consumption
Sailing hours	Port of departure	Sea force	Total marine diesel oil consumption
Report type (sailing, arrival, departure)	Port of arrival	Sea direction	Total marine gas oil consumption
Passage type (ballast, loaded)	Latitude (degrees)	Swell force	Main engine heavy fuel oil consumption
Mean draft	Latitude (minutes)	Swell direction	Main engine low sulphur fuel oil consumption
Forward draft	Latitude (compass)	Current direction	Main engine marine diesel oil consumption
Aft draft	Longitude (degrees)	Current speed	Main engine marine gas oil consumption
Trim	Longitude (minutes)		Main engine power
Comments	Longitude (compass)		Main engine RPM
Observed speed	Vessel Heading		Slip
Observed distance			Auxiliary heavy fuel oil consumption
			Auxiliary low sulphur fuel oil consumption
			Auxiliary marine diesel oil consumption
			Auxiliary marine gas oil consumption

Figure 16: List of typical fields within the ship reports used to perform the analysis presented in this paper

Because of the time and length of the present project this operational profile only presents the time and approximate miles sailed by the vessel used as a case study.

The operating profile of the vessel “King Fisher” has been done using the website **MarineTraffic**.

MarineTraffic provides free, near real-time information to the public regarding vessels' positions, their details and voyage-related information. The initial data collection is based on the Automatic Identification System (AIS). The AIS-Data information that vessels periodically send is being picked up by the network of coastal receiving stations (provided the vessel is within its range). The vast majority of these stations is operated by contributors who are using MarineTraffic-provided equipment or have added their already existing AIS-receiving stations to the network. All collected information is sent to the central database. The central database processes the incoming data, stores the most important part of it and, finally, utilizes it to display the relative information on the Live Map. Ports' and areas' geographic information is also stored along with other information. Thus, users of MarineTraffic can have access to any vessel's position history, statistics and details among other services or use this information to build their own applications using MarineTraffic API services.

Data received is uploaded in our database in real time and, therefore, it is immediately available on the Live Map and on other pages. However, several positions shown on it may not be continuously refreshed - for example, when a vessel goes out of range, as coastal receiving stations have a maximum range of a certain distance. Please, note also that the Live Map is only periodically being refreshed or whenever the user manually refreshes it. As you probably know, coloured icons represent any vessel's position, heading and movement status on the Live Map.

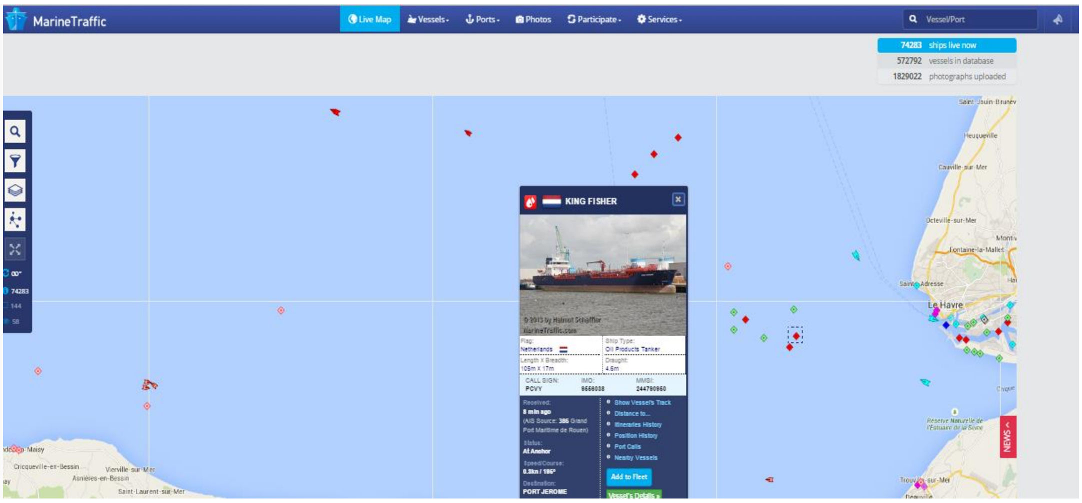


Figure 17: Screenshot of the Live Map and Information provided by the website

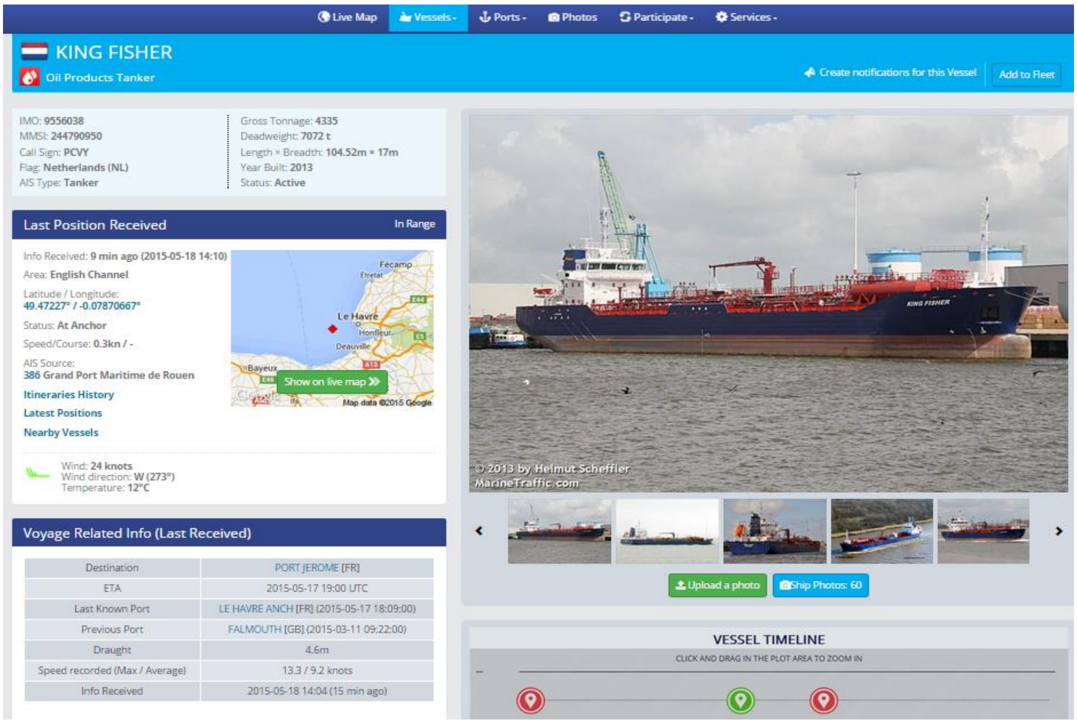


Figure 18: Information of the vessel provided by the website

Marinetraffic, provided the date and time of entry and exit of every port in the 2 months the ship has been studied. Because of the time and length of the present project this operational profile only presents the time and approximate miles sailed by the vessel used as a case study. The fact that the web presented the alert when the ship is inside the port and sometimes because of logistics reasons the ship has to wait outside it was presented as travelling time, when in reality it was non-sailing time or waits, the speed was sometimes very small. In order to have a profile as close to the reality as possible, the main velocity used is the operational speed of 12 knots given in the technical data of the ship. Moreover the length of the trip in nautical miles has been calculated using the Way Points (WP) and google maps. As an example, the longest trip performed by the present vessel is presented in the Appendix 8.1, including the screenshots and all the distances calculated.

The operating profile has been studied for a period of 2 months, and the main features of its trips are presented in the table below:

Operating Profile	
Total nautical miles	5068.06
Maximum distance	1066.24
Maximum time travelling	4 days

Table 14: Operating profile main characteristics

PORT	Latitude	Longitude	Distance [Nautical miles]	Travelling time [hours]
IMMINGHAM GB	53,636	-0,1852		
GRANGEMOUTH GB	56,029	-3,705	255,60	21,30
ROTTERDAM NL	51,943	4,141812	384,40	32,03
CANVEY ISLAND GB	51,512	0,5573133	135,82	11,32
GDANSK PL	54,378	18,67575	1066,24	88,85
RENDSBURG DE	54,307	9,6835	362,11	30,18
BRUNSBUETTEL DE	53,900	9,13189	508,66	42,39
IJMUIDEN NL	52,523	4,592	238,43	19,87
VELSEN ZUID NL	52,472	4,652	3,77	0,31
AMSTERDAM NL	52,379	4,896	10,54	0,88
BEVERWIJK NL	52,493	4,66	11,02	0,92
VELSEN NOORD NL	52,476	4,639	1,28	0,11
IJMUIDEN NL	52,523	4,592	3,30	0,28
ROTTERDAM NL	51,943	4,141812	45,21	3,77
CANVEY ISLAND GB	51,587	0,566	135,82	11,32
ROTTERDAM NL	51,943	4,141812	143,73	11,32

FALMOUTH GB	50,16	-5,073	393,05	32,75
WHITEGATE IE	51,832	-8,258	175,12	14,59
ANTWERP BE	51,302	4,312	622,06	51,84
LE HAVRE ANCH FR	49,553	-0,142	235,96	19,66
HARWICH GB	51,944	1,2799105	173,70	14,48
IMMINGHAM GB	53,636	-0,1852	162,23	13,52
TOTAL			5068,06	

Table15: Operating profile (marinetraffic)

The following graph shows the distance sailed in nautical miles during the observational period, 2 months. SSS vessels operating profile is defined by short-medium trips with periods of 2-3 days on port.

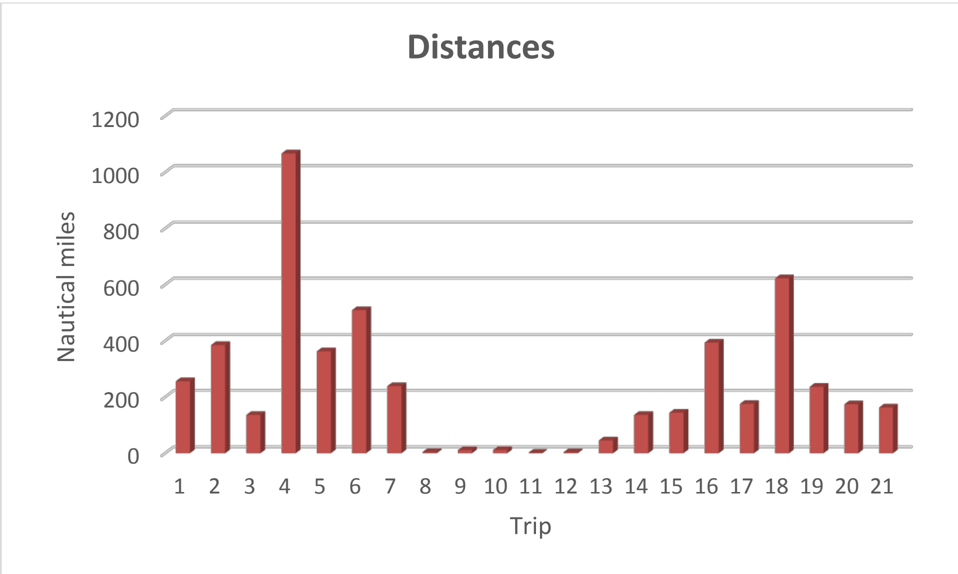


Figure 19: Distance sailed [nautical miles] per trip

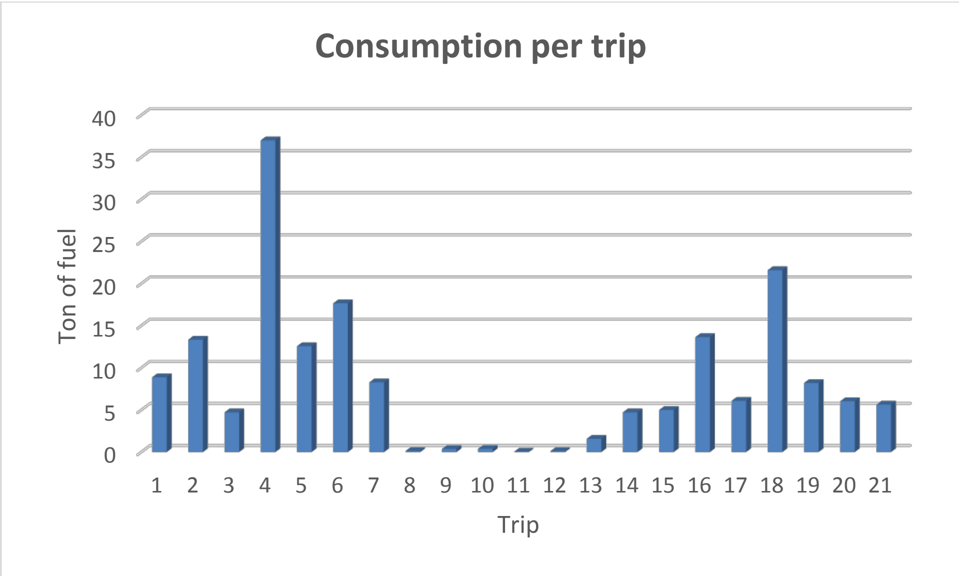


Figure 20: Consumption

Trip	Departure from:	Arrival to:
1	IMMINGHAM	GRANGEMOUTH
2	GRANGEMOUTH	ROTTERDAM
3	ROTTERDAM	CANVEY ISLAND
4	CANVEY ISLAND	GDANSK
5	GDANSK	RENDSBURG
6	RENDSBURG	BRUNSBUETTEL
7	BRUNSBUETTEL	IJMUIDEN
8	IJMUIDEN	VELSEN ZUID
9	VELSEN ZUID	AMSTERDAM
10	AMSTERDAM	BEVERWIJK
11	BEVERWIJK	VELSEN NOORD
12	VELSEN NOORD	IJMUIDEN
13	IJMUIDEN	ROTTERDAM
14	ROTTERDAM	CANVEY ISLAND
15	CANVEY ISLAND	ROTTERDAM
16	ROTTERDAM	FALMOUTH
17	FALMOUTH	WHITEGATE
18	WHITEGATE	ANTWERP
19	ANTWERP	LE HAVRE ANCH
20	LE HAVRE ANCH	HARWICH
21	HARWICH	IMMINGHAM

Table 16: Classification of the trips in order

From trip number 8 to trip number 12 the distances and subsequently consumption are minimum. The miles sailed between these ports are not representative of actual sailing time or miles covered by the ship. A good approximation would have been consider this entire period as “port time”. The following maps shows the ports of the previous trips:

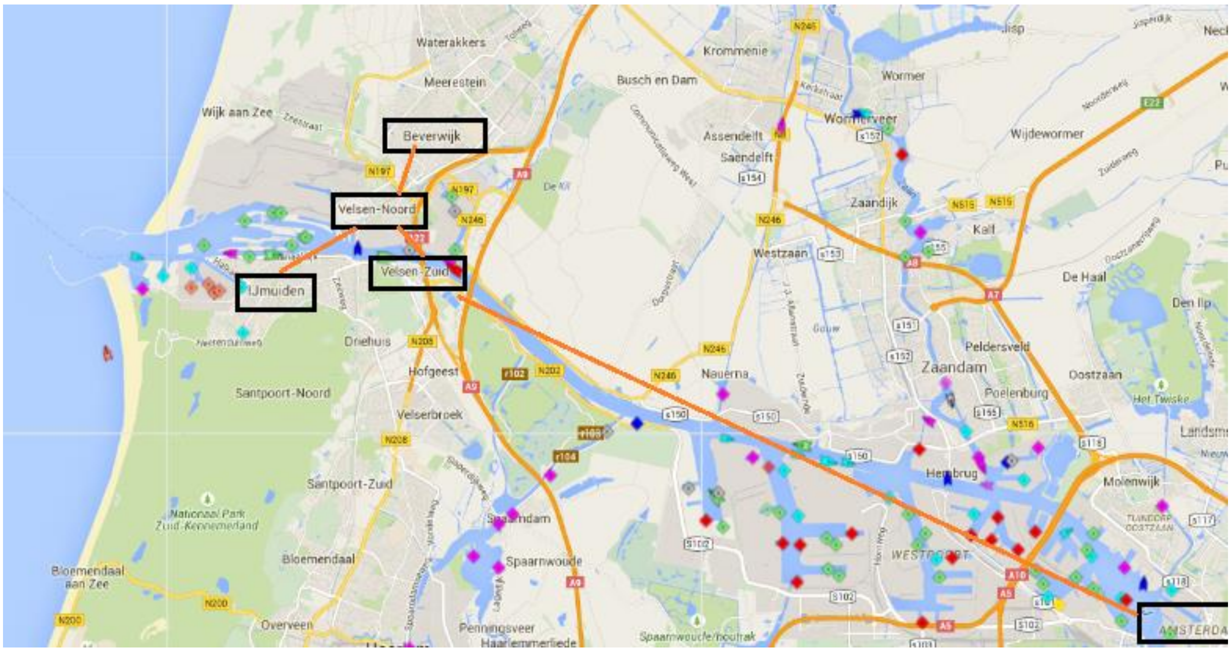


Figure 21: Ports in the Netherlands

4 Comparison of Power Plants

4.1 Introduction

The purpose of this project is to compare different types of power plant systems in order to increase energy efficiency of the vessel used as a case study. The main concern is the ability of this ship to navigate in restricted areas defined by the MARPOL (IMO, 2014): ECAs and SECAs. However the selection of the power plant needs to be based on several parameters, not just one.

The methodology presented defines three main indexes that will allow direct comparisons, these parameters cover the three main areas of concern: energy consumption, environmental impact and economic impact. The detailed calculation of the following indexes using real brochures of the three technologies is presented in the Appendix 8.1.

- Fuel consumption [t/mile]
- CO_2 Emissions [kg CO_2 equivalents /mile]
- Cost: Fuel price [$/mile]

The weight and volume of the power plant as well as the investment costs and the maintainability of the systems will be considered but not in the same detail. The size (weight & volume) of the required propulsion system is also a major concern in such small vessels. The more space for the cargo, the better.

In addition, an operating profile of the vessel "King Fisher" has been done, the detailed data is presented in the appendix 8.3. With the operating profile, a better understanding of the routes of the vessel and its hours on port and travelling are also found.

The procedure to make the comparison starts with a calculation of the efficiency (%) of the main propulsion using existing equipment and translating its technical characteristics to the model, then a calculation of the fuel consumption is made which is used to ascertain the price per mile and the CO_2 emissions. Finally these three indexes are going to be analysed together and compared. The proposed layouts will give a general idea of the space required.

Ships are usually operated at 80% MCR (Maximum Continuous Rating) of engine load. This speed is known as cruise speed. Using the performance data for the "King Fisher" (Adland, 2013):

PERFORMANCES

Trial speed at summer draft with 90% M.C.R. 12.3 knots

Figure 23: Performance of King Fisher (Significant ships, 2013)

Power (% MCR)	Speed (Knots)
100%	12,86
90%	12,30
80%	11,71
70%	11,07
60%	10,37
50%	9,61

Table 17: Speed (knots) per %MCR

The price of the MGO, fuel used in the comparison:

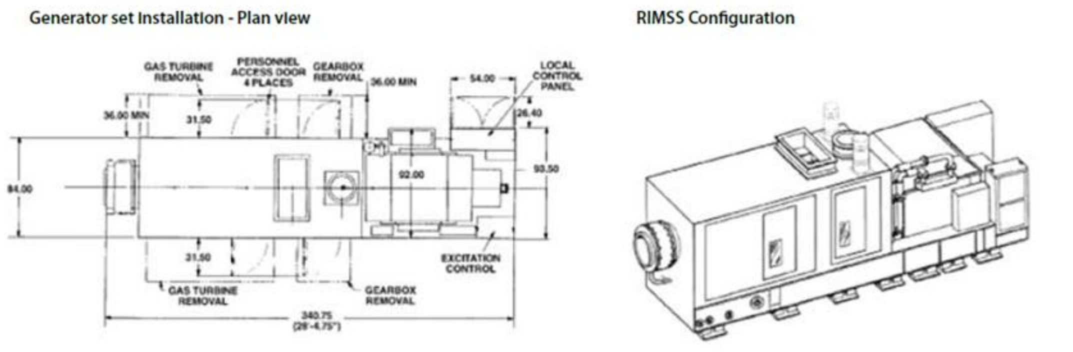
North Europe
Regional Prices

Port	IFO 380 (3.5%)	IFO 180 (3.5%)	MDO (0.1%)	MGO (0.1%)	Del.	Date
Antwerp	325.00 ↑+2.00	355.00 ↑+2.00	---	555.00 ↑+5.00	D	2015-04-17
Rotterdam	324.50 ↑+1.50	357.50 ↑+4.50	---	552.50 ↑+2.50	D	2015-04-17

Figure 24: Fuel prices (Bunker index, 2015)

4.2 Calculation

4.2.1 GAS TURBINE



Allison AG9140 and AG9140RF specifications:

	with bleed	w/o bleed		
Continuous kW*	2500	3000	Length ft.	28.4
Crisis capacity kW**	4500	4500	Width ft.	7.8
Fuel rate BTU/kW-hr.*	15375	13250	Height ft.	11.1
Turbine speed RPM	14340	14340	Weight lbs. (dry)	64,500
Generator speed RPM	18001	800		
Firing temperature °F***	2142	2142	Ratings are at 100°F, sea level with 6" inlet/10" exhaust losses & customer bleed flow as given using DF2 fuel.	
Exhaust gas flow lb./sec.	29.0	31.1		
Exhaust gas temperature °F	1117	1097		
Engine bleed capacity lb./sec.	2.37	0.0		

* Includes generator & gearbox losses. ** For emergency use up to 5 minutes. *** Calculated from turbine outlet temperature measurement.

Figure 25: Commercialised Turbine (Alison, Rolls Royce)

Efficiency:

Fuel rate = 13250 BTU/KWh

$$13250\ {}^{BTU}/_{kWh} \times 1{,}05587\ {}^{kJ}/_{BTU} = 13990.2775\ {}^{kJ}/_{kWh}$$

(To generate 1 kJ 3600 kJ is needed)

$$\eta_{electrical} = \left({}^{3600}/_{13990{,}2775}\right) \times 100 = 25.8\ \%$$

Using this turbine as the main propulsion system increases the efficiency to 27.1 % because there is no alternator generator. Assuming 5% loses in the generator.

