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**Fuel savings and emission reduction in large ocean-going vessels by using permanent magnet shaft generators**

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**UNIVERSITY OF VAASA****School of Technology and Innovations**

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**ABSTRACT:**

This thesis provided a comprehensive analysis of permanent magnet shaft generator systems in large ocean-going vessels, specifically focusing on power generation. By exploring the performance of permanent magnet shaft generators compared to conventional systems, the study aimed to illustrate the potential impact on fuel efficiency and emission reduction within the maritime industry.

The research delved into the operational aspects of two different vessel types, LNG carrier and product tanker, to evaluate the effectiveness of permanent magnet shaft generators in diverse maritime contexts. Through in-depth technical analysis, the study examined the fuel savings and CO<sub>2</sub> emission reduction potential associated with the implementation of permanent magnet shaft generator systems across various fuel types, including LNG, MGO, and HFO.

Furthermore, the thesis investigated permanent magnet shaft generators operational profiles and technical features, offering insights into their potential benefits and drawbacks compared to traditional power generation systems. By providing a detailed overview of the technical characteristics of permanent magnet shaft generators, the research aimed to contribute to a profound understanding of their role in advancing sustainable power generation solutions for large vessels. The study also addressed the practical implications of implementing permanent magnet shaft generator systems, considering factors such as cost-effectiveness and reliability.

The study findings showed clear benefits of PMSG utilisation. With the system, ships can lower fuel consumption, reduce emissions, and ultimately lower overall ship operation costs. By analysing real-world data and research findings, the thesis aimed to provide maritime industry stakeholders with valuable information to support informed decision-making regarding adopting permanent magnet shaft generator technology.

Overall, the research explores the potential impact of permanent magnet shaft generator systems on fuel efficiency, emissions reduction, and overall operational performance in the context of large vessels. By presenting a detailed analysis of the technical, operational, and environmental aspects of these systems, the study sought to contribute to the ongoing efforts to promote sustainable and efficient power generation solutions within the maritime industry.

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**KEYWORDS:** permanent magnet shaft generator, power generation, fuel savings, emission reduction

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**Tiivistelmä:**

Tässä tutkielmassa analysoitiin kestopagneettiakseligeneraattorijärjestelmien käyttöä suurissa valtamerilaivoissa ja keskityttiin erityisesti niiden sähköntuotantoon. Tutkimuksessa tarkasteltiin kestopagneettiakseligeneraattoreiden suorituskykyä verrattuna perinteisiin järjestelmiin ja tuotiin esille niiden vaikutus polttoainetehokkuuteen ja päästöjen vähentämiseen merenkulku-alalla.

Tutkimuksessa tarkasteltiin kahden eri alustyyppin, LNG-säiliöaluksen ja tuotesäiliöaluksen, toiminnallisia näkökohtia, jotta voitiin arvioida kestopagneettiakseligeneraattorin tehokkuutta ja hyötyjä erilaisissa asetelmissä. Kerätyn ja analysoidun operointitietojen avulla tutkimuksessa tarkasteltiin kestopagneettijärjestelmän avulla saavutettuja polttoainesäästöjä ja CO<sub>2</sub>-päästöjen vähentämismahdollisuuksia. Tarkastelu suoritettiin kolmella eri meripolttoainetyypillä: LNG, MGO ja HFO.

Lisäksi tutkielmassa käsiteltiin kestopagneettiakseligeneraattoreiden toimintaa ja teknisiä ominaisuuksia, jotka tarjoavat tietoa niiden mahdollisista eduista ja haitoista verrattuna perinteisiin generaattorijärjestelmiin. Tarjoamalla yksityiskohtaisen yleiskatsauksen kestopagneettiakseligeneraattoreiden teknisiin ominaisuuksiin tavoitteena oli auttaa ymmärtämään syvällisesti niiden roolia alusten kestävien sähköntuotantoratkaisujen edistämässä. Tutkimuksessa käsiteltiin myös kestopagneettiakseligeneraattorijärjestelmien käyttöönoton käytännön vaikutuksia ottaen huomioon sellaiset tekijät kuin kustannustehokkuus ja luotettavuus.