Fuel consumption

<u>At 100%MCR</u>

$$\eta_{mechanical} = \frac{25.8}{0.95} = 27.1\ \%$$

$$\left({}^{2640\ kWh}/_{\eta_{mechanical}}\right) = \left({}^{2640}/_{0.271}\right) = 9741.7\ kWh$$

Fuel LHV Lower Heating Value = 42.700 kJ/kg (Brochure)

$$\left({}^{42\ 700\ kJ/kg}/_{3\ 600\ s}\right) = 11.861\ {}^{kWh}/_{kg}$$

$$\left({}^{9741.7\ kWh}/_{11.861}\right) = 821.3\ {}^{kg}/_{h}$$

Ship speed = 12,86 knots (100% MCR)

$$Fuel\ consumption = \frac{821{,}3\,\frac{kg}{h}}{12{,}86\ mles/h} = 63.87\ {}^{kg}/_{mile}$$

$$Fuel\ price = 555\,\frac{\$}{T}\,x\ 0{,}06387\,\frac{T}{mile} = 35.45\ {}^{\$}/_{mile}$$

<u>At 80%MCR</u>

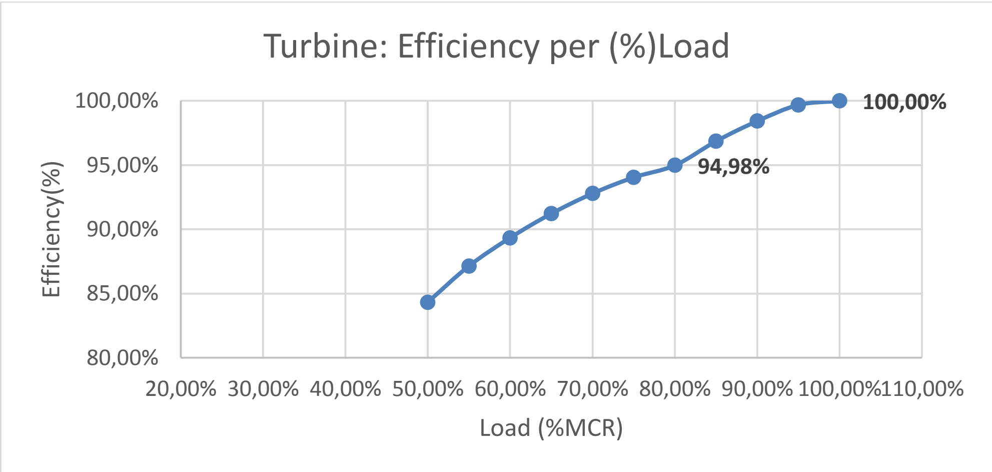


Figure 26: Gas Turbine Efficiency per (%) Load

Load (%MCR)	Efficiency
100,00%	100,00%
95,00%	99,69%
90,00%	98,43%
85,00%	96,87%
80,00%	94,98%
75,00%	94,04%
70,00%	92,79%
65,00%	91,22%
60,00%	89,34%
55,00%	87,15%
50,00%	84,33%

Table 18: Efficiency at different levels of load gas turbines

$$\eta_{mechanical} = 27.1\ \%\ x\ 0.9498 = 25.74\ \%$$

$$\left({}^{2640\ kWh\ x\ 0{,}8}/_{\eta_{mechanical}}\right) = \left({}^{2112}/_{0.25741}\right) = 8\ 205\ kWh$$

LHV Lower Heating Value = 42.700 kJ/kg (Brochure)

$$\left({}^{42\ 700\ kJ/kg}/_{3\ 600\ s}\right) = 11.861\ {}^{kWh}/_{kg}$$

$$\left({}^{8\ 205\ kWh}/_{11.861}\right) = 691.8\ {}^{kg}/_{h}$$

Ship speed = 11.71 knots (80% MCR)

$$Fuel\ consumption = \frac{691{,}8\frac{kg}{h}}{11{,}71\ mles/h} = 59.07\ {}^{kg}/_{mile}$$

$$Fuel\ price = 555\frac{\$}{T}x\ 0{,}05907\frac{T}{mile} = 32.78\ {}^{\$}/_{mile}$$

4.2.2 STEAM TURBINE

The steam turbine efficiency is not a straight forward calculation and a design of the whole plant is needed in order to obtain a comparison of the efficiency with the other plants.

$$\eta_{mechanical} = 25.7\%$$

Typical high pressure boiler efficiency 85%

Therefore, the overall efficiency of steam turbine propulsion will be

$$\eta_{mechanical} = 25{,}7\% \; x \; 85\% = 21.85\%$$

Boiler				Steam Turbine			
	Pinch Point	°C	20		Inlet Pressure	bar(g)	40,5
	Approach Point	°C	10		Inlet Temperature	(°C)	400
	Continuous drain	%	4%		Entalphy	kJ/kg	3.211,7
					Entrophy	kJ/kg°C	6,751
Superheated steam							
	Pressure	bar(g)	45	Condenser			
	Temperature	(°C)	400		Sea Water temperature	°C	15
	Entalphy	kJ/kg	3.203,8		Delta T	°C	10
	Entrophy	kJ/kg°C	6,695		Condensing Temperatu	°C	30
					Pressure	kPa(a)	4,25
Drum							
	Pressure	bar(g)	46	Isentropic Expansion			
	Temperature	(°C)	260,1		Pressure	kPa(a)	4,25
	Entalphy steam	kJ/kg	2.796,6		Temperature	°C	30
	Entrophy setam	kJ/kg°C	6,001		Entrophy	kJ/kg°C	6,751
	Entalphy water sat	kJ/kg	1.135,3		Entalphy	kJ/kg	2.040,0
	Entrophy water sat	kJ/kg°C	2,886		Title	%	78,8%

Figure 27: Design of the steam turbine power plant

Feedwater				Isentropic Efficiency		%	75%
	Pressure on economiz	bar(g)	55,2				
	Eco inlet temperature	°C	106,5	Exhausted Steam			
	Eco inlet Entalphy	kJ/kg	446,6		Pressure	kPa(a)	4,25
	Eco outlet temp	°C	250,1		Temperature	°C	30
	Eco oulet Entalphy	kJ/kg	1.086,2		Entrophy	kJ/kg°C	7,718
					Entalphy	kJ/kg	2.332,9
Feedwater pumps					Title	%	91%
	Inlet Pressure	bar(g)	0,196				
	Inlet temperature	°C	105	Condenser			
	Inlet entalphy	kJ/kg	440,213		Condensate Temperatu	°C	30
	Inlet entrophy	kJ/kg/°C	1,363		Condensate Pressure	kPa(a)	4,25
	Outlet Pressure	bar(g)	58,0		Condensate entalphy	kJ/kg	125,7
	Outlet temperature	°C	106,5		Heat to be disipated	kJ/kg	2.207,2
	Outlet entalphy	kJ/kg	446,90				
	Outlet entrophy	kJ/kg °C	1,380	Steam Turbine work			
	Efficiency	%	85%		Energy	kJ/kg	878,8
	Pump power	kJ/kg	6,69		Mechanical Looses	%	2,50%
	Electrical motor efficie	%	94%		Gear box Looses	%	1%
	Power	kJ/kg	7,12		Power	kJ/kg	848,3
Condensate preheaters				Steam Turbine Power			
					Power	kW	2640
					Overload	%	0%
					Max steam demand	kg/s	3,11
						t/h	11,20
Noiler efficiency			85%		Efficiency	%	27,5%

Figure 28: Design of the steam turbine power plant

Fuel consumption

At 100%MCR

$$\eta_{mechanical} = 21.85\%$$

$$\left(2640\ kWh/\eta_{mechanical}\right) = \left(2640/0.2185\right) = 12082.38\ kWh$$

Fuel LHV Lower Heating Value =42,700 kJ/kg (Brochure)

$$\left(42\,700\ kJ/kg\ /3\,600\ s\right) = 11.861\ kWh/kg$$

$$\left(12082.38\ kWh/11.861\right) = 1018.66\ kg/h$$

Ship speed = 12,86 knots (100% MCR)

$$Fuel\ consumption = \frac{1018.66\frac{kg}{h}}{12{,}86\ miles/h} = 79.21\ kg/mile$$

$$Fuel\ price = 555\frac{\$}{T}x\ 0{,}07921\frac{T}{mile} = 43.96\ \$/mile$$

At 80%MCR

Load (%MCR)	Efficiency
100,00%	100,00%
95,00%	99,69%
90,00%	98,43%
85,00%	96,87%
80,00%	94,98%
75,00%	94,04%
70,00%	92,79%
65,00%	91,22%
60,00%	89,34%
55,00%	87,15%
50,00%	84,33%

Table 19: Efficiency at different levels of load Steam Turbines

$$\eta_{mechanical} = 21.85\% \times 0.9498 = 21.19\%$$

$$\left({}^{2640\ kWh\ \times 0.8}/_{\eta_{mechanical}} \right) = \left({}^{2112}/_{0.2119} \right) = 9966.97\ kWh$$

Fuel LHV Lower Heating Value = 42.700 kJ/kg (Brochure)

$$\left({}^{42\ 700\ kJ/kg}/_{3\ 600\ s} \right) = 11.861\ {}^{kWh}/_{kg}$$

$$\left({}^{9966.97\ kWh}/_{11.861} \right) = 840.314\ {}^{kg}/_{h}$$

Ship speed = 11.71 knots (80% MCR)

$$Fuel\ consumption = \frac{840.314\,\frac{kg}{h}}{11.71\ miles/h} = 71.76\ {}^{kg}/_{mile}$$

$$Fuel\ price = 555\,\frac{\$}{T}\,x\ 0{,}07176\,\frac{T}{mile} = 39.827\ {}^{\$}/_{mile}$$

4.2.3 DIESEL ENGINE

2-Stroke Diesel Engine

Wärtsilä X82	IMO Tier II
Cylinder bore	820 mm
Piston stroke	3375 mm
Speed	65–84 rpm
Mean effective pressure at R1/R1+	21.0/19.0 bar
Stroke / bore	4.12

Rated power, principal dimensions and weights

Cyl.	Output in kW at 76 / 84 rpm		Output in kW at 65 rpm		Length A mm	Weight tonnes
	R1 / R1+	R2 / R2+	R3	R4		
6	28 500	21 720	24 390	18 600	11 045	805
7	33 250	25 340	28 455	21 700	12 550	910
8	38 000	28 960	32 520	24 800	14 055	1 020
9	42 750	32 580	36 585	27 900	16 500	1 160

Dimensions mm	B	C	D	E
	5 320	1 800	12 250	5 400
	F1	F2	F3	G
	14 820	14 800	13 800	2 700

Brake specific fuel consumption (BSFC) in g/kWh

Full load					
Rating point		R1/R1+	R2/R2+	R3	R4
BMEP, bar		21.0/19.0	16.0/14.5	21.0	16.0
BSFC	Standard Tuning	165/163	158	165	158

Part load, % of R1/R1+	85	70	85	70	65
Tuning variant	Standard	Standard	Delta	Delta	Low-Load
BSFC	161.4/159.4	161.0/159.0	160.7/158.7	159.5/157.5	156.2/154.5

For definitions see page 56

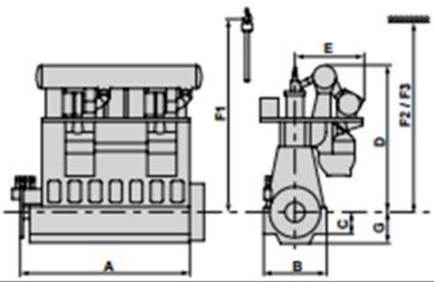


Figure 29: 2-Strokes Diesel Engine Low speed X82 (WÄRTSILÄ)

BSFC (Breal Specific Fuel Consumption) = 158 g/kWh

Fuel specific Heating Value = 42000 kJ/kg

$$0.158\ {}^{kg}/_{kWh} \times 42000\ {}^{kJ}/_{kg} = 6336\ {}^{kJ}/_{kWh}$$

(1 kWh is 3600 kJ)

$$\eta_{mechanical} = \left({}^{3600}/_{6336}\right) \times 100 = 56.8\ \%$$

Due its low speed, this 2-Stroke Diesel Engine doesn't need a gearbox.

Fuel consumption

At 100%MCR

$$\eta_{mechanical} = 56.8\%$$

$$\left(2640\ kWh/\eta_{mechanical}\right) = \left(2640/0.568\right) = 4647.887\ kWh$$

Fuel LHV Lower Heating Value = 42.700 kJ/kg (Brochure)

$$\left(42\ 700\ kJ/kg\ /3\ 600\ s\right) = 11.861\ kWh/kg$$

$$\left(4647.887\ kWh/11.861\right) = 391.863\ kg/h$$

Ship speed = 12,86 knots (100% MCR)

$$Fuel\ consumption = \frac{391.863\frac{kg}{h}}{12{,}86\ miles/h} = 30.47\ kg/mile$$

$$Fuel\ price = 555\frac{\$}{T}x\ 0{,}03047\frac{T}{mile} = 16.91\ \$/mile$$

At 80%MCR

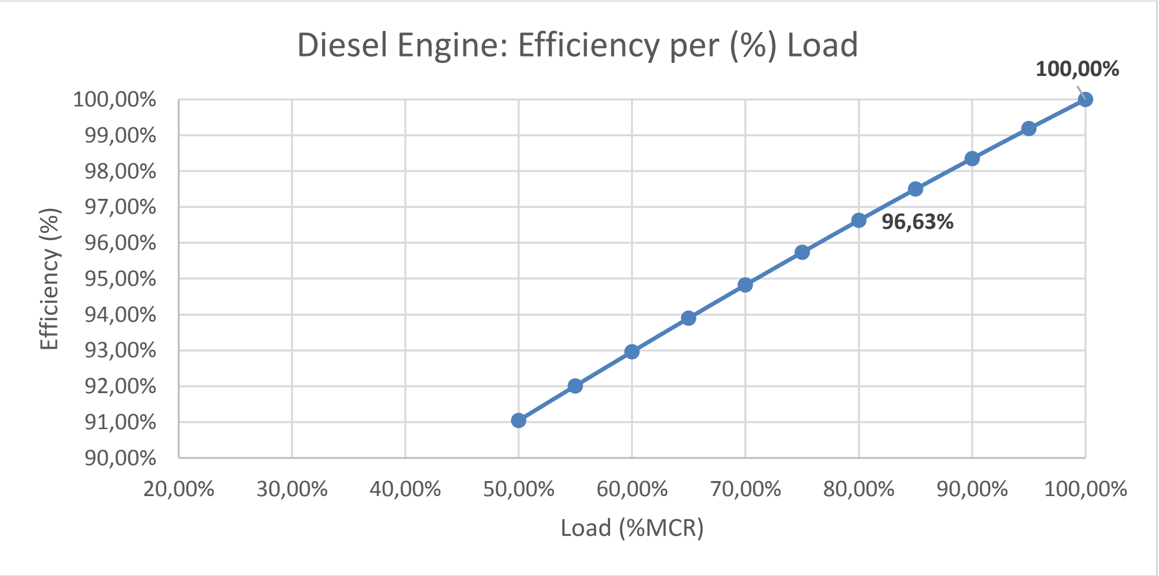


Figure 30: Diesel Engine Efficiency per (%) Load

Load (%MCR)	Efficiency
100,00%	100,00%
95,00%	99,19%
90,00%	98,35%
85,00%	97,50%
80,00%	96,63%
75,00%	95,73%
70,00%	94,83%
65,00%	93,90%
60,00%	92,96%
55,00%	92,01%
50,00%	91,05%

Table 20: Efficiency at different levels of load 2-Strokes Diesel Engine

$$\eta_{mechanical} = 56.8\% \times 0.9663 = 54.89\%$$

$$\left({}^{2640\ kWh \times 0.8}/_{\eta_{mechanical}}\right) = \left({}^{2112}/_{0.5489}\right) = 3847.7\ kWh$$

Fuel LHV Lower Heating Value = 42.700 kJ/kg (Brochure)

$$\left({}^{42\ 700\ kJ/kg}/_{3\ 600\ s}\right) = 11.861\ {}^{kWh}/_{kg}$$

$$\left({}^{3847.7\ kWh}/_{11.861}\right) = 324.4\ {}^{kg}/_{h}$$

Ship speed = 11.71 knots (80% MCR)

$$Fuel\ consumption = \frac{324.4\frac{kg}{h}}{11.71\ miles/h} = 27.7\ {}^{kg}/_{mile}$$

$$Fuel\ price = 555\frac{\$}{T} x\ 0{,}03047\frac{T}{mile} = 15.375\ {}^{\$}/_{mile}$$

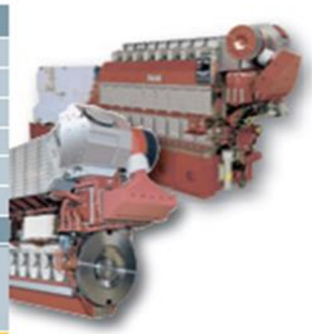
4-Stroke Diesel Engine

Technical Data

PROPULSION + GENERATOR SETS

Number of cylinders	in-line	6, 8, 9							
Bore	mm	255							
Stroke	mm	400							
Cylinder rating	kW	300		308		317		333	
Speed	rpm	720		750		720		750	
Mean piston speed	m/s	9.6		10.0		9.6		10.0	
BME	bar	24.5		23.5/24.2		23.7/25.8		26.1	
Engine rating:		kW		kW		kW		kW	
	6 M 25 C	1,800		1,850		1,900		2,000	
	8 M 25 C	2,320		2,400		2,540		2,660	
	9 M 25 C	2,610		2,700		2,850		3,000	
		60 Hz		50 Hz		60 Hz		50 Hz	
Generator rating:*		kWe	kVA	kWe	kVA	kWe	kVA	kWe	kVA
	6 M 25 C	1,710	2,140	1,760	2,200	1,800	2,250	1,900	2,380
	8 M 25 C	2,200	2,750	2,280	2,850	2,400	3,000	2,530	3,160
	9 M 25 C	2,480	3,100	2,570	3,210	2,700	3,370	2,850	3,560
Specific fuel oil consumption (g/kWh)** tolerance 5 %	MCR 100%	183		183		184		184	
DNV Clean Design		185		185		186		186	
Specific lub oil consumption:		0.6 g/kWh, tol. ± 0.3 g/kWh							
The engine fulfills MARPOL 73/78 Annex VI regulations.									

* Generator efficiency: 0.95, cos φ : 0.8 ** LCV = 42700 kJ/kg, without engine driven pumps



■ M 25 C Propulsion ■ M 25 C Generator Set

Figure 31: 4-Strokes Diesel Engine MAK M25C (MAK)

Fuel Consumption = 184 g/kWh

Fuel specific Heating Value = 42.700 kJ/kg (Brochure)

$$0.184\ {}^{kg}/_{kWh} \times 42700\ {}^{kJ}/_{kg} = 7856.8\ {}^{kJ}/_{kWh}$$

(To generate 1 kJ 3600 kJ is needed)

$$\eta_{mechanical} = \left({}^{3600}/_{7856.8}\right) \times 100 = 45.82\ \%$$

This 4-Stroke Diesel Engine needs a gearbox, regarding the size the losses are approximately 1% of the transmitted power, and as a result the efficiency decreases.

$$\eta_{mechanical} = 45.82 \times 0.99 = 45.3618\ \%$$

Fuel consumption

At 100%MCR

$$\eta_{mechanical} = 45.362\%$$

$$\left({}^{2640\ kWh}/_{\eta_{mechanical}}\right) = \left({}^{2640}/_{0.45362}\right) = 5423.041\ kWh$$

Fuel LHV Lower Heating Value = 42.700 kJ/kg (Brochure)

$$\left({}^{42\ 700\ kJ/kg}/_{3\ 600\ s}\right) = 11.861\ {}^{kWh}/_{kg}$$

$$\left({}^{5423.041\ kWh}/_{11.861}\right) = 457.22\ {}^{kg}/_{h}$$

Ship speed = 12,86 knots (100% MCR)

$$Fuel\ consumption = \frac{457.22\frac{kg}{h}}{12{,}86\ miles/h} = 35.55\ {}^{kg}/_{mile}$$

$$Fuel\ price = 555\frac{\$}{T}x\ 0{,}03047\frac{T}{mile} = 19.77\ {}^{\$}/_{mile}$$

At 80%MCR

Load (%MCR)	Efficiency
100,00%	100,00%
95,00%	99,19%
90,00%	98,35%
85,00%	97,50%
80,00%	96,63%
75,00%	95,73%
70,00%	94,83%
65,00%	93,90%
60,00%	92,96%
55,00%	92,01%
50,00%	91,05%

Table 21: Efficiency at different levels of load 4-Strokes Diesel Engine

$$\eta_{mechanical} = 45.362\% \times 0.9663 = 43.833\%$$

$$\left({}^{2640\ kWh \times 0.8}/_{\eta_{mechanical}}\right) = \left({}^{2112}/_{0.4383}\right) = 4818.617\ kWh$$

Fuel LHV Lower Heating Value = 42.700 kJ/kg (Brochure)

$$\left({}^{42\ 700\ kJ/kg}/_{3\ 600\ s}\right) = 11.861\ {}^{kWh}/_{kg}$$

$$\left({}^{4818.617\ kWh}/_{11.861}\right) = 406.26\ {}^{kg}/_{h}$$

Ship speed = 11.71 knots (80% MCR)

$$Fuel\ consumption = \frac{406.26\frac{kg}{h}}{11.71\ miles/h} = 34.7\ {}^{kg}/_{mile}$$

$$Fuel\ price = 555\frac{\$}{T} x\ 0,03047\frac{T}{mile} = 19.256\ {}^{\$}/_{mile}$$

4.3 Results

	(%MCR)	Efficiency (%)	Fuel Consumption (kg/mile)	Fuel Price ($/mile)	CO2 Emissions (kg/mile)
Gas Turbine	100%	27.1	63.87	35.45	199.09
	80%	25.74	59.07	32.78	184.13
Steam Turbine	100%	21.85	79.21	43.96	246.91
	80%	21.19	71.76	39.83	223.68
2-Strokes	100%	56.8	30.47	16.91	94.978
	80%	54.89	27.7	15.37	86.344
4-Strokes	100%	45.86	35.5	19.77	110.66
	80%	43.8	34.7	19.257	108.16

Table 22: Quantitative Comparison

1. Comparison Gas Turbine 100% and 80% MCR:
   The efficiency is decreased by a 1,9% when the %MCR is the 80%. This reduction makes the fuel prices as well as the consumption together with the CO_2 emissions lower. While the reduction of the efficiency is of the order of 2, the consumption and emissions are reduced by 7.5%. In summary, using this technology at the 80% MCR is more suitable.