Tutkimuksen tulokset osoittivat, että kestopagneettiakseligeneraattorijärjestelmän käytöstä on selviä hyötyjä. Järjestelmän avulla alukset pystyvät vähentämään polttoaineen kulutusta ja päästöjä sekä alentamaan aluksen toiminnan kokonaiskustannuksia. Analysoimalla laivojen käyttötietoja ja aiempia tutkimustuloksia sekä näiden avulla saatujen tuloksien kautta tavoitteena oli tarjota merenkulqualalle tietoa, joka tukee faktatietoon perustuvaa päätöksentekoa kestopagneettiakseligeneraattoritekniikan käyttöönotosta.

Kaiken kaikkiaan tutkimus tarjoaa selvityksen kestopagneettiakseligeneraattorijärjestelmien vaikutuksista polttoainetehokkuuteen, päästöjen vähentämiseen ja yleiseen toiminnalliseen suorituskykyyn suurten alusten yhteydessä. Esittämällä yksityiskohtaisen analyysin näiden järjestelmien teknisistä, toiminnallisista ja ympäristönäkökohdista tutkimus pyrki edistämään meillä olevia tavoitteita edistää kestäviä ja tehokkaita sähköntuotantoratkaisuja merenkulku-alalla.

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**Avainsanat:** kestopagneettiakseligeneraattori, sähköntuotanto, polttoainetehokkuus, päästöjen vähentäminen

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## Symbols

$B$	Magnetic flux density [Wb/m <sup>2</sup> ]
$C$	Deadweight [t]
$C_F$	Fuel consumption and CO <sub>2</sub> emission factor [Kg <sub>CO2</sub> /Kg <sub>fuel</sub> ]
$\cos \Phi$	Power factor [/]
$D$	Nautical mile [M]
$D_r$	Diameter [m]
$E_{rms}$	Magnitude of induced voltage in stator phase [V]
$E_{tot}$	Annual energy consumption [kWh]
$f$	Frequency [Hz]
$FC$	Total mass of consumed fuel [g]
$F_d$	Mechanical radial force [N]
$F_m$	Magnetic pull [N]
$G_V$	Vertical mass [kg]
$I_A$	Armature current [A]
$I_F$	Field winding current [A]
$I_L$	Line current [A]
$L_p$	Pole length [m]
$m_{tot}$	Annual fuel consumption [ton]
$n$	Shaft speed [rpm]
$N_C$	Stator coil turns [/]
$P$	Power [kW]
$p$	Number of poles [/]
$P_{air}$	Windage losses [kW]
$P_B$	Brake power [kW]
$P_b$	Brush-slip ring losses [kW]
$P_{bear}$	Bearing losses [kW]
$P_{conv}$	Converted electrical power [kW]
$P_D$	Delivered power [kW]
$P_{ex}$	Rotor excitation losses [kW]

$P_{exsh}$	Total excitation system losses [kW]
$P_{in}$	Input power [kW]
$P_{MSB}$	Average MSB load [kW]
$P_{out}$	Output power [kW]
$P_{scl}$	Stator copper losses [kW]
$R_A$	Armature phase resistance [ $\Omega$ ]
$R_F$	Field winding resistance [ $\Omega$ ]
$SFOC$	Specific fuel oil consumption [g/kWh]
$t_{ME}$	Annual generator running hours [h]
$U_{a\ bear}$	Axial bearing peripheral speed [m/s]
$U_{bear}$	Radial bearing peripheral speed [m/s]
$V_L$	Line voltage [V]
$V_{ref}$	Reference speed [kn]
$\tau_{app}$	Prime mover torque [Nm]
$\tau_{ind}$	Induced torque [Nm]
$\Phi$	Magnetic flux [Wb]
$\omega_m$	Angular velocity [rad/s]
$\eta_{ex}$	Efficiency of the static exciter [/]
$\eta_g$	Generator efficiency [/]