2. Comparison Steam Turbine 100% and 80% MCR:
   The efficiency is decreased by a 2% when the %MCR is the 80%. This reduction makes the fuel prices, the consumption and the CO_2 emissions a 9.4% less.
   The reduction in efficiency is almost 1/5 of the decrease of the other features, so this technology also suits the most common performance of the ship.

3. Comparison 2-Strokes Diesel Engine 100% and 80% MCR:
   The efficiency is decreased by a 1,4% when the %MCR is the 80%. A 9.1% reduction is presented in the fuel consumption, the fuel price and the CO_2 emissions.
   The 2-Strokes Diesel engine presents the greatest difference between the decrease in the efficiency and the decrease in the other categories making this technology the most suitable in terms of sailing at the operational speed 12,3 knots.

4. Comparison 4-Strokes Diesel Engine 100% and 80% MCR:
   The decrease of the efficiency is the lowest 0.7%. The fuel price, the fuel consumption and the emissions are decreased over 2%. This technology has the second position in terms of the overall indexes studied, but in terms of space, weight and investment cost the suitability of this type of power plant is greater, this facts will be explained in detail in the next section.

5. Comparison of the four technologies at 80% MCR, which the usual operating point:

   - **Efficiency (%)**: The best efficiency belongs to the 2-Strokes Diesel engine followed by the 4-Strokes (-11.9%), the Gas Turbine (-39.1%) and finally the Steam Turbine has the worst efficiency being 33.7% less than the first one.
   - **Fuel consumption (kg/mile)**: The order is the same but the differences are significantly greater. The consumption of the 4-Strokes Diesel engine is 25.2% more than the consumption of the 2-Strokes. And both turbines because of the lower efficiency increased the consumption by a 113.2% for the Gas Turbine and by a 159.1% for the Steam Turbine.
   - **Price per sailed mile ($/mile)**: It is also directly related to the fuel consumption and the percentages are the same as the Fuel consumption presented above.
   - **CO_2 emissions (kg/mile)**: The emissions calculated in this project are made in terms of the fuel used, using the same fuel for all the technologies the comparison gives a general conclusion the less consumption the less CO_2 emitted to the atmosphere.

In summary, the Diesel Engines (2-Strokes and 4-Strokes) are better alternatives than the turbines (Gas or Steam) in terms of efficiency, fuel consumption, price per sailed mile and CO_2 emissions, using the same type of fuel throughout the comparison.

Regarding fuel consumption per mile, the order is the same but the consumptions in the turbines are: 113,2% more for the gas turbine and 159,1% more for the steam turbine. This great difference in consumption is transferred to the price per sailed mile. Finally, in terms of CO_2 emissions again the prime mover with the less amount of emissions is the 2-Strokes, followed by the 4-Strokes, the Gas Turbine and the Steam Turbine.

Using the operating Profile of the vessel, the total amount of nautical miles sailed is **5068.05** . With this number the total fuel consumption has been calculated for each type of power plant and always using the same type of fuel.

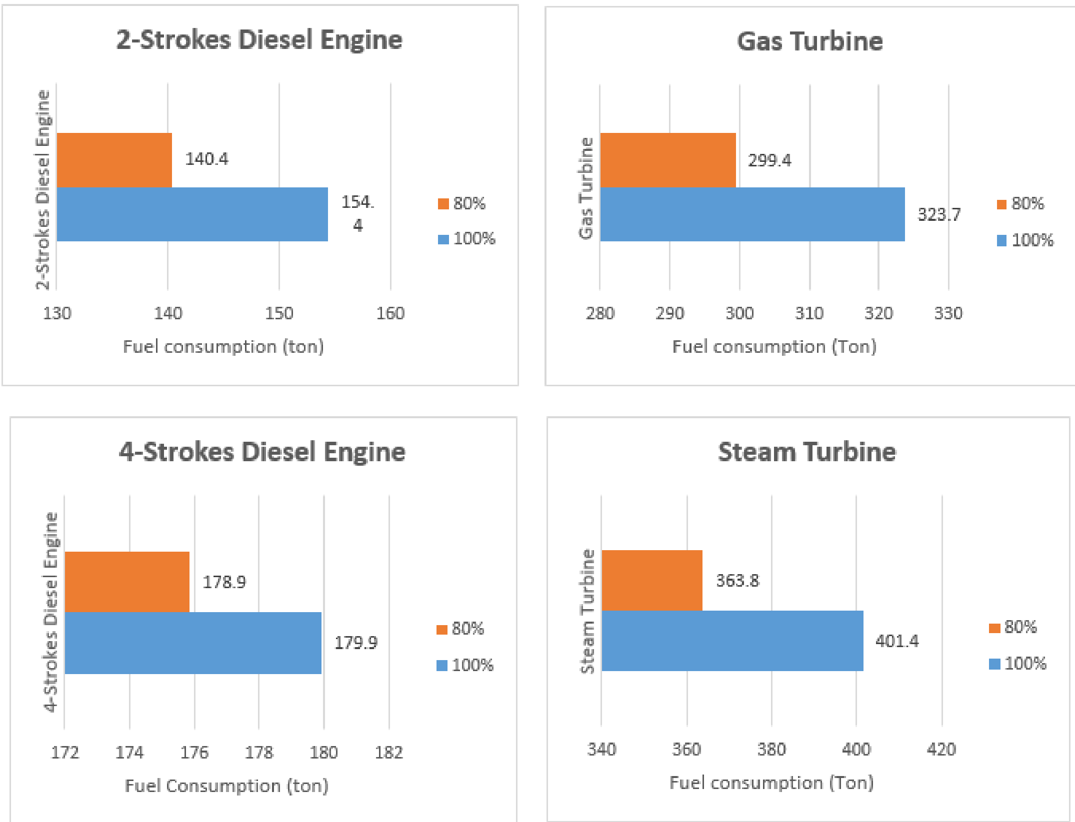


Figure 32: Total Fuel consumption in each type of Power Plant system

Figure 33: CO_2 emissions in each propulsion system

The emissions have been calculated according to the following table, also the graph below shows the reduction of emissions depending on the type of fuel.

Propulsion Technology	Load (% MCR)	Fuel	Fuel consumption	kg/mile	Conversion factor		kWh (PCI)	Emission Factor (CO2 eq kg/kWh)		CO2 kg / mile
4-Strokes Diesel Engine	100%	**HFO**	35.5	kg/mile	**12,42**	kWh/kg	440949	**0,2736**	Kg de CO2 eq/kWh	120.64
		MGO	35.5	kg/mile	**11,86**	kWh/kg	421069	**0,2628**	Kg de CO2 eq/kWh	110.657
		Natural Gas	35.5	kg/mile	**10,7056**	kWh/kg	380049	**0,2016**	Kg de CO2 eq/kWh	76.62

Table 23: Fuel emissions

The increase and reduction of CO_2 emissions rely on the type of fuel (DNV, 2007) as it is shown in the figure below using the fuel consumption of the installed 4-Strokes Diesel Engine.

Figure 34: (%) Emissions with different fuels for the consumption of the installed engine

If the analysis was only based in the emissions, the best solution is using LNG. The use of LNG deletes both the SOx and PM, and reduces the NOx emissions by a 85% and the CO_2 by a 31% (Semolinos et al. 2014). However, that the storage and bunkering of this type of fuel is not easily adapted to the small size ships.

The following table presents the best and worst features of each technology always in terms of the suitability of the technology to the technical characteristics of the vessel used as a case study.

	GAS TURBINE	STEAM TURBINE	DIESEL ENGINE
Efficiency	✗	✗	✓✓
Consumption	✗	✗	✓
Emissions			
CO_2	✗	✗	✓
NOx	✓	✓	✗
SOx	✓	✓	✗
Cost	✗	✗	✓✓
Size	✓	✗	✓
Weight	✓	✗	✗

Table 24: Final comparison

In summary:

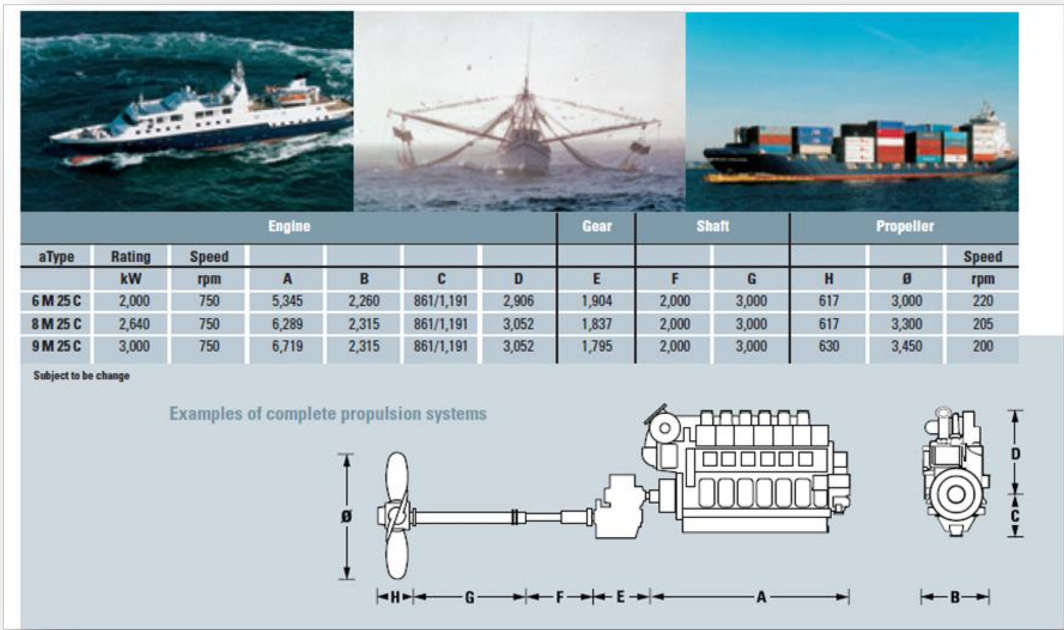
Regarding efficiency, diesel engines are better than Turbines.

In terms of fuel consumption nowadays the best technology are Diesel Engines.

Referring to the emissions, CO_2 emissions as it has been previously explained are less in diesel engines, but on the other hand, the NO_X emissions which are nowadays a real concern inside the ECAs are hardly non-existent in turbines.

The investment cost of the turbines are significantly higher than the cost of the installation of the equivalent diesel engine. This is also because of the stage of development of the technologies, while the diesel engines are widely spread and commonly used in small size vessel the other technologies are at least one step backwards.

As for volume, the high speed 4-Strokes diesel engine is the most suitable. The space required for all the propulsion system in the studied vessel is only **161.312 m³.** In terms of weight the lighter technology is the Gas Turbine, but the investment cost together with the indexes previously studied make the gas turbine a really expensive technology to implement and does not stand as a realistic option for small cargo vessels.



Engine							Gear	Shaft		Propeller		
aType	Rating	Speed										Speed
	kW	rpm	A	B	C	D	E	F	G	H	Ø	rpm
6 M 25 C	2,000	750	5,345	2,260	861/1,191	2,906	1,904	2,000	3,000	617	3,000	220
8 M 25 C	2,640	750	6,289	2,315	861/1,191	3,052	1,837	2,000	3,000	617	3,300	205
9 M 25 C	3,000	750	6,719	2,315	861/1,191	3,052	1,795	2,000	3,000	630	3,450	200

Subject to be change

Figure 35: 8M 25 C layout

Another inconvenient of the Gas Turbines is the high rotational speed which makes the reduction gearbox needed bigger, and more expensive due to the quality needed. Its application in electricity generation and as a prime mover in naval vessels such as frigates is increasing. Due to the fact that they are rotational machines, their availability can easily reach 95% and their reliability is about 99%, in electrical generation and this could possibly be translated to mechanical propulsion. The development of Gas turbines will be a great improvement while Steam Turbines are more likely to only be used in LNG or nuclear propelled vessels.

In conclusion, the most suitable technology in general terms combining both the calculated indexes and the qualitative analysis make the 4-Strokes Diesel engine the strongest technology. The main problem of this display is the increasing regulations that is why a review or improvement of the other technologies is completely needed. In a short-term view, 4-Strokes diesel engines would probably be the favourite option maintaining their leading position which nowadays is a fact. But in the long term view, substantial modifications in order to make the LNG the main fuel or newer technologies such as gas engines, electric propulsion or fuel cells are likely to be a realistic option if the research continues in the same direction.

5 The Potential impact on emissions level using developing technology

5.1 Introduction

Due to increasing regulations, after the previous comparison of the traditional prime movers in terms of energy efficiency, the next step in the research is the analysis of newer technologies. There are a wide range of methods to reduce CO2 emissions: the inclusion of renewable energy systems such as wind or solar devices and the use of alternative fuels with lower carbon footprints (Smith et al.., 2014), but the final focus of the project is to study how electrochemical energy storage devices such as lithium batteries and fuel cells could be implemented inside the vessel used as model for study.

5.2 Theory

5.2.1 BATTERIES

The batteries are responsible for energy storage as well as for providing the required energy to propel the ship. The main features of the ship, such as autonomy, maximum speed, mean time between recharge, cost and weight, directly rely on the batteries. The most commonly used and most efficient batteries in hybrid and electrical propulsion are: lead, Ni-MT and lithium (San Martin et al., 2011).

Batteries are devices capable of storing and supplying electrical energy by electrochemical oxidation / reduction. When the battery is used, the chemical energy contained in the electrodes is directly transformed into electrical energy. The basic units of batteries are cells, and the bonding of two or more cells constitutes a battery. The main technical characteristics are: voltage [V], capacity [Ah], specific energy [Wh], recharging cycles [nº cycles] and specific power [W/kg o W/L] (Bucknall, 2015).

The most suitable type of battery is one whose specific energy Wh / kg and specific power W / kg have the best rate: **Lithium Batteries**. The first parameter gives the energy that can be stored per unit mass and the second gives the power per unit mass that could be supplied.

In the following graph the batteries are compared to H_2 and other fuels, for instance methanol and gasoline. Both specific energy and power are one order of magnitude less than fossil fuels, 100 Wh/kg of Lithium batteries compared to 1000 Wh/kg of H_2 fuel cells or 2000 Wh/kg of Gasoline, and the price is still higher.

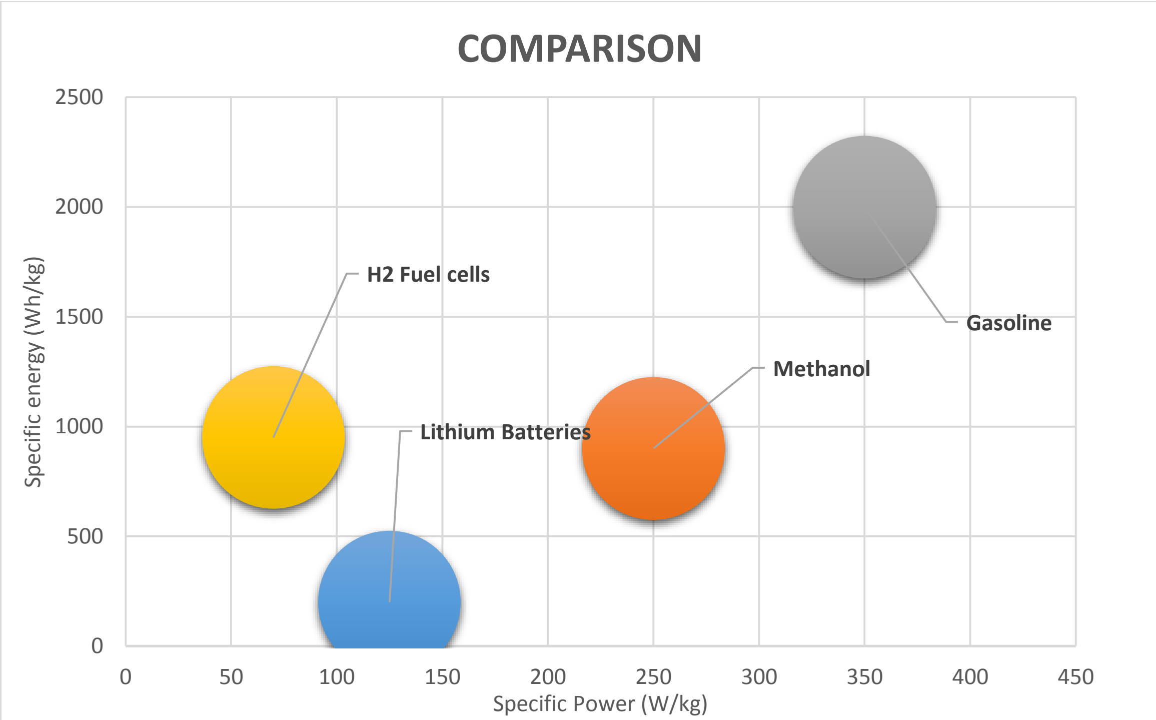


Figure 36: Comparison of batteries and other fuels.

In summary, lithium batteries are the most suitable option for propulsion; bedsides the higher specific energy and power, Li batteries have a cycle durability ranged between 400 and 1200 cycles (ThermoAnaltics,2011) and their environmental impact is less because of the lack of high poisoning components (Pb, Cd & Hg).

5.2.2 FUEL CELLS

Fuel cells transform the chemical energy from a fuel into electrical energy. The chemical reaction converts the stored energy of the molecules of fuel into electricity, due to a reverse of water electrolysis. As a result of the conversion, some by-products are also generated - mainly pure water and heat. The main difference between fuel cells and internal combustion engines is that the transformation does not rely on the combustion (Nightingale, 2015).

The main configuration of a unit fuel cell consists of an electrolyte, solid or liquid, in contact with one positive electrode (cathode) and one negative electrode (anode). While the fuel is continuously fed to the anode, the oxidant is fed to the cathode. Moreover, the last elements of the configuration are two gas backing layers and bipolar plates separating the unit cells (Larminie, 2003). The general classification is made according to the nature of the electrolyte used, each type is suitable for different applications and needs specific fuels and materials (Fuelcelltoday.com, 2014).

According to Sattler (2012), there are certain types of fuel cells that can be used to provide the main propulsion power for marine purposes, specifically for merchant ships such as the product tanker studied. A brief description of these types is listed below:

PEMFC (Polymer electrolyte membrane fuel cell)		
Operational Temperature	60-80 °C	Fast start-up
Reactants	Air	Reformate (H_2)
Fuel	Hydrogen	High quality
Electric efficiency	39-42%	
Units	Maximum 100 kW	Compact
Application	60-70 kW	Ferry Nemo H_2, Amsterdam
	2-50 kW	FCS Alsterwasser, Hamburg

Table 25: PEMFC characteristics

HTPEM (High Temperature PEM)		
Operational Temperature	200°C	
Reactants	Air	Reformate (H_2)
Fuel	Hydrogen	Lower quality due to the High T.
Electrical efficiency	42-45%	
Units	5-15 kW	Small built-in reformer units
Application	12 kW	Harbour Ferry MF Vagen, Bergen

Table 26: HTPEM characteristics

MCFC (Molten Carbonate Fuel Cell)		
Operational temperature	600-700°C	
Reactants	Air	Methane
Fuel	NG, methanol, biogas…	More flexible
Electrical efficiency	40-55%	Heat recovery
Units	200-500 kW	Complex balanced plant
Operational mode	Continuous	Low tolerance to load changes
Application	Base-load electricity on ships	Viking Lady

Table 27: MCFC characteristics

SOFC (Solid Oxide Fuel cell)		
Operational Temperature:	600-1000 °	High temperature
Reactants	Air	Methane
Fuel	NG, methanol, biogas…	More flexible
Electrical efficiency	45-60%	Heat recovery
Units	1-20 kW	Complex balanced plant
Operational mode:	Continuous	Low tolerance to load changes
Application	Base-load electricity on ships	Car carrier Undine 2010

Table 28: SOFC characteristics

The use high SOFC and MCFC are suitable for uninterruptable power supplies, due to their lack of dynamic capabilities, such as hospitals, servers' parks, and power generation from landfill or biogas.

5.3 Evaluation of the proposed technologies

The application of fuel cells as a power supply is a reality in buses. For instance Wright fuel cells are used on the RV1 London route along with Ballard fuel cells (showbus.co.uk, 2014).Fuel cells have also recently found their way into ship propulsion systems, although these specific systems are at an early stage of development.

Due to their low noise levels the main application of fuel cells is inside naval submarines, and because of their small volumetric power density, (up to 20 times less than diesel engines, actual applications of fuel cells in maritime transport are to supply auxiliary power (Clelland et al., 2012) or its use in combination with micro gas turbines (He et al., 2012).

Fuel cells use either gases with a high hydrogen content, for instance methane, or hydrocarbons such as diesel fuels. Because of the storage difficulties, the most suitable type for product tankers is diesel, or in the case of specific tankers, carrying either hydrogen or methane as boil-off, hydrogen (Sattler, 2012).

The advantages of the use of this type of energy generation are many:

- High efficiency about a 40% (Fuelcelltoday.com, 2014) in some cases the efficiency could reach 50% which is higher than the equivalent diesel engine whose efficiency in this specific case is 45.3618% (calculated in the report).

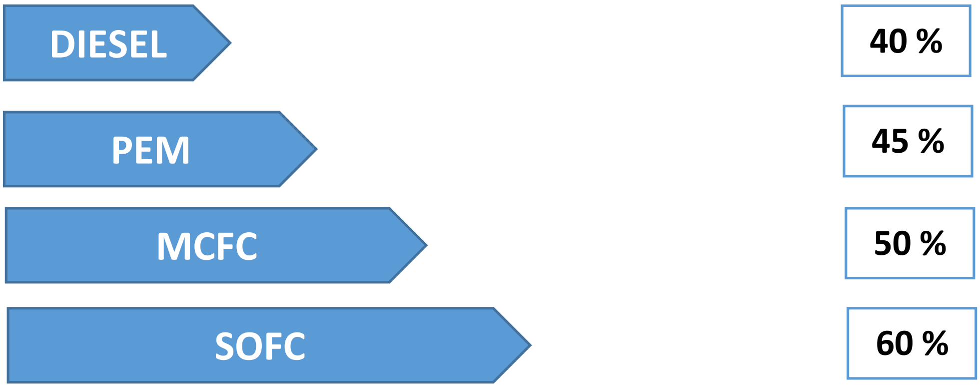


Figure 37: Average efficiency (DNV, 2012)

- Fuel savings to the order of 30% that could be easily translated to reduce the operational costs of the vessel.
- Lower emissions due to the lack of internal fuel combustion, which helps to meet the regulations for sensitive areas (ECAs & SECAs) (IMO, 2014) in terms of CO2, carbon and with a reduction of 96% in NOx.
- The modular installation gives flexibility in terms of meeting the diverse power outputs from 1000 to 4500 kW (crls.com, 2014) found in coastal vessels.
- Reliability, quietness, and the lack of moving parts implies less maintenance due to the absence of mechanical wear and tear to components (e4ships.de, 2014).

However, there are also challenges to face to make fuel cells a real alternative:

- The installation costs are very high, it is true that because of the lower fuel consumption almost the half of this cost could be compensated (Gross, 2008).

Investment Cost	
Diesel Engines	3-400 $/kW
MCFC (data available)	3000 $/kW

Table 29: Investment cost

- Fuel cells have not reached 40000 operating hours yet. Because of the recent interest and R&D efforts to achieve further development in this type of technology, the fuel cells' lifetime will be increased soon (DNV, 2012).
- Their small volumetric capacity makes meeting high power demands a challenge, and therefore they are more often used to supply auxiliary demand. For very large cases the maximum output that could be provided is 3MW (Clelland et al., 2012).
- The operation of these systems together with the frequent replenishment of fuel, needs a specific training of the crew, with implies increased cost of training and operation (Sattler, 2000).
- In terms of size and volume, it is impossible to compete against Diesel Engines because of the complex plant-balance to handle fuel-air treatment, and also large tankers are required due to the low volumetric density.
- Fuel cell weight is 10% more than the equivalent diesel engine, with the same power output. Further, the volume required is up to 15 times greater the volume required by the Diesel Engine. Approximately 85% of the space of the plant is occupied by the supplementary equipment such as thermal recuperators, power converter units, and DC/AC inverters (Smith et. Al , 2013)

Two of the previously mentioned disadvantages make use of this technology which is more suitable for Short Sea Shipping transport than the high-seas vessels. SSS vessels, and specifically the product tanker used as a case study, have a low power output demand and after the evaluation of its operating profile it does short trips with frequent visits to ports, where the fuel replenishment can be conducted.

Possible application in maritime transport:

- Auxiliary systems (Clelland et al., 2012):
    - If H_2 is available, PEM or HTPEM
    - Using low carbon fuels, HTPEM or hybrid systems using MCFC/SOFC and batteries
    - In combination with micro gas turbines (He et al., 2012).
- Propulsion systems: Ferries sailing on short routes or ships operating on inland waterways.
    - **Hybrid system batteries - PEM**
- Integration of the fuel cells inside Diesel Electric propulsion systems (cruise ships).

Proposed layout of the power plant system using fuel cells has H_2 as the fuel, if other fuels than H_2 are used, a reformer plant is needed, which increases complexity and decreases efficiency (Gätjens, 2010).

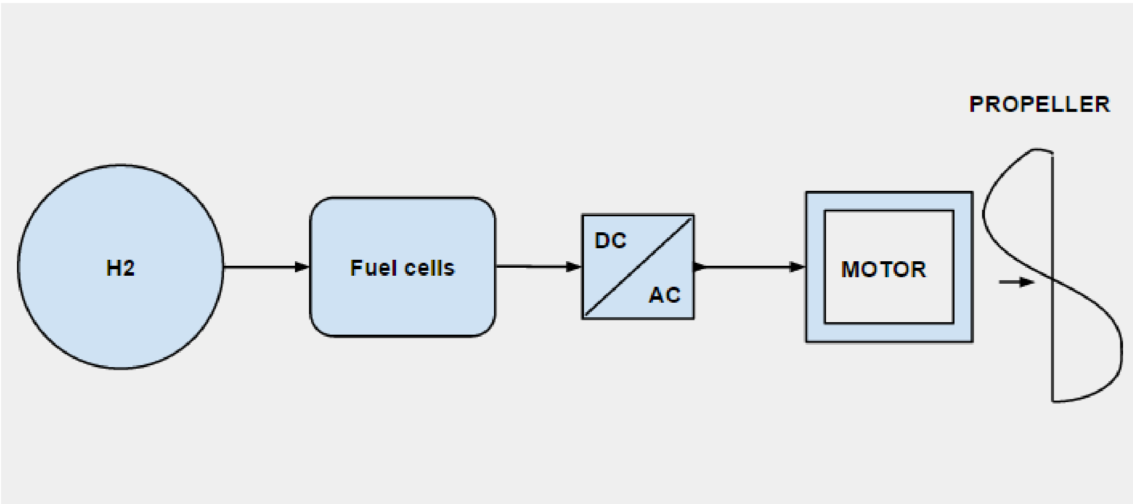


Figure 38: Layout of the main propulsion system using Fuel Cells (PEM; H_2)

The major problems for this system are weight and volume, both combined make the actual implementation of this system inadequate for the type of vessel regarded in the project, as the weight of the vessel will be increased while the space for the cargo will be significantly reduced.

Volume (m^3) comparing Diesel Engine, PEM and MCFC fuel cells, and then inside the range of power outputs of the SSS vessels included in the study (1-4.5 MW):

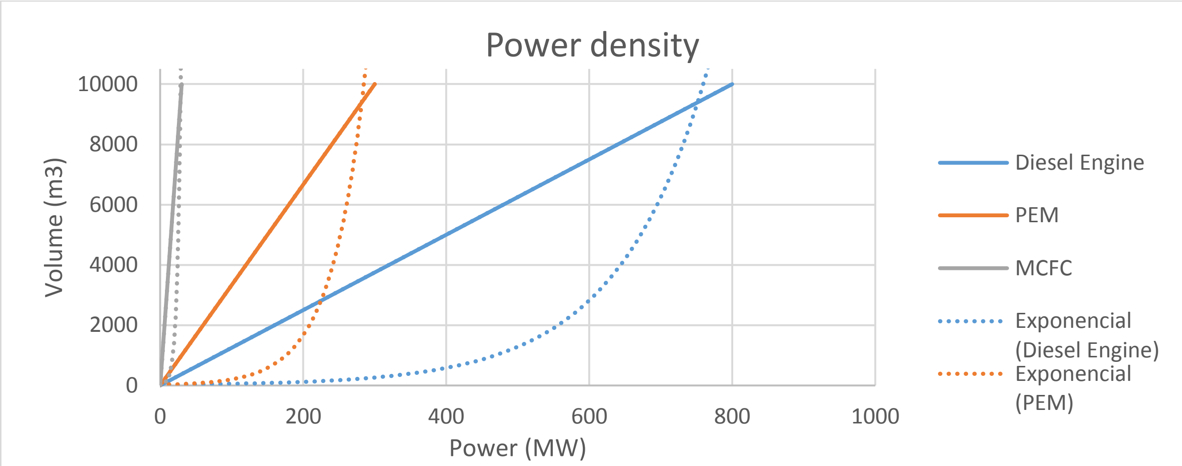


Figure 39: Power density Fuel cells

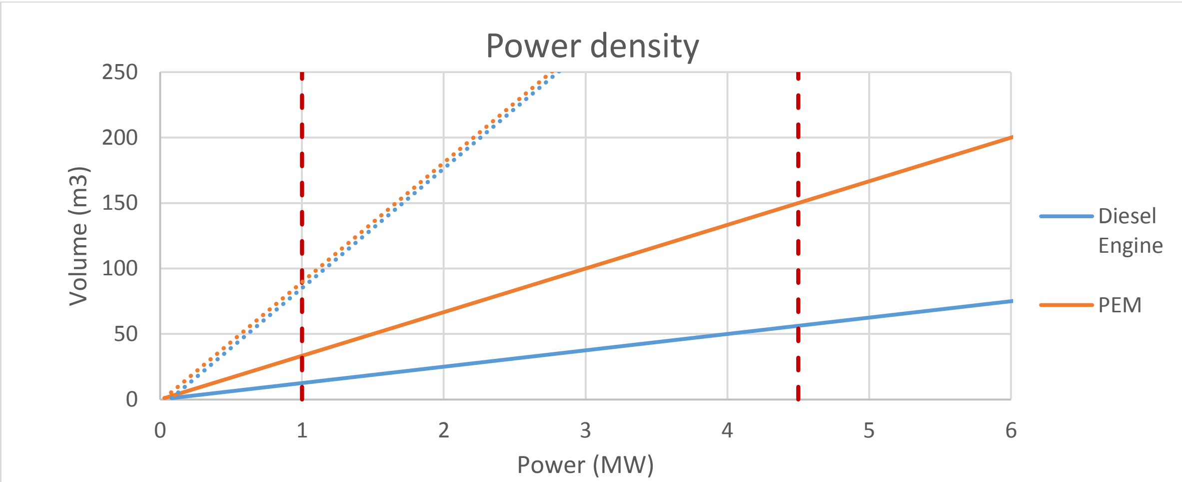


Figure 40: Power density in the range studied

Weight comparing Diesel Engine, PEM and MCFC fuel cells and after in the range of outputs:

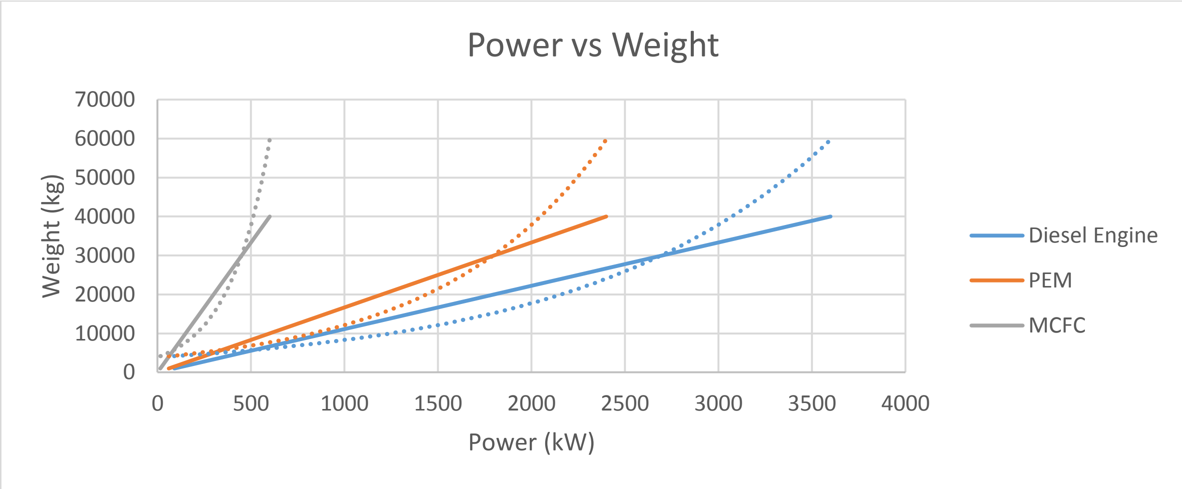


Figure 41: Power vs Weight

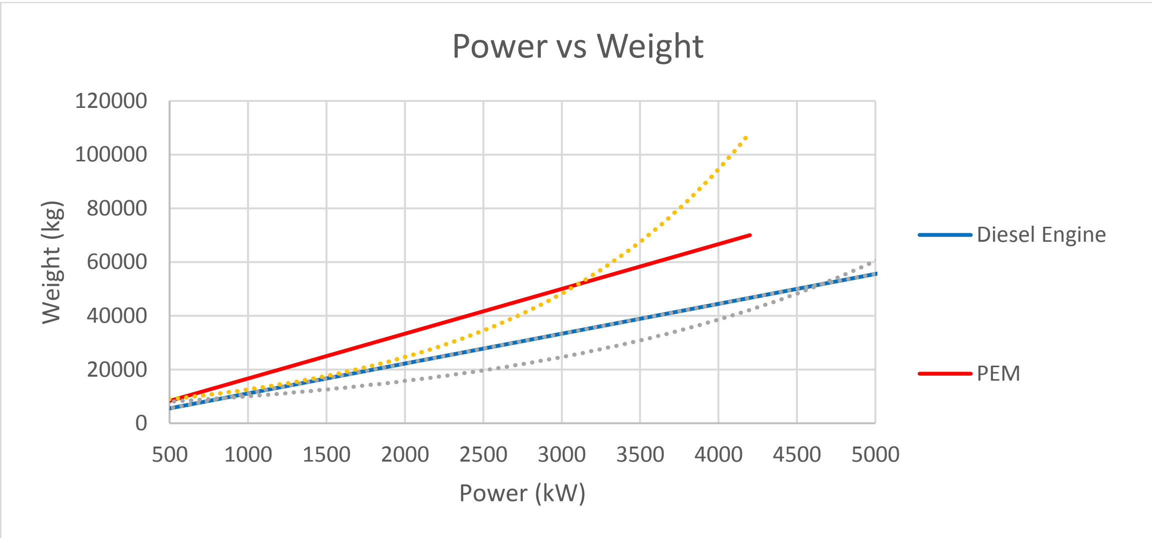


Figure 42: Power vs Weight for the range studied

The second concern is the volume and storage problems of the Hydrogen required for this propulsion system, the following figures show the energy density and the specific energy of the H_2 compared to diesel. In terms of volume for H_2 the space required is 64 times the space required by the fuel, while the weight of the H_2 is 3 times less.

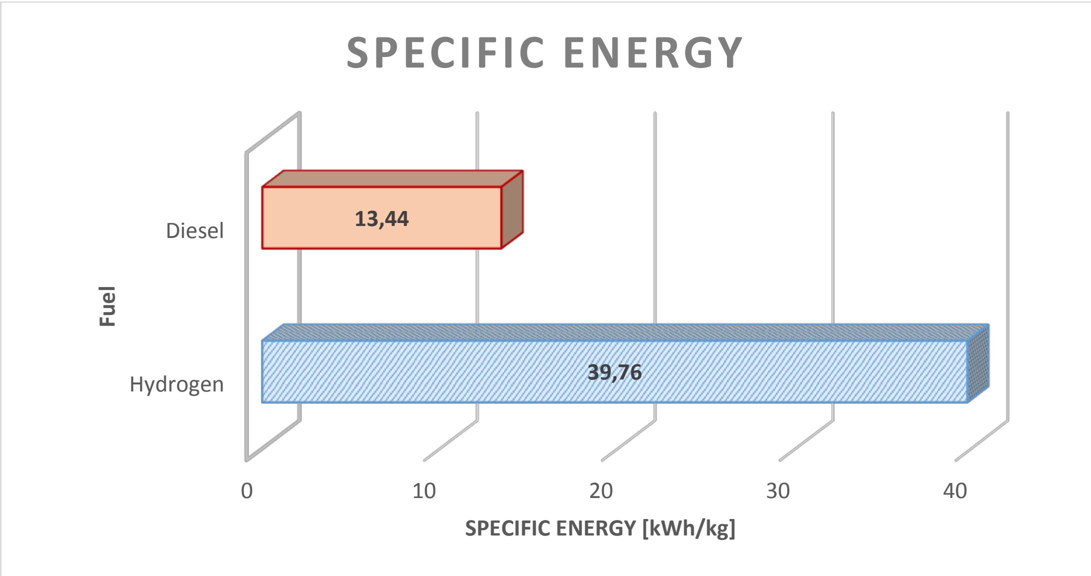


Figure 43: Specific energy (kWh/kg) (Morsy, 2013)

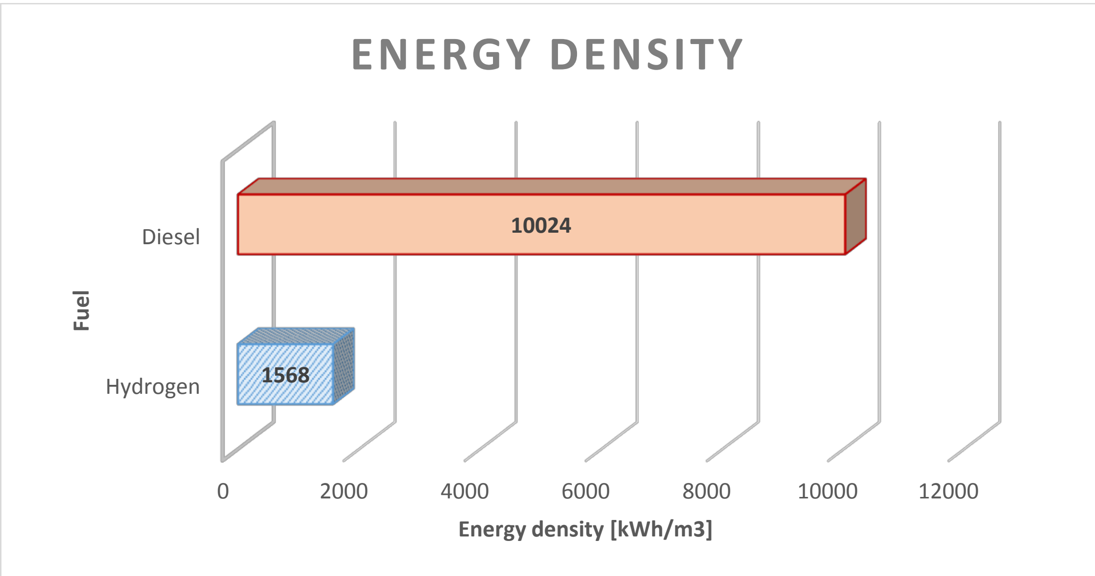


Figure 44: Energy density [kWh/m3]

In summary, the main problems of the proposed layout as shown above are the volume required either for the fuel cell devices and the H_2 required. There are also another concerns such as the complex storage of H_2 and the cost of the installation of fuel cells is approximately 15 times higher.

6 CONCLUSION

For the propulsion of Short Sea shipping cargo vessels whose main characteristics are: short trips, medium-small size and a tight budget, the actual solution is a 4-Stroke diesel engine. Its efficiency and fuel consumption is significantly better than both steam and gas turbines, while its volume and weight requirements combined with the investment cost makes them more suitable than low speed 2-Strokes. As this vessels does short-distance trips the sailing hours are less than ocean crossing vessels, and the efficiency is not as relevant. Also the heat recovery systems used with power plant diesel engines works on lower temperatures compared to the turbines. To make turbines more profitable they should be operating at maximum load, while diesel present smaller variations for instance at 80% load the efficiency in turbines decreases by 5.02% and in diesel engines by 3.37%.

In terms of flexibility, diesel engines are easily adapted to the changing power outputs (1000-4500 Kw) presented in SSS because of their modular character. And the investment cost of the turbines increases as the power output decreases, because of that the gas turbines are more economically suitable for larger vessels.

Diesel engines as a mature technology are highly developed in order to limit their emissions (MAK, 2013), these abatement technologies are listed in gas emissions from shipping.

The tendency of increasing regulations will shortly need a significant change in the use of this technology and due to this, there are another technologies that should be taken under consideration. Fuel cells and batteries as electrochemical energy storage devices, which are already being used as a part of the auxiliary systems, can make a significant change in marine propulsion if future research improves the two main problems: H_2 storage and consumption, and low power density. In addition, the space required by this layout makes its use inside small size cargo vessels impossible, because its installation implies a great reduction of the space for cargo.

However, it is not the only option, as biofuels or the use of LNG can also be considered. Using LNG the emissions will be reduced but the storage of this type of fuel is complex and needs cryogenic trailers. The studied gar or steam turbines are ready to be operated burning LNG, on the contrary Diesel Engines need several modifications.

In conclusion, the actual solution for the studied vessels are High speed 4-strokes diesel engines optimized to reduce emissions as much as possible, but future research should be focused on improve the previous early stage technologies in order to make them a real option in the upcoming years.

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8 APPENDIX

8.1 CALCULATION OF THE REAL DISTANCES SAILED BY THE KING FISHER, the vessel used as a case study.

In order to understand how has been developed the operating profile of the vessel, the detailed procedure of the longest trip between CANVEY ISLAND [GB] and GDANSK [PL] is presented below:

PORT	Latitude	Longitude	Distance
CANVEY ISLAND [GB]	51,512	0,557	0,00
WP 1	51,509	0,814	9,60
WP 2	53,300	4,392	169,55
WP 3	57,262	7,913	266,62
WP 4	58,014	10,858	104,88
WP 5	56,066	11,077	117,21
WP 6	54,610	10,989	87,50
WP 7	54,997	18,856	273,18
GDANSK [PL]	54,378	18,676	37,70
			1066,24

Time travelling (12 knots)	88,85	hours
	3,70	days
Consumption	43,183	Ton HFO

Table 30: Distance calculated using the WP. Trip between Canvey Island and Gdansk.