**Abbreviations**

AC	Alternating Current
AE	Auxiliary engine
AVR	Automatic voltage regulator
CFE	Constant frequency electrical
CFM	Constant frequency mechanical
CII	Carbon Intensity Indicator
CO <sub>2</sub>	Carbon dioxide
DC	Direct current
ECA	Emission Control Area
EE	Electrically excited
EEDI	Energy Efficiency Design Index
EESG	Electrically excited shaft generator
EEXI	Energy Efficiency Existing Ship Index
ETS	European Trading System
EU	European Union
EUA	European Union Allowance
FAT	Factory acceptance test
GCR	Gear constant ratio
GHG	Greenhouse gas
HFO	Heavy fuel oil
HSFO	High sulfur fuel oil
HVAC	Heating, ventilation, and air conditioning
LFO	Light Fuel Oil
LHV	Lower heating value
LNG	Liquefied natural gas
MDO	Marine diesel oil
ME	Main engine

MGO	Marine gas oil
MSB	Main switch board
IFO	Intermediate fuel oil
IMO	International Maritime Organization
IPM	Interior permanent magnet
MEPC	Marine Environment Protection Committee
MSB	Main switch board
NO <sub>x</sub>	Nitrogen oxide
PM	Permanent magnet
PMSG	Permanent magnet shaft generator
PTH	Power-take-home
PTI	Power-take-in
PTO	Power-take-out
REN	Renewable Energy Network
SFOC	Specific fuel oil consumption
SG	Shaft generator
SO <sub>x</sub>	Sulfur oxide
SPM	Surface permanent magnet
ULCC	Ultra large crude carriers
ULSFO	Ultra Low Sulphur Fuel Oil
US	United States of America
VLCC	Very large crude carriers
VLSFO	Very Low Sulphur Fuel Oil

## 1 Introduction

The world is currently undergoing an energy transition, because there is an urgent need to reduce emissions and the use of fossil fuels to curb climate change. According to a report produced by the Renewable Energy Network 21 (REN21), the transportation sector accounts for roughly a third of the world's total energy consumption and approximately 60% of total oil consumption (REN21, 2021). Maritime transport accounts for a significant share of this; the report reveals that maritime activity consumes approximately 9.6% of the total energy consumption of the transportation sector. The total capacity of goods transported by ships has tripled in the last three decades, indicating maritime transport's importance worldwide (Patel, 2021).

International Maritime Organization (IMO) has set a target of a 40% reduction of greenhouse gas emissions from ships by the year 2030 and 70% by 2050 compared to the 2008 baseline (IMO, 2022a). To achieve this short-term emission reduction, IMO required large vessels from 1 January 2023 to calculate and certificate their attained Energy Efficiency Existing Ship Index (EEXI) and annual operational Carbon Intensity Indicator (CII). According to IMO to qualify for EEXI certification, a ship must meet the minimum energy efficiency requirements specified for each individual ship. CII certification determines the reduction factor needed to ensure continuous improvement of a ship's operational carbon intensity within a specific rating level, such as produced emissions and the amount of cargo carried over the distance travelled.

Various maritime industry regulations are forcing ship owners to invest at a rapid pace in more environmentally friendly solutions, and thus, this creates a trend throughout the marine business. For both new and retrofitted vessels, there are a number of different solutions to meet the IMO GHG strategy. According to IMO (2022b), individual or combined solutions to improve vessels' energy efficiency are, for example, reduction of sailing speed, implementation of energy savings devices, vessel's hybridisation or full electrification, the use of low or zero-carbon fuels, ensuring optimal engine performance and applying energy efficient power generation system.