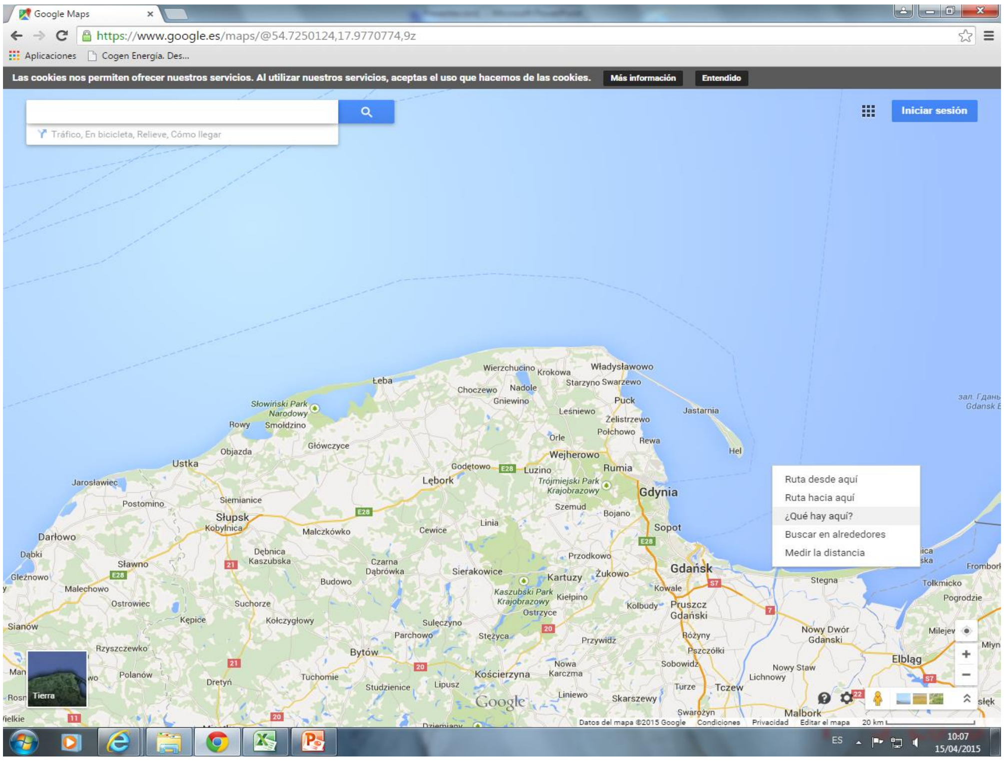


Figure 45: WAY POINT 1: trip between CANVEY ISLAND [GB] and GDANSK [PL]

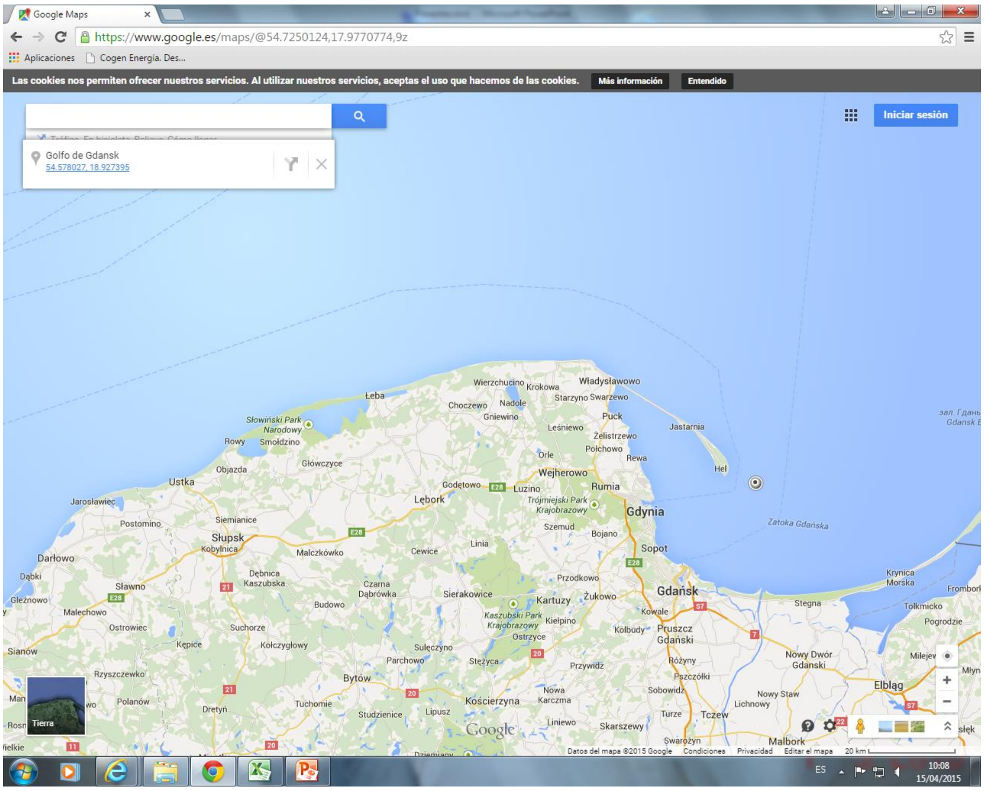


Figure 46: WAY POINT 2: trip between CANVEY ISLAND [GB] and GDANSK [PL]

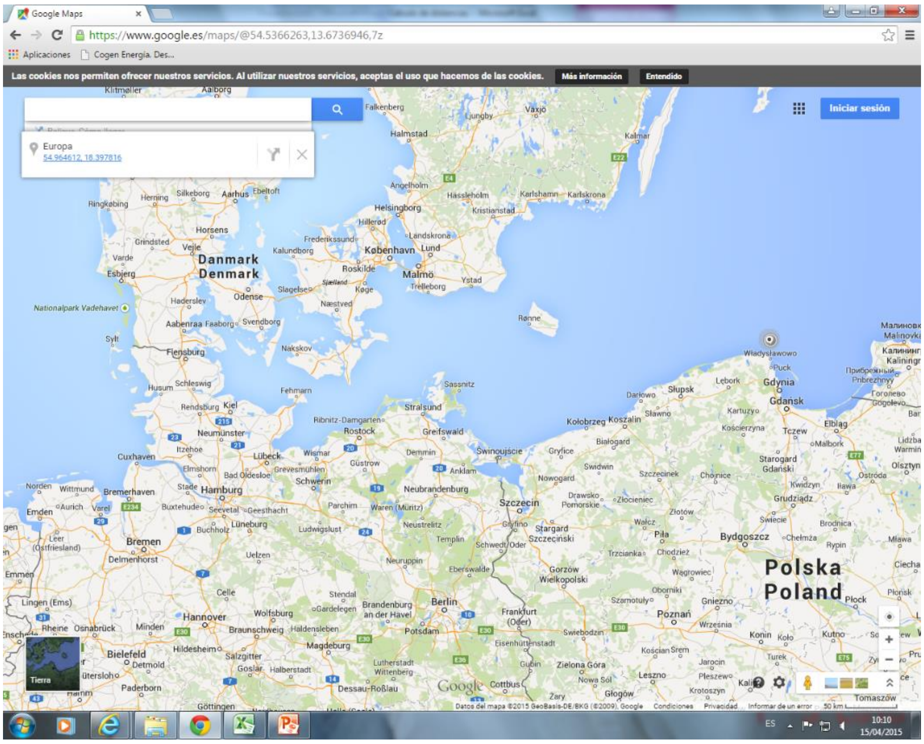


Figure 47: WAY POINT 3: trip between CANVEY ISLAND [GB] and GDANSK [PL]

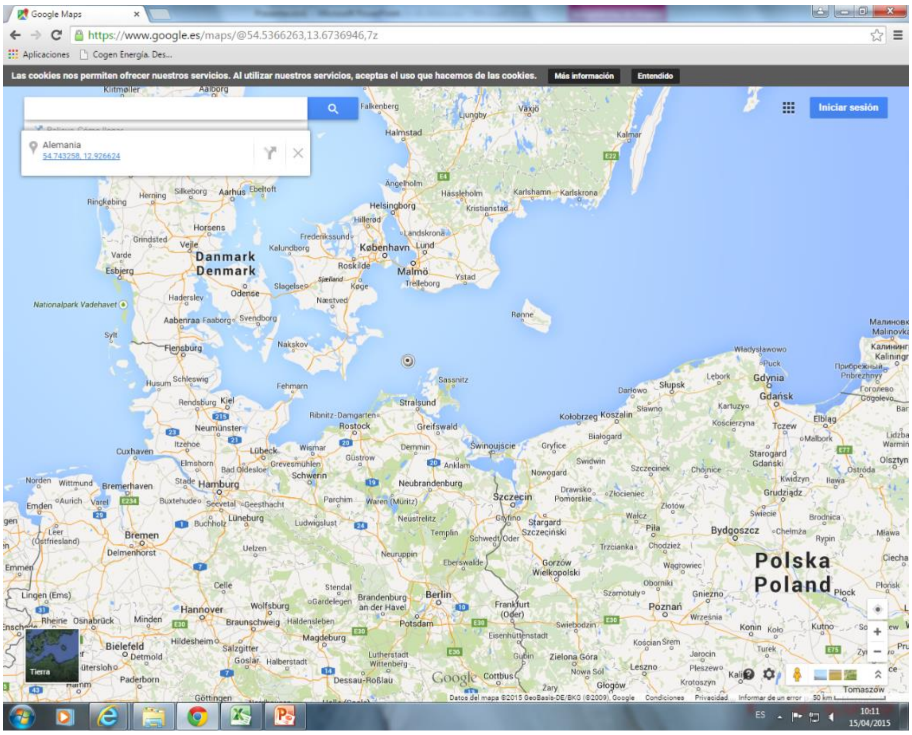


Figure 48: WAY POINT 4: trip between CANVEY ISLAND [GB] and GDANSK [PL]

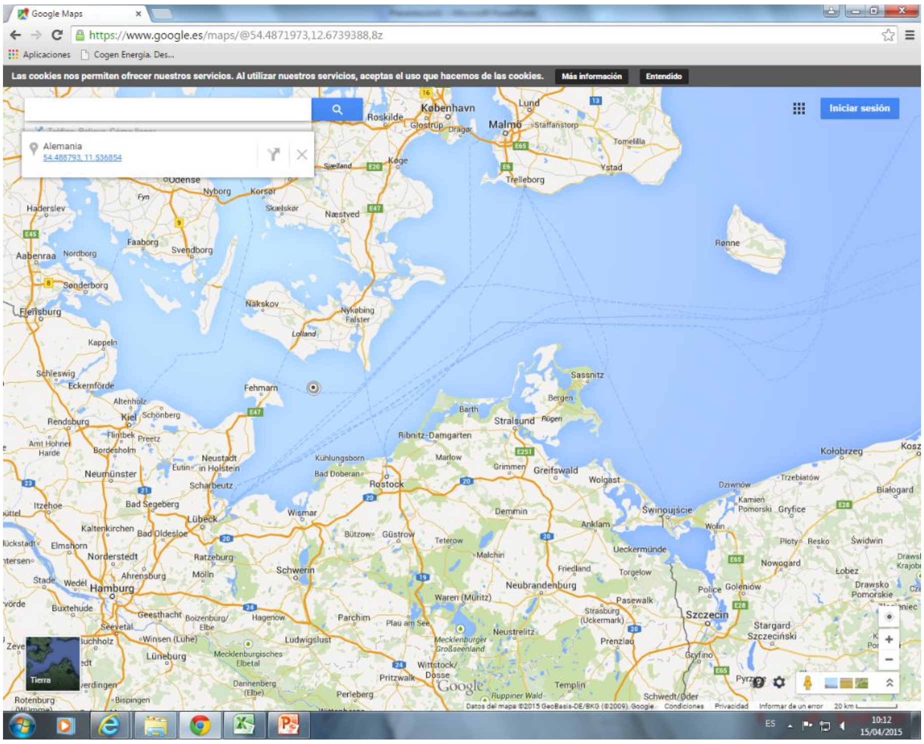


Figure 49: WAY POINT 5: trip between CANVEY ISLAND [GB] and GDANSK [PL]

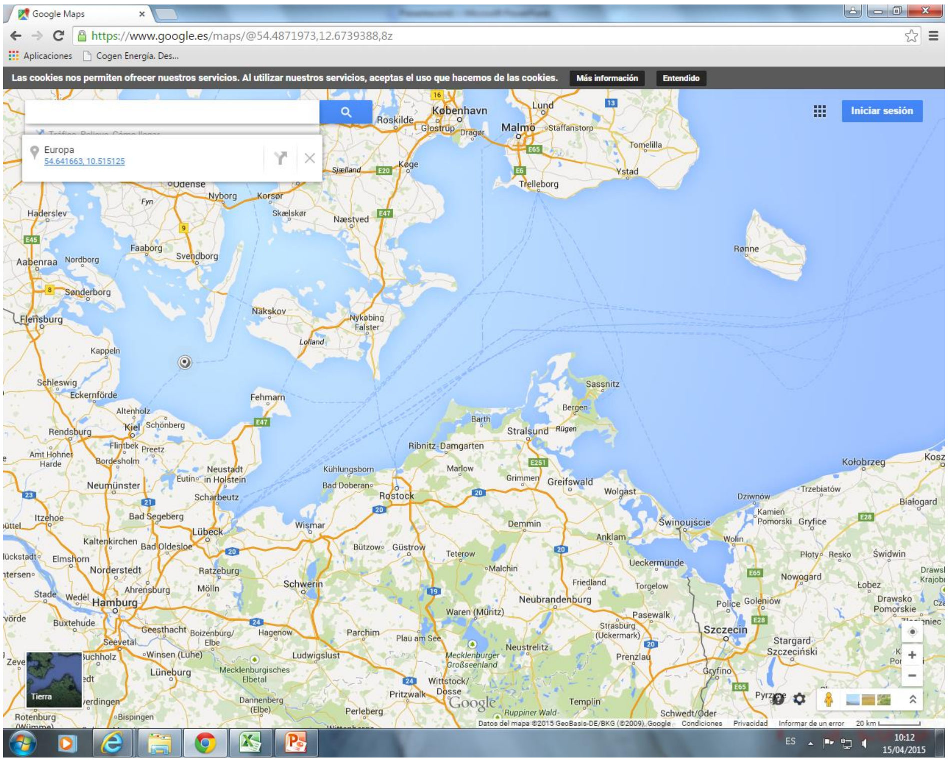


Figure 50: WAY POINT 6: trip between CANVEY ISLAND [GB] and GDANSK [PL]

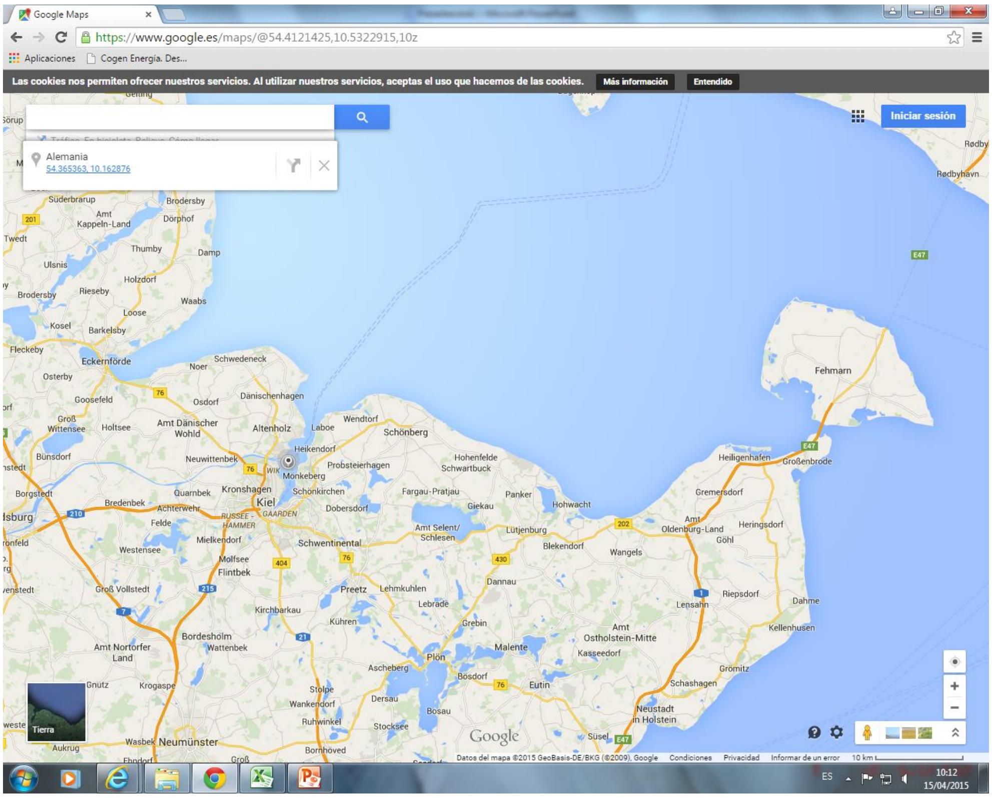


Figure 51: WAY POINT 7: trip between CANVEY ISLAND [GB] and GDANSK [PL]

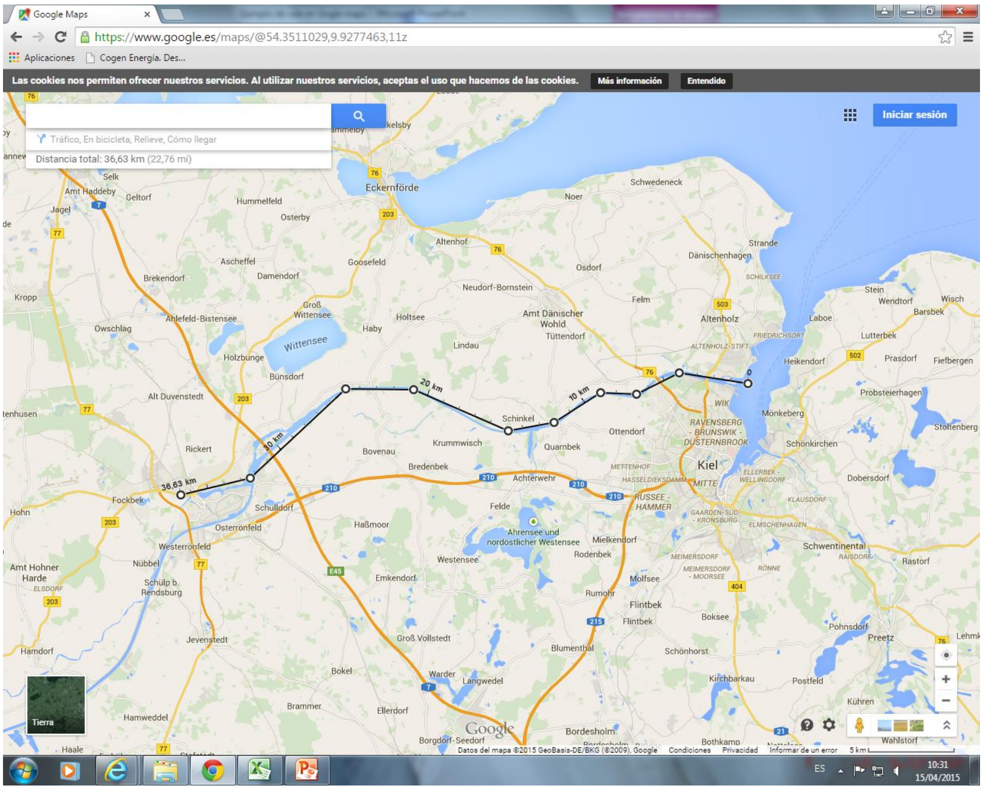


Figure 52: WAY POINT 8: trip between CANVEY ISLAND [GB] and GDANSK [PL]

All the distances sailed have been calculated following the same procedure shown above. The following tables present the information of each trip performed by the vessel during the period of 2 months which the operating profile lasted.

1. From IMMIGHAM to GRANGEMOUTH

PORT	Latitude	Longitude	Distance
IMMINGHAM [GB]	53,636	-0,185	0,00
WP 1	53,673	0,659	30,13
WP 2	56,124	-2,384	180,83
GRANGEMOUTH [GB]	56,029	-3,705	44,64
			255,60
Travelling time 12 Knots	21,30	hours	
	0,89	days	
Consumption	10,352	Ton HFO	

Table 31: IMMIGHAM to GRANGEMOUTH

2. From GRANGEMOUTH to ROTTERDAM

PORT	Latitude	Longitude	Distance
GRANGEMOUTH [GB]	56,0290	-3,7050	0,00
WP 1	56,0089	-3,3575	11,73
WP 2	56,1403	-2,4924	30,05
ROTTERDAM [NL]	51,9433	4,1418	342,62
			384,40
Travelling time 12 knots	32,03	hours	
	1,33	days	
Consumption	15,568	Ton HFO	

Table 32: GRANGEMOUTH to ROTTERDAM

3. From ROTTERDAM to CANVEY ISLAND

PORT	Latitude	Longitude	Distance
ROTTERDAM [NL]	51,9433	4,1418	0,00
CANVEY ISLAND [GB]	51,5120	0,5573	135,82
			135,82
Travelling time 12 knots	11,32	hours	
	0,47	days	
Consumption	5,501	Ton HFO	

Table 33: ROTTERDAM to CANVEY ISLAND

4. From CANVEY ISLAND to GDANSK

Shown below in the Table 28, detailed example.

5. From GDANSK to RENDSBURG

PORT	Latitude	Longitude	Distance
GDANSK [PL]	54,378	18,676	0,00
WP 1	54,578	18,927	14,87
WP 2	54,965	18,398	29,60
WP 3	54,743	12,927	189,57
WP 4	54,489	11,537	50,70
WP 5	54,642	10,515	36,74
WP 6	54,365	10,163	20,65
RENDSBURG [DE]	54,307	9,684	19,98
			362,11
Travelling time 12 Knots	30,18	Hours	
	1,26	Days	
Consumption	14,666	Ton HFO	

Table 34: GDANSK to RENDSBURG

6. From RENDSBURG to BRUNSBUETTEL

PORT	Latitude	Longitude	Distance
RENDSBURG [DE]	54,3070	9,6835	0,00
WP 1	54,365	10,163	19,98
WP 2	54,7580	10,8830	34,43
WP 3	54,0620	10,6790	42,41
WP 4	56,9520	7,4940	204,55
WP 5	54,0420	8,3070	176,94
BRUNSBUETTEL [DE]	53,9005	9,1319	30,35
			508,66
Travelling time 12 knots	42,39	hours	
	1,77	days	
Consumption	20,601	Ton HFO	

Table 35: RENDSBURG to BRUNSBUETTEL

7. From BRUNSBUETTEL to IJMUIDEN

PORT	Latitude	Longitude	Distance
BRUNSBUETTEL [DE]	53,9005	9,1319	0,00
WP 1	54,1590	8,4970	25,30
WP 2	53,7870	4,6630	137,17
IJMUIDEN	52,5230	4,5920	75,96
			238,43
Travelling time 12 knots	19,87	Hours	
	0,83	days	
Consumption	9,656	Ton HFO	

Table 36: BRUNSBUETTEL to IJMUIDEN

8. From IJMUIDEN to VELSEN ZUID

PORT	Latitude	Longitude	Distance
IJMUIDEN	52,5230	4,5920	0,00
WP 1			
WP 2			
VELSEN ZUID	52,4720	4,6520	3,77
			3,77
Travelling time 12 knots	0,31	hours	
	0,01	Days	
Consumption	0,153	Ton HFO	

Table 37: IJMUIDEN to VELSEN ZUID

9. From VELSEN ZUID to AMSTERDAM

PORT	Latitude	Longitude	Distance
VELSEN ZUID	52,4720	4,6520	0,00
WP 1			
WP 2			
AMSTERDAM	52,3790	4,8960	10,54
			10,54
Travelling time 12 knots	0,88	Hours	
	0,04	Days	
Consumption	0,427	Ton HFO	

Table 38: VELSEN ZUID to AMSTERDAM

10. From AMSTERDAM to BEVERWIJK

PORT	Latitude	Longitude	Distance
AMSTERDAM	52,3790	4,8960	0,00
WP 1			
WP 2			
BEVERWIJK	52,4930	4,6600	11,02
			11,02
Travelling time 12 knots	0,92	Hours	
	0,04	Days	
Consumption	0,446	Ton HFO	

Table 39: AMSTERDAM to BEVERWIJK

11. From BEVERWIJK to VELSEN NOORD

PORT	Latitude	Longitude	Distance
BEVERWIJK	52,4930	4,6600	0,00
WP 1			
WP 2			
VELSEN NOORD	52,4760	4,6390	1,28
			1,28
Travelling time 12 knots	0,11	Hours	
	0,00	Days	
Consumption	0,052	Ton HFO	

Table 40: BEVERWIJK to VELSEN NOORD

12. From VELSEN NOORD to IJMUIDEN

PORT	Latitude	Longitude	Distance
VELSEN NOORD	52,4760	4,6390	0,00
WP 1			
WP 2			
IJMUIDEN	52,5230	4,5920	3,30
			3,30
Travelling time 12 knots	0,28	Hours	
	0,01	Days	
Consumption	0,134	Ton HFO	

Table 41: VELSEN NOORD to IJMUIDEN

13. From IJMUIDEN to ROTTERDAM

PORT	Latitude	Longitude	Distance
IJMUIDEN	52,5230	4,5920	0,00
WP 1	52,1330	3,9830	32,38
WP 2			

ROTTERDAM [NL]	51,9433	4,1418	12,83
			45,21
Travelling time 12 knots	3,77	horas	
	0,16	días	
Consumption	1,831	Ton HFO	

Table 42: IJMUIDEN to ROTTERDAM

14. From ROTTERDAM to CANVEY ISLAND

PORT	Latitude	Longitude	Distance
ROTTERDAM [NL]	51,9433	4,1418	0,00
CANVEY ISLAND [GB]	51,5120	0,5573	135,82
			135,82
Travelling time 12 knots	11,32	hours	
	0,47	days	
Consumption	5,501	Ton HFO	

Table 43: ROTTERDAM to CANVEY ISLAND

15. From CANVEY ISLAND to ROTTERDAM

Same distance as the previously calculated.

16. From ROTTERDAM to FALMOUTH

PORT	Latitude	Longitude	Distance
ROTTERDAM [NL]	51,9433	4,1418	0,00
WP 1	52,1060	3,9000	11,27
WP 2	50,1730	-0,4010	202,07
FALMOUTH	50,1600	-5,0730	179,71
			393,05
Travelling time 12 knots	32,75	Hours	
	1,36	days	
Consumption	15,919	Ton HFO	

Table 44: ROTTERDAM to FALMOUTH

17. From FALMOUTH to WHITEGATE

PORT	Latitude	Longitude	Distance
FALMOUTH	50,1609	-5,0730	0,00
WP 1	48,891	-5,938	55,48
WP 2			

WHITEGATE	51,8320	-8,2580	119,64
			175,12
Travelling time 12 knots	14,59	Hours	
	0,61	Days	
Consumption	7,092	Ton HFO	

Table 45: FALMOUTH to WHITEGATE

18. From WHITEGATE to ANTWERP

PORT	Latitude	Longitude	Distance
WHITEGATE	51,8320	-8,2580	0,00
WP 1	49,1090	-6,4820	177,06
WP 2	51,6040	2,8780	388,35
ANTWERP	51,3020	4,3120	56,65
			622,06
Travelling time 12 knots	51,84	Hours	
	2,16	Days	
Consumption	25,193	Ton HFO	

Table 46: WHITEGATE to ANTWERP

19. From ANTWERP to LE HAVRE ANCH

PORT	Latitude	Longitude	Distance
ANTWERP	51,3020	4,3120	0,00
WP 1	51,611	2,043	86,91
WP 2			
LE HAVRE ANCH	49,5530	-0,1420	149,05
			235,96
Travelling time 12 knots	19,66	Hours	
	0,82	Days	
Consumption	9,556	Ton HFO	

Table 47: ANTWERP to LE HAVRE ANCH

20. From LE HAVRE ANCH to HARWICH

PORT	Latitude	Longitude	Distance
LE HAVRE ANCH	49,5530	-0,1420	0,00
WP 1	51,299	1,835	129,29
WP 2			
HARWICH	51,9447	1,2799	44,41
			173,70
Travelling time 12 knots	14,48	hours	

	0,60	Days
Consumption	7,035	Ton HFO

Table 48: LE HAVRE ANCH to HARWICH

21. From HARWICH to IMMINGHAM

PORT	Latitude	Longitude	Distance
HARWICH	51,9447	1,2799	0,00
WP 1	52,759	2,241	60,29
WP 2			
IMMINGHAM [GB]	53,636	-0,185	101,94
			162,23
Travelling time 12 knots	13,52	Hours	
	0,56	Days	
Consumption	6,570	Ton HFO	

Table 49: HARWICH to IMMINGHAM

8.2 DATA BASED ANALYSIS

The research has been focused on the following types of cargo containers:

Liquid cargo container ships:

Product tanker is a cargo ship designed to transport crude oil, petroleum or other distilled products such as kerosenes or naphtas. Its main characteristics are carrying capacity [t], total volume and volume per tank [m^3].

LPG (Liquefied Petroleum Gas) is a specific chemical carrier which transports Petroleum Gas which is in liquid state when it is pressurize and brought under atmospheric conditions but which would be gas under ambient conditions.

LNG (Liquefied Natural Gas) is another chemical carrier which transport liquefied Natural Gas.

Gasses are transported in liquefied condition because the space it takes is approximately 1/600 of the space needed under atmospheric conditions. (Van Dokkum, 2013)

Dry cargo container ships:

Container vessel is a dry cargo ship which transports the goods in truck-sized containers.

Bulk cargo is used to transport unpacked cargo for instance coal, cement, cereals (Ayub, 2010)

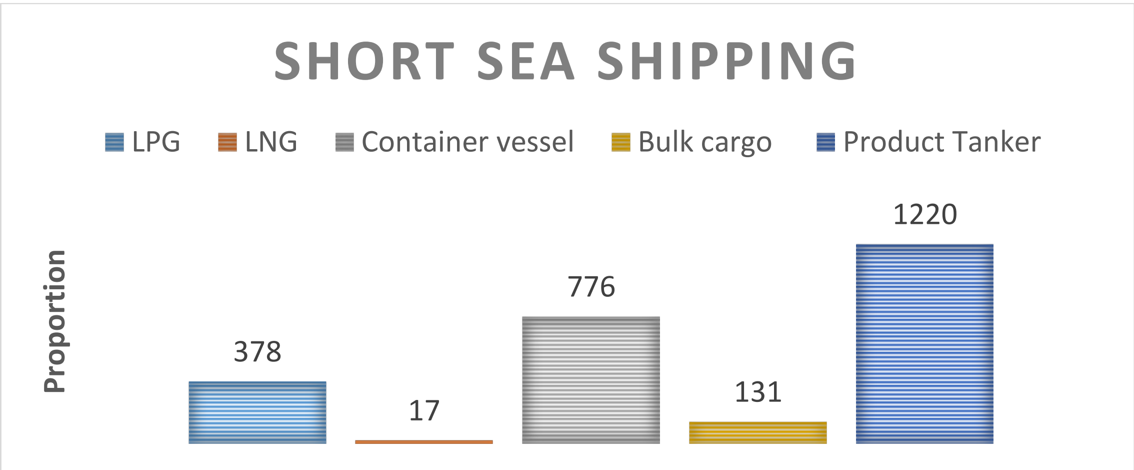


Figure 53: Proportion of SSS vessels

After the overall view of the five types of vessels, a more detailed analysis of each type of vessel is presented, regarding to:

1. Type of Power Plant: proportion of ships with an specific type of power plant
2. Number of engines in each type of power plant
3. Trend line of the types of power plant during the last 10 years
4. Trend line of the types of fuel during the last 10 years

8.2.1 Liquid Cargo Containers

Product Tanker

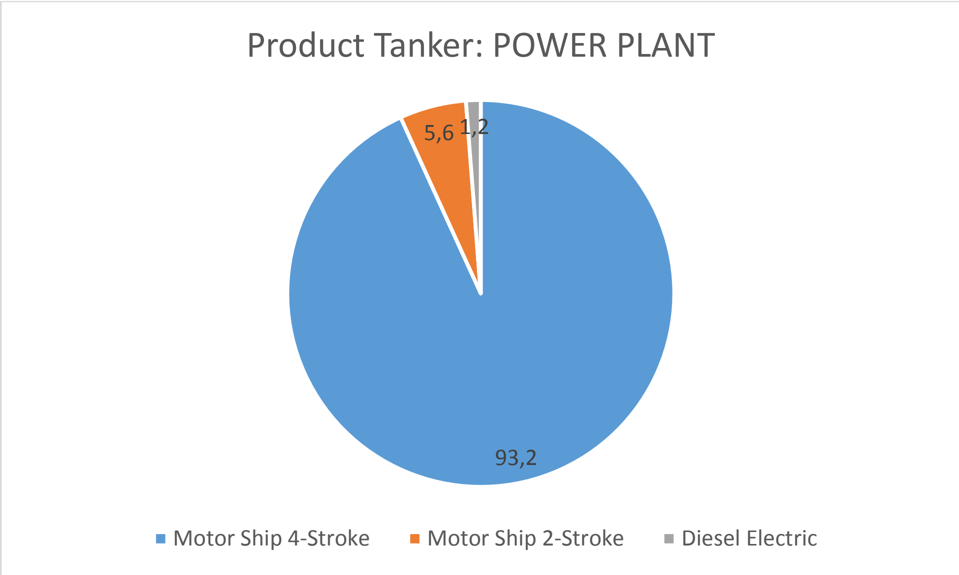


Figure 54: Proportion of each type of power plant (Crsl.com, 2014)

In Power Tankers the use of 4-Strokes Diesel Engine (93,2%) is significantly greater than the two other options Diesel Electric (1,2%) and 2-Strokes (5,6%).

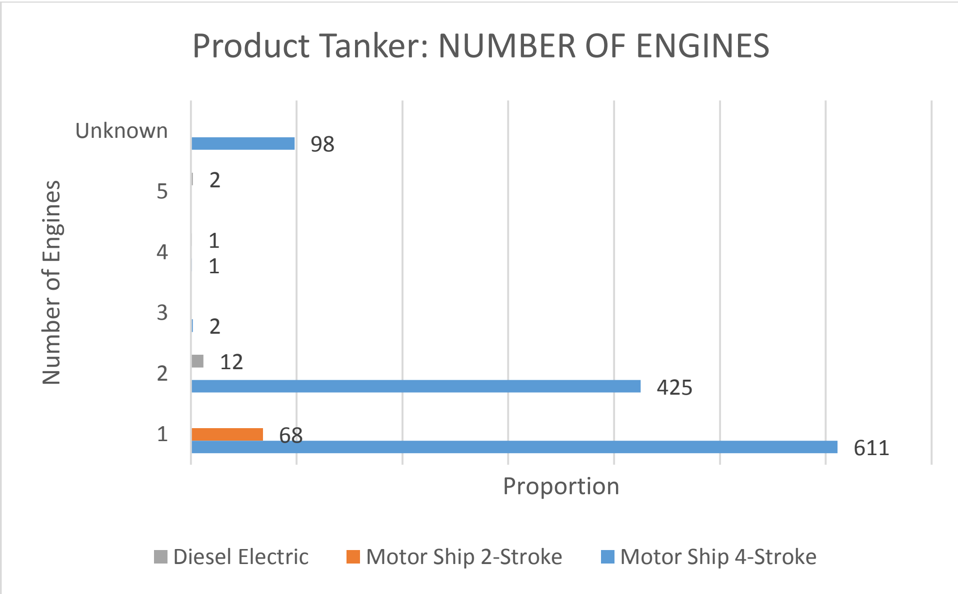


Figure 55: Number of engines in each type of power plant (Crsl.com, 2014)

While in Diesel Electric power plants there are 2,4 or 5 engines, regarding 4-Strokes the common layout has 1 or 2. In 2-Strokes power plants , all the energy is given by one only engine.

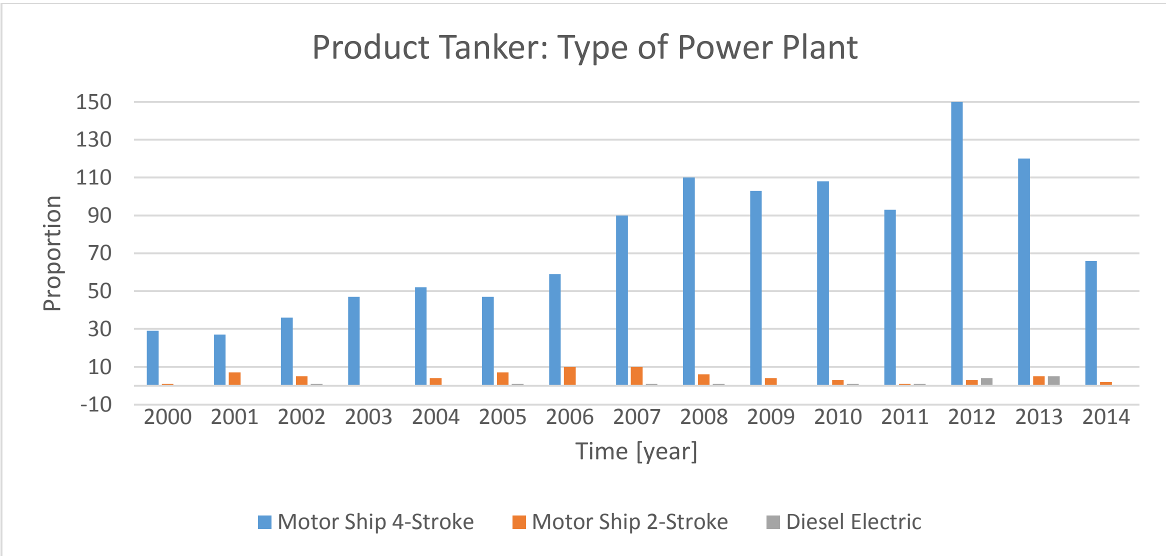


Figure 56: Trend line in time. Type of Power Plant. (Crsl.com, 2014)

The trend line confirms the widely spread use of 4-Strokes Diesel engines. But it is also shown that however the start in the use of Diesel Electic was in 2002, there is a growing tendency in this recent years (2012 and 2013).

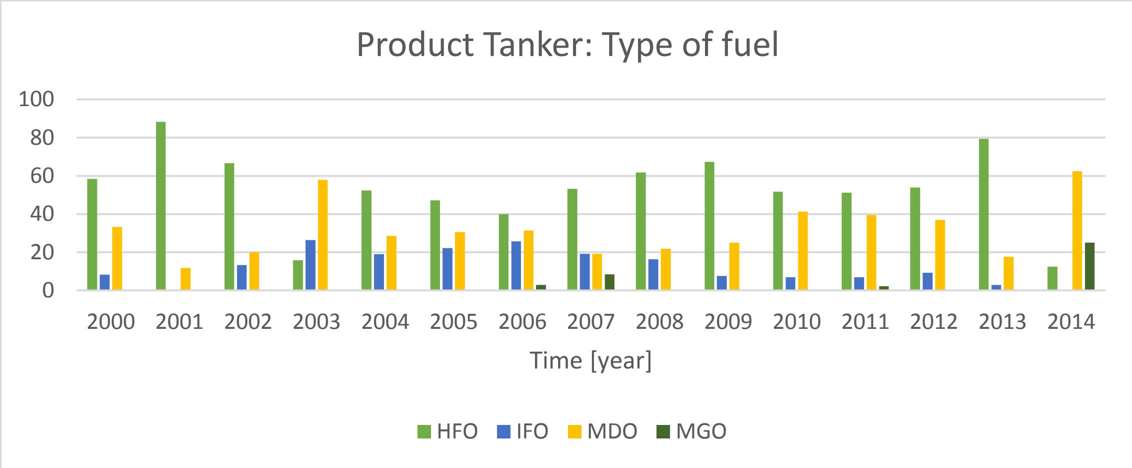


Figure 57: Trend line in time. Type of fuel. (Crsl.com, 2014)

Regarding the types of fuel, there is a significant change in 2014, when there was a reduction in the use of HFO, which until that date was the most used, and the use of MDO and MGO is significantly increased. The use of these fuels as an alternative to the HFO, it is one of the steps in order to minimize the emissions from Short Sea Shipping. This alternative is now focus of a lot of research towards to achieve a greener maritime transport.

LPG

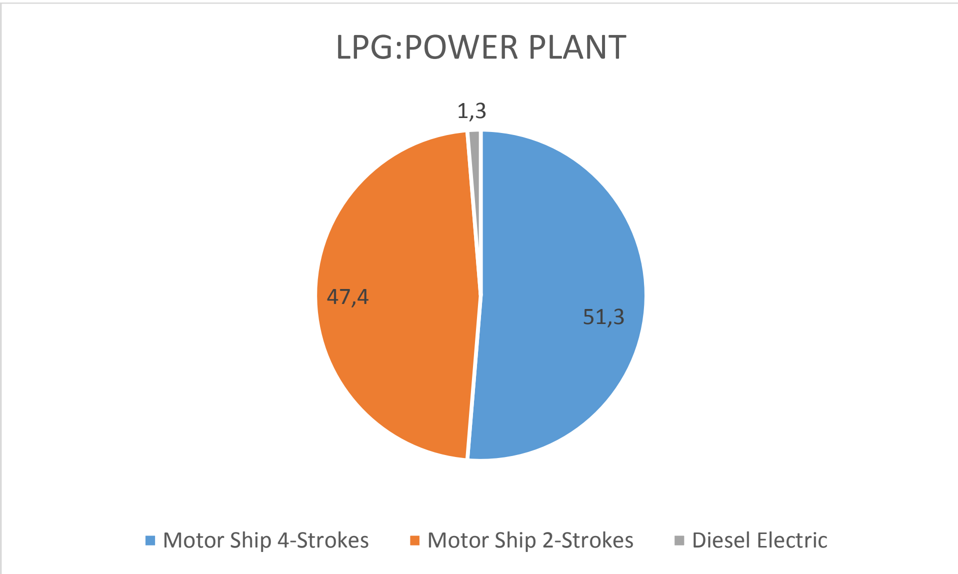


Figure 58: Proportion of each type of power plant. (Crsl.com, 2014)

The use of this type of chemical tankers in relatively small ships is not common, the amount of this ships makes generalization inappropriate. In terms of Power plants, the use is split in two among 2-Strokes and 4-Strokes.

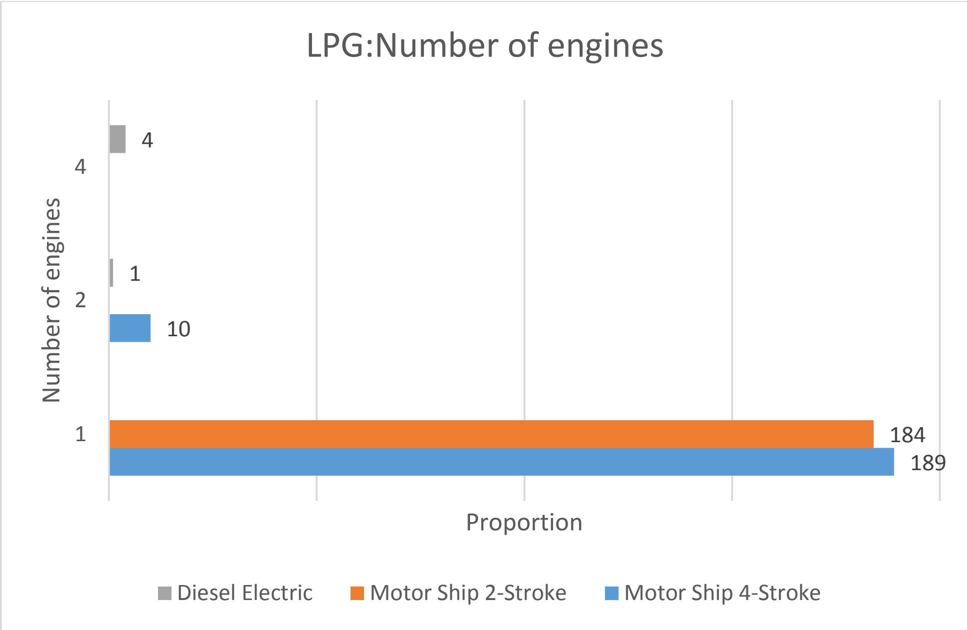


Figure 59: Number of engines in each type of power plant. (Crsl.com, 2014)

As expected, Diesel Electric's power plants requiered multiple engines (2,4) while the 2-Strokes's layout only uses one. In 4-Strokes's power plants, there is a great difference between the use of one and two engines, being the first one significantly more used.