With the help of shaft generator system, vessels can reduce emissions significantly compared to a conventional auxiliary generator set (genset) system, and in addition, when applying a permanent shaft generator (PMSG), emission reduction is even bigger (Dziuba, 2022). Vessel operators can reduce emissions and cut fuel consumption without compromising sailing speed. Thus, using the PMSG system, ship owners can reduce fuel expenses and cut carbon intensity compared to conventional solutions.

This thesis has been commissioned by The Switch. The aim of the thesis was to establish fuel saving and carbon dioxide (CO<sub>2</sub>) emission reduction potential with a permanent magnet shaft generator system compared to conventional electrically-excited shaft generator system (EESG) and standalone generator (genset) system. The research was conducted on two vessel types: a liquefied natural gas (LNG) carrier and a product tanker. The anticipated fuel savings and emission reduction results were calculated for three different fuel types: LNG, marine gas oil (MGO) and heavy fuel oil (HFO). The assumption of this thesis was that PMSG will be the most efficient way of generating power and result in most fuel savings and emission reductions.

The thesis consists of a theoretical part based on literature and publications in the field and an empirical part carried out as quantitative data analysis. The theoretical part covers the general theory behind large vessel power systems from both propulsion and electrical power generation points of view and marine emission regulations and legislations. Lastly, the theory section concludes with an in-depth look at the PMSG system.

For the empirical part, the necessary data on the operations of the different vessels were collected from marine operators utilising PMSGs. Other research material is based on literature studies as well as material provided by The Switch. The aim was to produce a convenient material for presenting the benefits of PMSG in terms of both fuel consumption savings and CO<sub>2</sub> reductions.

## 2 Power generation in large vessels

The history behind electric power generation on ships goes back to 1880 when the American ship Columbia installed the first electrical light on board (Patel, 2021). After this historical milestone, power generation in vessels has come a long way; nowadays, vessels demand megawatt-class electricity generation. According to Patel (2021), the large demand for electrical power is due to loads such as propulsion machinery, auxiliary machinery, cargo-handling machinery, deck machinery, equipment for heating, ventilation, and air conditioning (HVAC), control electronics, communication electronics, and hotel load.

Different vessels can be grouped according to their drive system, more precisely on their mechanical and electrical power system (Patel, 2021). Different vessels can have four different propulsion systems: diesel-mechanic system, diesel-electric system, integrated-electric system and all-electric system.

According to Patel (2021), the majority of merchant cargo vessels have the diesel-mechanic system. In these types of propulsion systems, the main engine (ME) powers the propellers via a long shaft and, optionally, a mechanical gear system. Patel further explains that conventional electrical power for service loads is produced by gensets and shaft generators. Both this chapter and the thesis focus on vessel types that fall under this group.

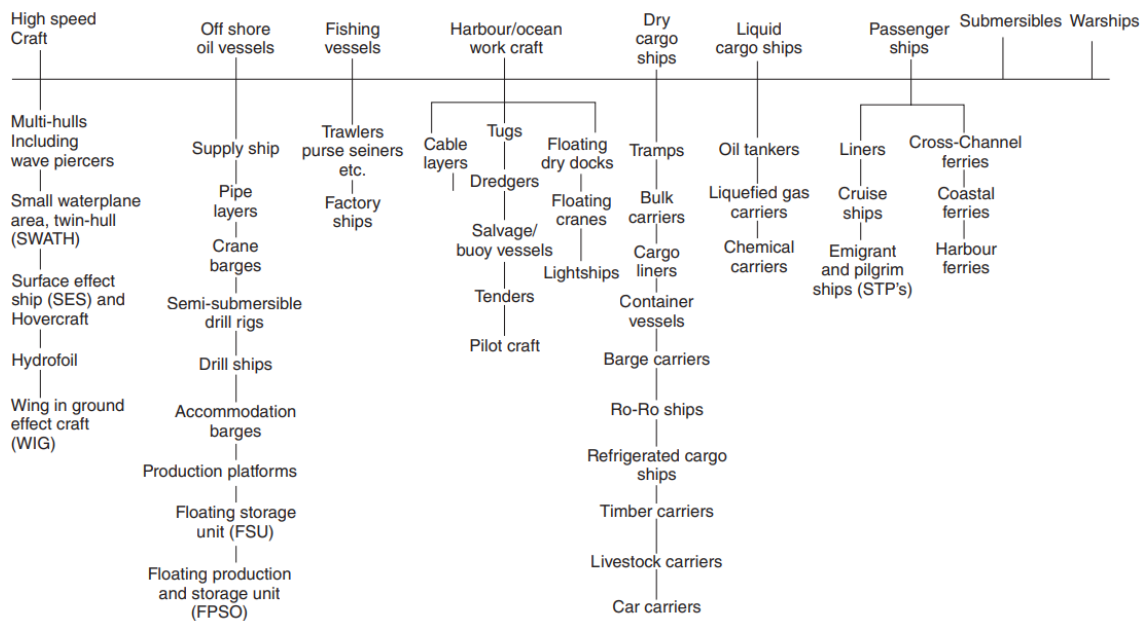
Most passenger cruise vessels have the diesel-electric system (Patel, 2021). These vessel's propulsion is carried out with large electric motors. Patel explains that electricity for propulsion is generated with dedicated propulsion power generators, and electricity for service loads is generated with separate auxiliary gensets.

Vessels that have integrated-electric systems are operated in such a way that the main gensets provide all the necessary power for both electric propulsion and other systems (Patel, 2021). A step-down transformer from the main bus provides the vessels service

loads. This is a common practice in naval vessels, as the system allows the shutdown of non-essential systems easily in combat situations to divert the power for combat weapons. Patel concludes that many navies around the world are adopting this type of integrated power system. All-electric systems are those vessels where, no combustion engines are used, thus batteries are only used for providing power for all the energy-draining functions, such as propulsion, auxiliary equipment, and hotel load (Patel, 2021).

## 2.1 Large merchant cargo vessels

Ocean-going vessels can be divided into transport, non-transport, and warships (Molland, 2008). The transport category includes cargo, container, and passenger vessels, while non-transport vessels consist of fishing vessels, service vessels such as tugs, and supply vessels. Figure 1 shows a wide range of different vessel types.



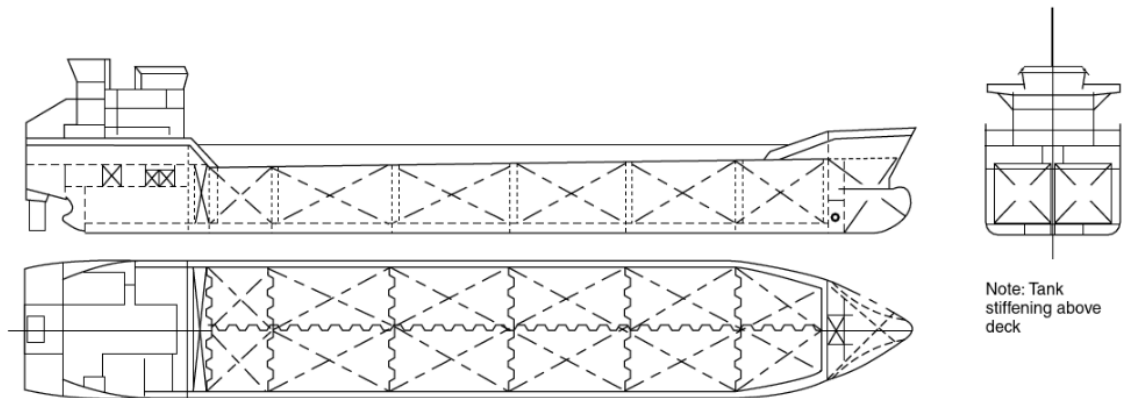
**Figure 1.** Ship types (Eyres, 2007).