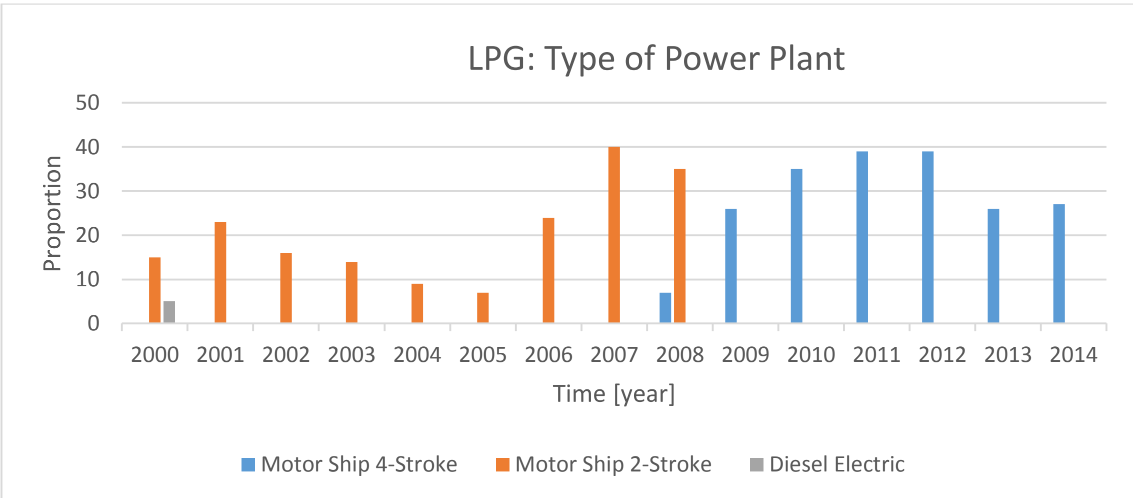


Figure 60: Trend line in time. Type of Power Plant. (Crsl.com, 2014)

The LPG's trend line, shows the general change from 2-Strokes big diesel engines to 4-Strokes inside the Maritime Transport, regarding small ships. The 4-Strokes engine is lighter and faster, these two characteristic made it more suitable to Medium/High Speed vessels and it is typically used in small ships and ferries' power systems.

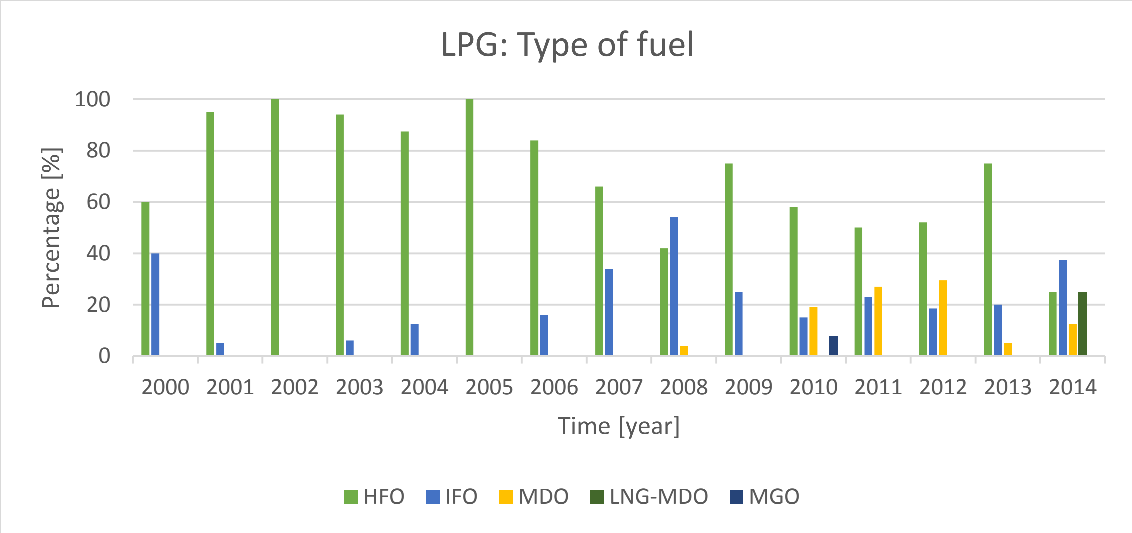


Figure 61: Trend line in time. Type of Fuel. (Crsl.com, 2014)

Regarding the types of fuel, while between 2000 and 2007 the dominant fuels was HFO with only a small use of IFO, the recent improvements in the engines make the use of alternative fuels (LNH-MDO, MDO) as significant as the use of the typical ones (2014). Using LNG has many advantages such as less maintenance, cleaner that typical fuels (HFO , MDO) and less emissions SOX , NOX and the combustion emits 20% less of CO2 (Semolinos, Olsen and Giacosa, 2014).

LNG

The use of this type of LNG chemical tankers in relatively small ships is not common, the amount of this ships makes generalization inappropriate.

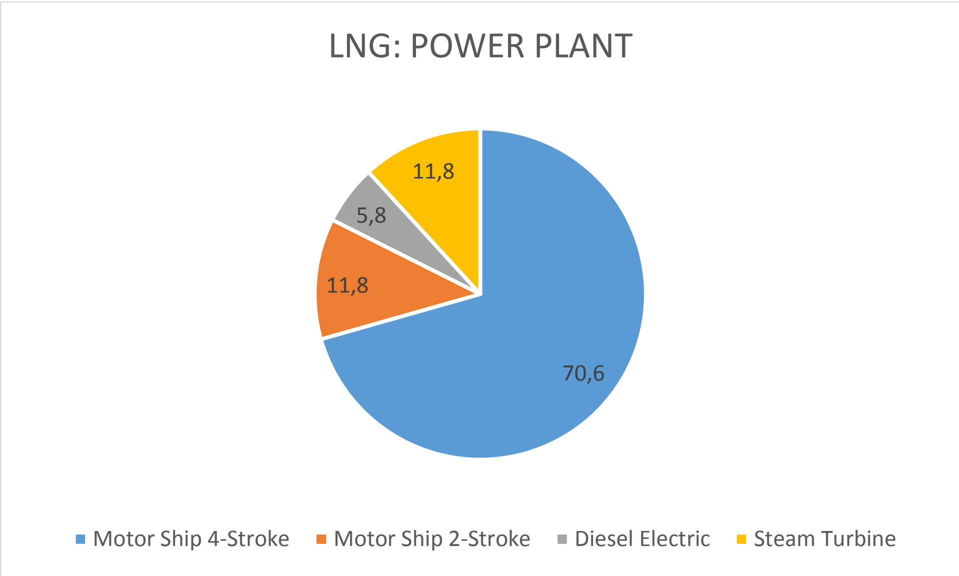


Figure 62: Proportion of each type of power plant. (Crsl.com, 2014)

The use of 4-Strokes is predominant, but the other three configuration are almost equally used. The use **of Steam Turbines**, which has not been found in other vessels, is significant.

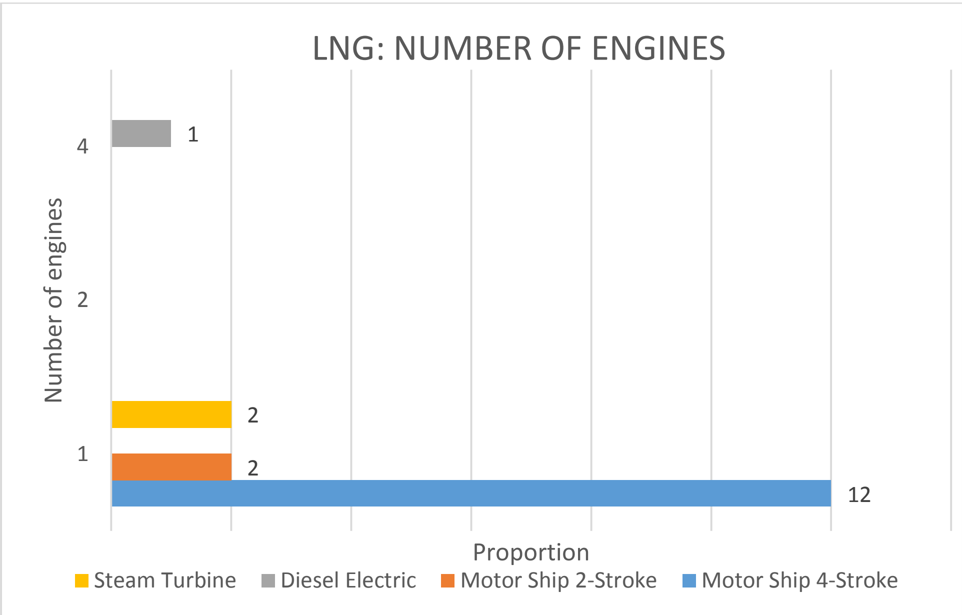


Figure 63: Number of engines in each type of power plant. (Crsl.com, 2014)

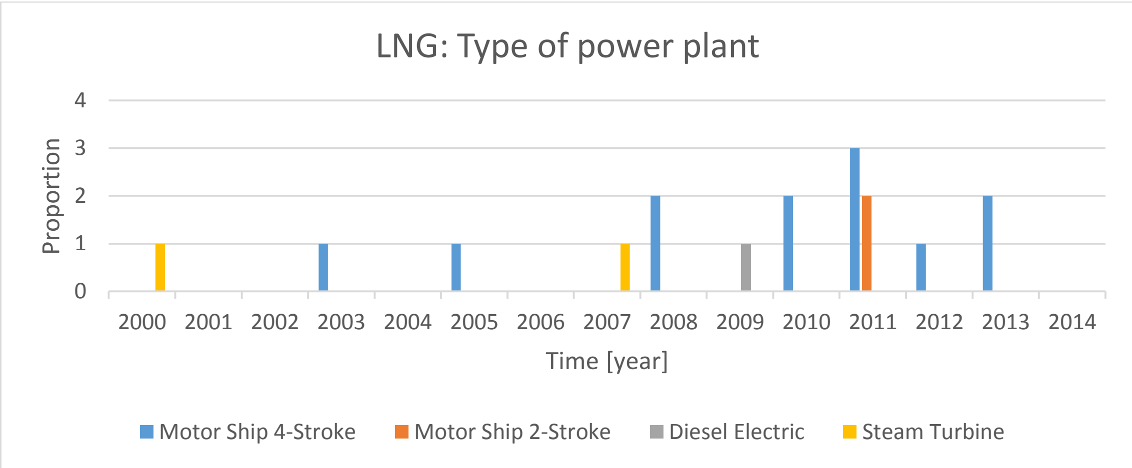


Figure 64: Trend line in time. Type of Power Plant. (Crsl.com, 2014)

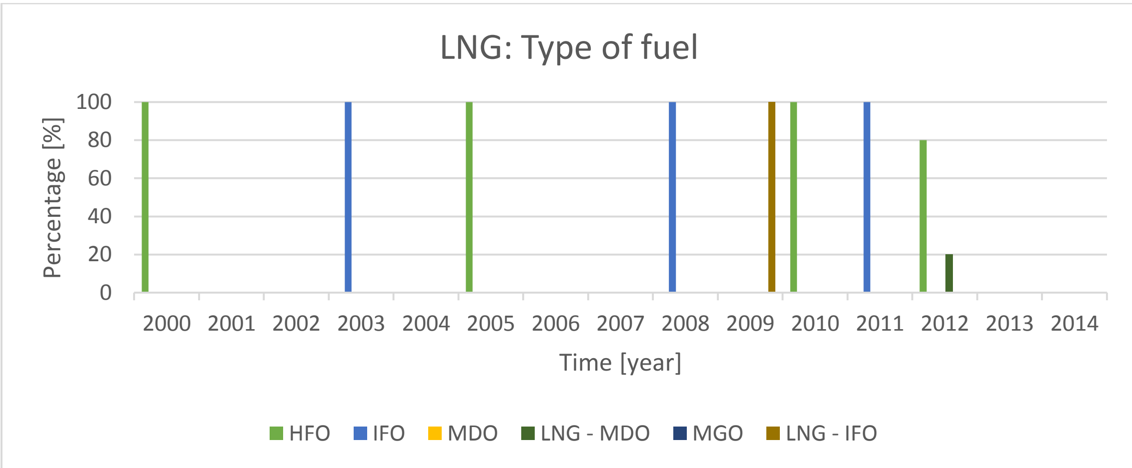


Figure 65: Trend line in time. Type of Fuel. (Crsl.com, 2014)

Because of the small amount of LNG's vessels in Short Sea shipping, the trend lines do not show relevant trends or future changes. Both the fuel as the power plants are spread without following a concrete pattern. The use of LNG-MDO and LNG-IFO need much lower maintenance and while the CO2 emissions decrease, there is a methane slip that has to be controlled (Semolinos, Olsen and Giacosa, 2014).

8.2.2 Dry Cargo Containers

Container vessel

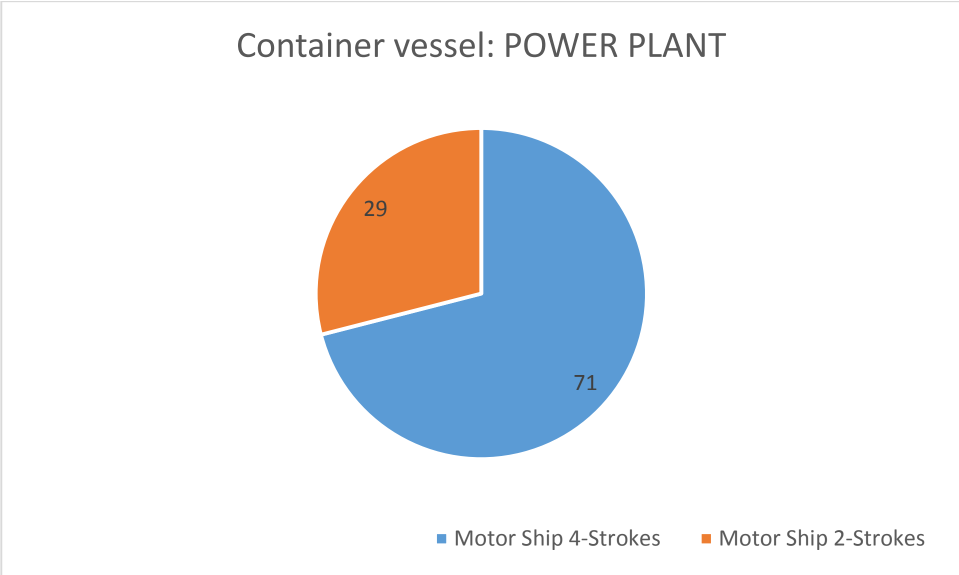


Figure 66: Proportion of each type of power plant. (Crsl.com, 2014)

In proportion the use of 4-Strokes is bigger but in the last five years the use of 2-Strokes is increasing. These power plants only use one engine no matter if it is a 2-Strokes or a 4-Strokes Marine Diesel Engine. The main advantages of a 2 – Strokes Marine Diesel engine are the fact that it has the best power-to-weight ratio, usually burns low-cost fuels and offers the highest thermal efficiency. On the contrary, its scavenging efficiency decreases its favoured position in terms of power (Ayub, 2010).

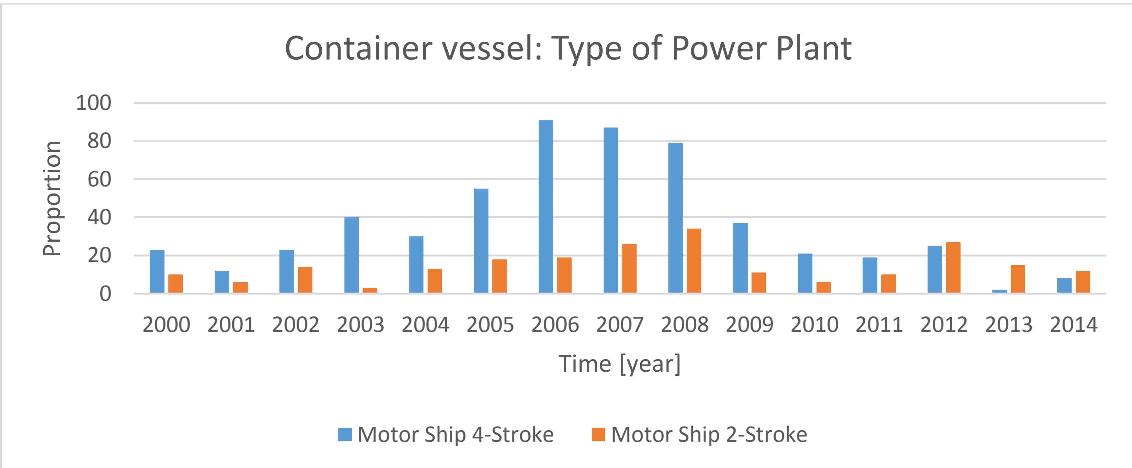


Figure 67: Trend line in time. Type of Power Plant. (Crsl.com, 2014)

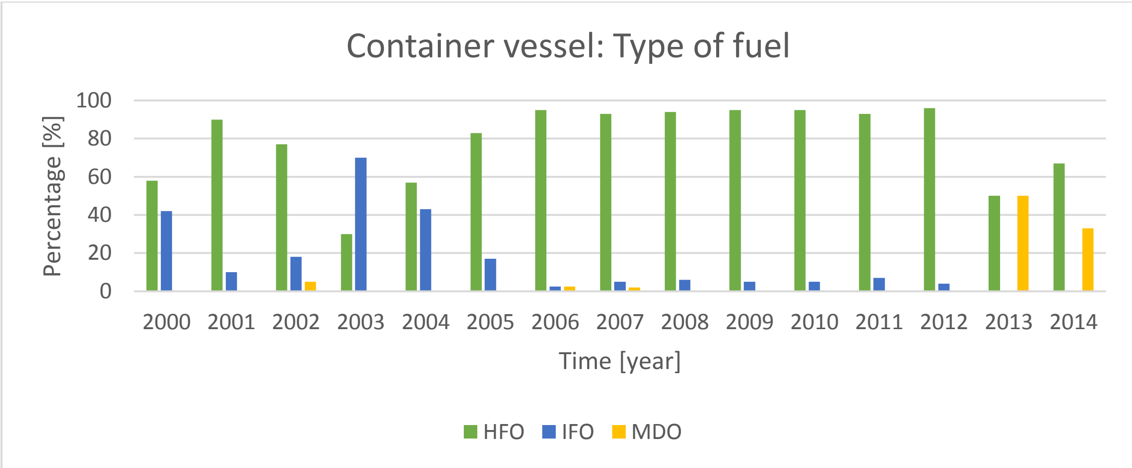


Figure 68: Trend line in time. Type of fuel. (Crsl.com, 2014)

The HFO is predominant but nowadays MDO is becoming significant.

Bulk cargo

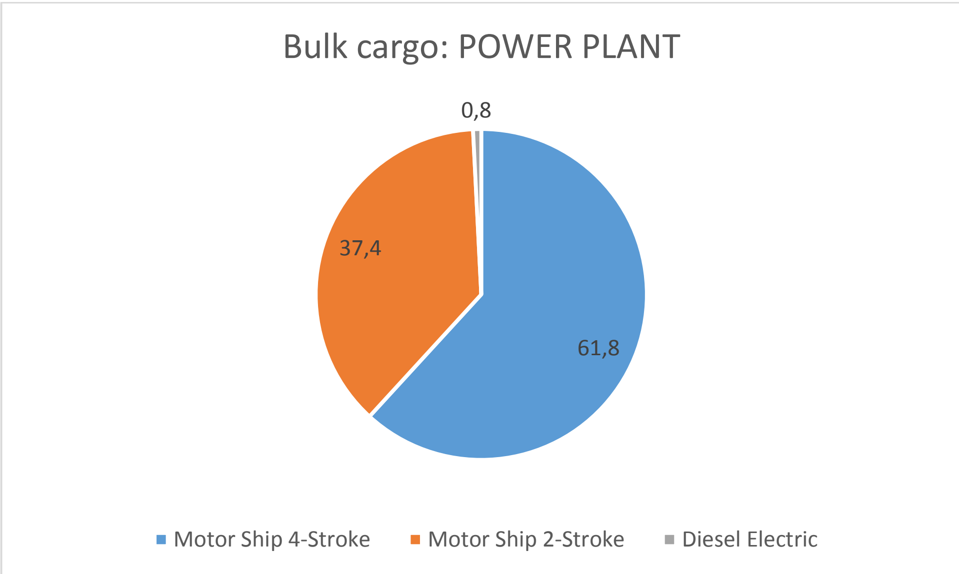


Figure 69: Proportion of each type of power plant. (Crsl.com, 2014)

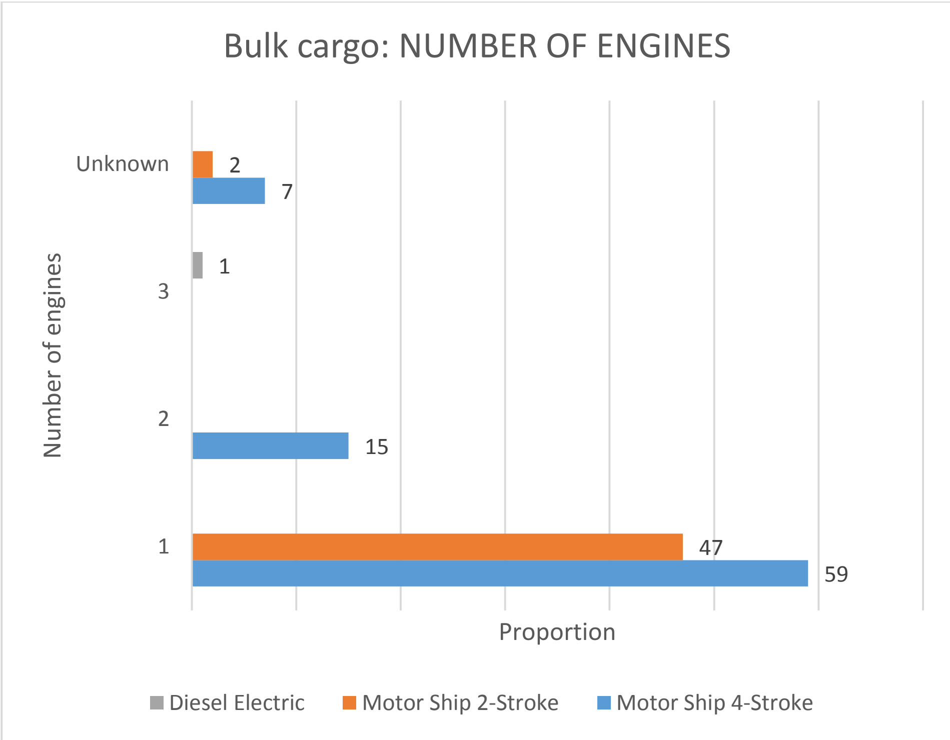


Figure 70: Number of engines in each type of power plant. (Crsl.com, 2014)

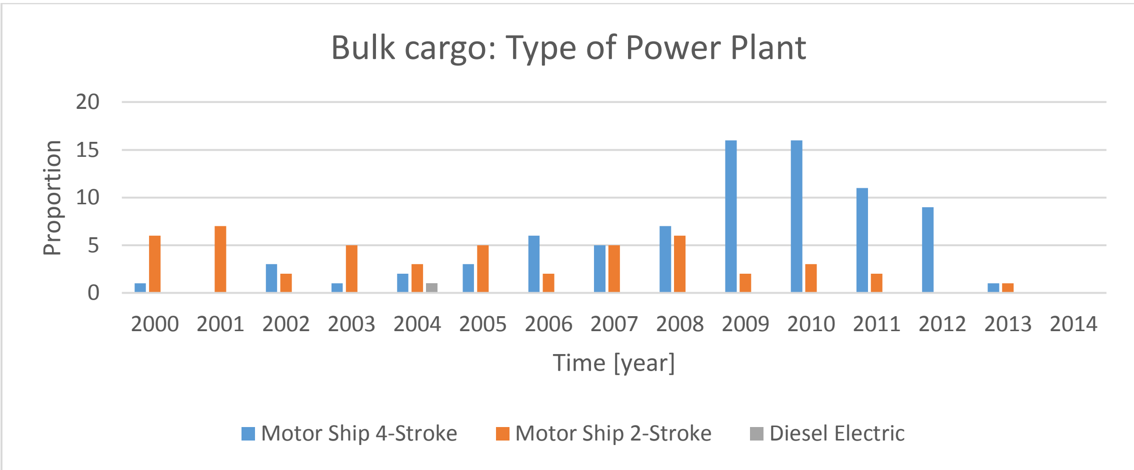


Figure 71: Trend line in time. Type of Power Plant. (Crsl.com, 2014)

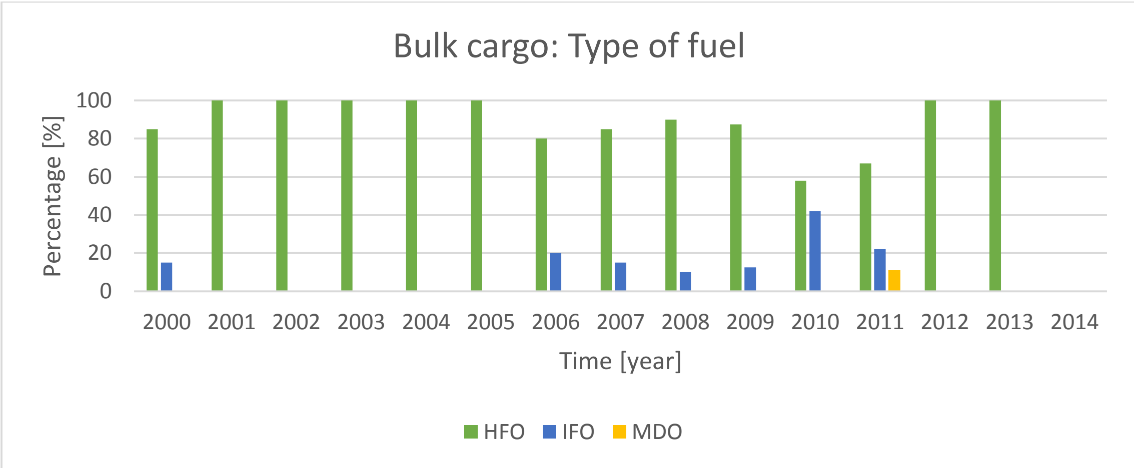


Figure 72: Trend line in time. Type of Fuel. (Crsl.com, 2014)

To provide a better understanding of the type of fuels used, it is presented a classification of the fuels used in Marine Engines (Viscopedia.com, 2014):

- **HFO** (Heavy Fuel Oil) also known as "Bunker oil": a residual fuel oil.
- **IFO** (Intermediate Fuel Oil): a blend of MGO and HFO, with less gasoil than MDO.
- **MGO** (Marine Gas Oil): a distillate fuel oil.
- **MDO** (Marine Diesel Oil): a blend of MGO and HFO.
- **LNG-MDO** (Liquefied Natural Gas)

Heavy Fuel Oil is the most widely used type of oil, because of that "bunker fuel" is often used as a synonym for this type. HFO requires heating before the oil can be pumped due to its high viscosity.

8.3 PROGRESS REPORT

Title: **Energy efficient optimisation of energy flows within the ships' engineering systems**

Supervisor: Prof Richard Bucknall

Student: Marta García Sansigre (UCL ID: 14092007)

This report responds to the request on the progress of my individual project, which is an "Energy efficient optimisation of energy flows within the ships engineering systems". The aim of the project titled above is to present a list of suggestions which will reduce the general amount of emissions provided by a ship. As presented in my first report, the project will be focused on coastal ships and the type of emissions which a ship produce, emphasizing in these three types: CO_2, SO_X and NO_X. The following objectives had been identified to be covered during the progress of the project:

(1) Definition of coastal ships and identification of different types.

(2) Detailed research of the technical characteristics for each type of ship.

(3) Conclude which is the most common type of vessel and which are its technical characteristics.

(4) Detailed research of the emissions which each ship produce. (CO_2, SO_X and NO_X).

- IMO Emission Regulations (Annex 6)
- EEDI (Influence of Energy efficiency Design Index)
- The Technology abatement for ships.

(5) Obtain the emissions of the vessel mainly focused in CO_2 emissions. (EEDI)

(6) Suggestions/ Methods to reduce emissions in a [20, 40…%] within Short Sea Shipping.

During this first two months, the first three objectives have been completed.

1. Definition of coastal ships and identification of different types

Coastal ships are generally known as “Short Sea Shipping” (SSS), this term will be used from now on. The general definition is the type of vessel which does not cover ocean crossing. The concept of Short Sea Shipping includes goods and passengers transport along the coast, rivers, and to/from the islands. This type of maritime transport represents the 43% of the total Intra- EU Transport [tonne-km] and the 69% International Intra- EU Transport. As a result of the improvement of SSS efficiency, the generation of emissions per country will be greatly decreased (European Commission, 1999).

There are many different types of SSS ships but in order to narrow the selection, the research has been focused on **five types**: (1) LPG (2) LNG (3) Container vessel (4) Bulk cargo (5) Product Tanker.

LPG (Liquefied Petroleum Gas) and **LNG** (Liquefied Natural gas) are two specific types of carriers, which are not commonly used in short sea shipping. The carried gas is commonly cooled until it is liquefied to reduce its volume, the space that the liquefied gas requires is about 1/600 of the space required by the gaseous (Van Dokkum, 2013).

The main difference between a **Container vessel** and a **Bulk cargo** is that the first one carries the goods in truck-sized containers and the second is used to transport unpackaged cargo for instance coal, cement, cereals…(Ayub, 2010). Container vessels and Bulk cargos can also be classified in three designations according to passage criteria: Panamax, Post Panamax and Suezmax ships.

A **Product Tanker** is a carrier designed to transport crude oil, petroleum or other distilled products such as kerosenes or naphthas (Ricardo Gadea, 2004). Its main characteristics are carrying capacity [t], total volume and volume per tank [m^3].

As there is not a consensus in how the vessels should be classified according to GT or DWT, the **main assumption** was to include <u>ships whose DWT is between 1000 and 15,000.</u>

2. Research of the technical characteristics for each type of vessel

The next step on this research was to look at the technical characteristics such as Power Plant systems, type of fuel, and number of engines. And evaluate them to establish trend lines in time, because of that the **second assumption** was to make a year range of 15 years, vessels built between 2000 and 2014. The figure below shows the types of Power Plants founded for each type of vessel:

Type of Power Plant	LPG	LNG	Container vessel	Bulk cargo	Product tanker
Motor Ship 4-Stroke	✓	✓	✓	✓	✓
Motor Ship 2-Stroke	✓	✓	✓	✓	✓
Diesel Electric	✓	✓	✗	✗	✓
Steam Turbine	✗	✓	✗	✗	✗

After this, a more detailed analysis of the main technical characteristics is presented. The purpose of the following study is to achieve an overall view of the Short Sea Shipping environment ending with which is the most common type of vessel, regarding to: Type of Power Plant, Number of Engines and Type of Fuel.

To provide a better understanding of the type of fuels used, it is presented a classification of the fuels used in Marine Engines (Viscopedia.com, 2014):

- **HFO** (Heavy Fuel Oil) also known as "Bunker oil": a residual fuel oil.
- **IFO** (Intermediate Fuel Oil): a blend of MGO and HFO, with less gasoil than MDO.
- **MGO** (Marine Gas Oil): a distillate fuel oil.
- **MDO** (Marine Diesel Oil): a blend of MGO and HFO.
- **LNG-MDO** (Liquefied Natural Gas)**:**

Heavy Fuel Oil is the most common oil, that's why "bunker fuel" is often used as a synonym for this specific type. HFO requires heating before the oil can be pumped due to its high viscosity.

Firstly, **LPG**'s Power Plant System is mainly divided between Motor Ship 4-Strokes and 2- Strokes, but there is a minimum amount of ships that use Diesel Electric (2 or 4 engines). During these last fifteen years there has been a radical change of tendency in 2008 from the Motor 2 - Strokes to the Motor 4 – Strokes. In terms of type fuel, the recent developments in this field are shown by the implementation of LNG-MDO in 2014. Using LNG has many advantages such as less maintenance, cleaner that typical fuels (HFO , MDO) and less emissions SO_X , NO_X and the combustion emits 20% less of CO_2 (Semolinos, Olsen and Giacosa, 2014).

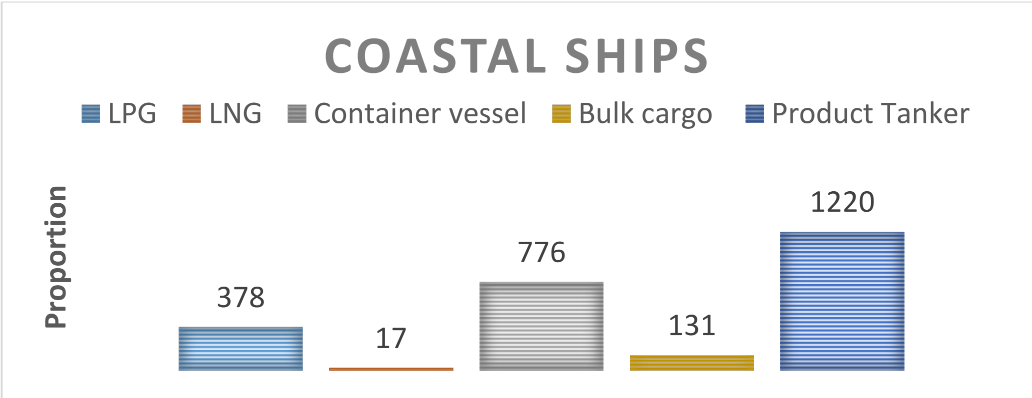
Secondly, **LNG vessel** is the only type founded which uses Steam Turbines as its main Power Plant System. This type of power plant has been replaced by 2-Stokes Engines mainly for economic reasons. Its main strengths are high reliability and low maintenance (Brighthub Engineering, 2014).When it comes to fuel there is a wide variety in type: HFO, IFO, MDO, LNG-MDO, MGO and LNG-IFO. The use of LNG-MDO and LNG-IFO need much lower maintenance and while the CO_2 emissions decrease, there is a methane slip that has to be controlled (Semolinos, Olsen and Giacosa, 2014).

The main technical characteristics of a **Container vessel** are easily recognised. Its Power Plant uses one engine no matter if it is a 2-Stroke or a 4-Stroke Marine Diesel Engine. In proportion the use of 4-Strokes is bigger but in the last five years the use of 2-Strokes is increasing. The HFO is the widely spread fuel but nowadays MDO is becoming significant. The main advantages of a 2 – Strokes Marine Diesel engine are the fact that it has the best power-to-weight ratio, usually burns low-cost fuels and offers the highest thermal efficiency. On the contrary, its scavenging efficiency decreases its favoured position in terms of power (Ayub, 2010).

The following type is **Bulk cargo**. Its analysis shows that there are three types of Power Plants: Diesel Engine, 2 - Strokes and 4 - Strokes Marine Diesel Engine. The most popular design is a unique 4 – Stokes Diesel Engine using HFO. Medium/high speed 4 – Strokes engines are used to power smaller ships (SSS), they are very often connected to a gearbox to drive the propeller. Motor Ship 4 – Strokes can have either in-line or V configuration (Ayub, 2010).

Finally, the **Product tanker** uses one or two 4 – Stokes Marine Diesel engines and in terms of fuel type in this case HFO, MDO, IFO and MGO, in order from most used to least. (Crsl.com, 2014).

3. Conclude which is the most common type of vessel and which are its characteristics.



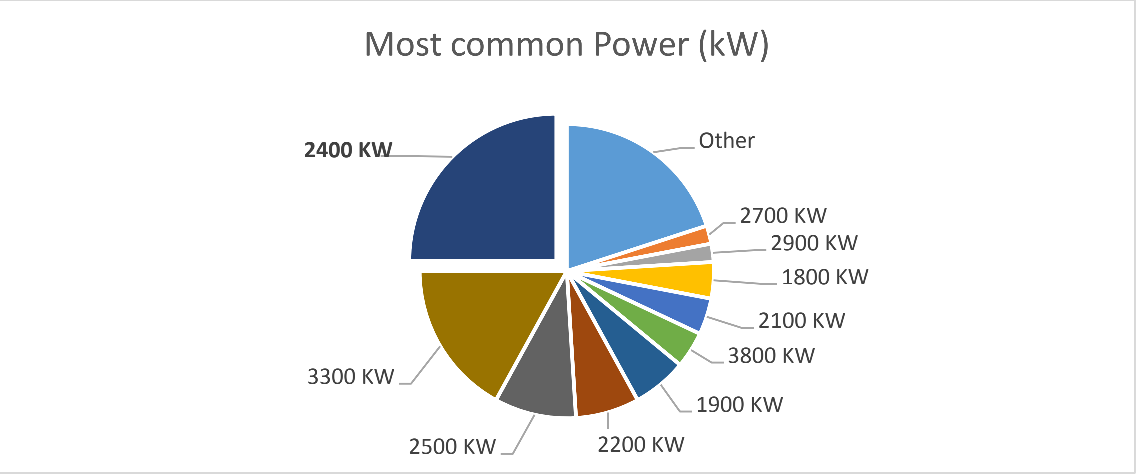
In conclusion, the **Product tanker** represents the **48, 4%** of the Coastal Ships considered in research. The most typical Power Plant system is a 4 – Strokes Marine Diesel engine and inside this category using a single engine and HFO. Moreover, the average Power (KW) of the vessel is another important feature to take into account. To analyse the Power a greater number of assumptions have been made in order to narrow the portion of vessels studied.

In addition to the first two assumptions (1000-15,000 dwt and Built in the last 15 years), the following:

Assumption/Filter	New Proportion of Ships
Product Tanker (In service)	1212
Motor Ship 4 - Strokes	1137
One Engine	611
Fuel: HFO	235

**During the analysis of the data, there are some gaps in the information provided, especially when it comes to Number of engines or Fuel type. For all of the assumptions the empty cells of each category have been rejected.*

The Power range for the obtained proportion of 235 ships is from 1000-4500 KW. After organizing the data in intervals of 100 KW and working with percentages, the most common Power supply is 2400 KW which represents the 25% of the ships.



To summarize, the energy efficient optimisation of the energy flows will be concentrated in a **<u>Product Tanker with a single 4 – Strokes Marine Diesel (2400 KW) engine that uses HFO.</u>** The reason of this selection is to define the standard design. If the standard design, understood at the most popular or common vessel, is improved in terms of emissions efficiency, the overall SSS could benefit from this general conclusions. Also, this is a wide field with a lot of different types of ships, power supplies, etc., consequently, it is a necessity to narrow the limits of this project's research.

The remaining objectives (4-6) are focused on the emissions and the energetic efficiency of the engine and its thermal processes. Firstly, a detailed literature review of the existing reports and regulations, with a careful look at the following sources:

IMO Emission Regulations (Annex 6) restraints the amount of SO_X and NO_X which is contained in ships exhaust gas, and impedes the emission of substances that destroy the ozone layer (Imo.org, 2014). This annex aims to reduce emissions by making technological improvements and re-designing processes and systems.

Energy Efficiency Design Index (EEDI) counts with the support of Governments, industry associations and organizations representing civil society interests. The EEDI should guarantee environmental sustainability by generating efficiency measures which end in a significant decrease of the emissions from ships.

The reduction of CO_2 emissions, one of the main greenhouse gases and responsible of the 63% of the global warming effect, are the main type of emissions regarded during the research. An effective reduction on this specific type of gas will help countries or communities (EU) to match regulations such as The Kyoto Protocol.

Secondly, the next objective to be completed is the application of this knowledge to the specific type of ship selected, a Product Tanker with a single 4 – Strokes Diesel Engine that burns HFO. Finally, the project concludes by making recommendations into the improvements of the main engine in terms of sustainability in energy production of the most common Short Sea Shipping (SSS) vessel.

This report has presented the progress of my individual project, and in which direction I am going to continue. There are three separated parts in this project: (1) The first research about SSS types of vessels and a detailed study of each type, (2) The second research about Emissions provided by ships and its regulations and how to measure the emissions (mainly CO_2) (3) The recommendations into the improvements in sustainability in energy production of the selected type of ship. Until now, the first part has been completed and the second is developing.

By this moment, I think I am on schedule and I should complete the project by the original deadline, although I might require a further effort during the next month to reach the dates and leave enough time to work on the final report.

8.4 ABSTRACT: ORAL PANNEL PRESENTATION

Title: **Energy efficient optimisation of energy flows within the ships' engineering systems**

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Energy efficiency is commonly defined as the production of the same service with lower energy consumption. Regarding Transport, energy efficiency is typically related to fuel consumption, and consequently to energy emissions.

The latest regulation for CO2, NOX, SOX and PM is stablished in the Annex VI of the MARPOL (The International Convention for the Prevention of Pollution from Ships). In terms of Greenhouse Gases, the European Commission has set a target of 40-50% reduction by 2050. The purpose of this project is to identify and compare different power plants layouts in order to make the system more energy efficient.

The Maritime Transport has a broad spectrum of possibilities to study regarding energy efficiency, therefore the first step is to define and narrow down the boundaries of this project. To begin with, the growing interest in the use of Short Sea Shipping (SSS) as an alternative to road and rail transport makes the study of this type of maritime transport a necessity. It has been estimated that the improvement potential is ranged between 25-75% of CO2 reduction, combining different types of measures. This project will look at the main propulsion system which has a 5-15 % range of improvement itself.

Looking at LNG, LPG, Container vessel, Bulk cargo and Product Tanker's main propulsion systems, the conclusion is the Product Tanker accounts the 48,4% of the Coastal Ships considered in research. Its most common propulsion layout is a 4-Strokes Marine Diesel Engine which burns Heavy Fuel Oil. To undertake the comparisons a real Product Tanker, built in 2013, will be used as a model. Assuming that this type of ship spends 50% of the time travelling and 50% of time on port, the approximated 85% amount of emissions came from the main engine, while the remaining 15% came from the diesel generator.

There are four types of power plants found among the SSS's studied: 2-Strokes Diesel Engine, 4-Strokes Diesel Engine, Steam Turbines and Diesel Electric. Regarding the Product Tanker, the use is divided in 5.6%, 93.2 %, 0% and 1.2% respectively.

The systems analysed so far in the comparison are:

1. Steam Turbine

2. Gas Turbine

3. Diesel Engine

3.1 Different types of fuels: HFO-MDO (Combined), LNG

I, Marta García Sansigre , confirm that the panel presentation which I intend to present for assessment and whose abstract is given above, is my own and is expressed in my own words. Any uses made within the presentation slides of the works of others in any form (ideas, equations, figures, text, tables, programs etc.) are properly acknowledged at the point of their use. A full list of the references employed is included.