Today, approximately 90 % of the world's trade by volume is carried out by ships (Patel, 2021). The marine industry has grown rapidly due to the expansion of industrial

production worldwide, which has increased trade both within and between continents, with the most important parties being China, the USA, and Europe.

### 2.1.1 Product tanker

A product tanker is a vessel type that generally falls under tankers (Molland, 2008). Tankers transport liquids such as crude oil, oil products, gas, and chemicals. The size and other characteristics of the vessels vary slightly, but in principle, they have the same concept. Figure 2 shows a double-hulled product tanker.



**Figure 2.** Product tanker (Eyres, 2007).

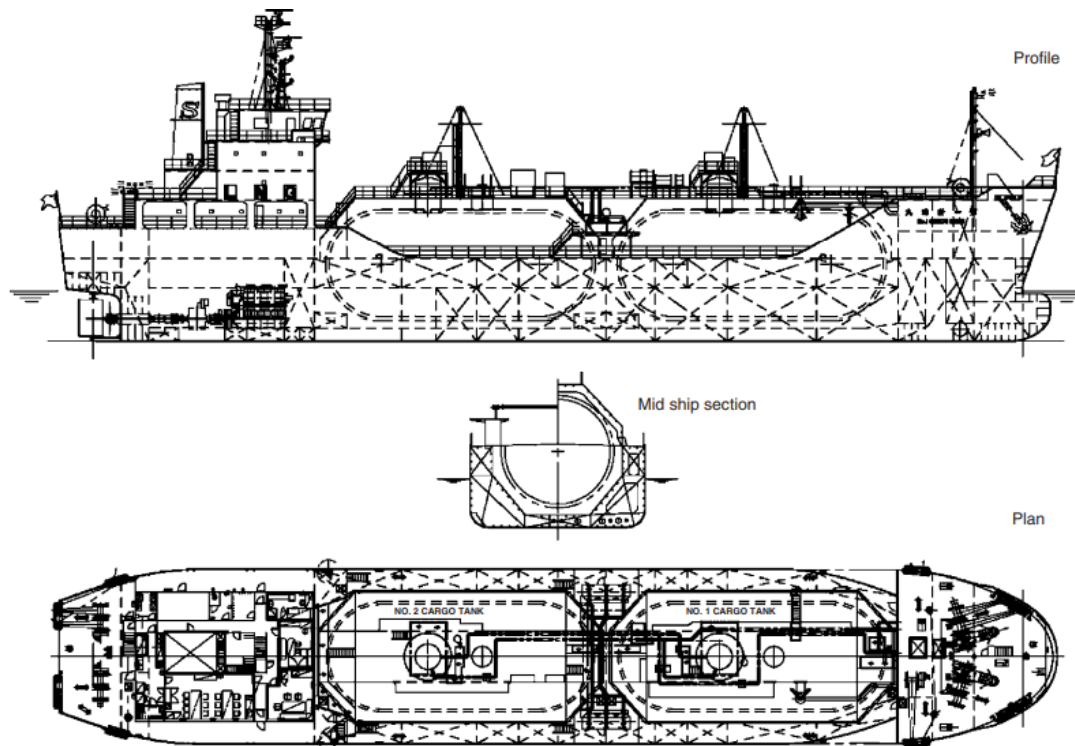
Molland (2008) states that tankers have become increasingly larger over time to take advantage of economies of scale and meet the growing demand for oil. The largest of ships are referred to as ultra large crude carriers (ULCC) and very large crude carriers (VLCC), with ULCCs having a capacity of over 300,000 deadweight tonnage (dwt) and VLCCs having a capacity of 200,000-300,000 dwt. Molland states that some crude oil tankers have been built with capacities exceeding half a million dwt, but the recent trend has been building somewhat smaller crude oil carriers.

Refined products from crude oil, such as gas oil, aviation fuel, and kerosene, are transported in smaller ships known as product tankers (Molland, 2008). These vessels have

more divided tanks to accommodate the transport of multiple products at the same time. Product tankers can range in size from 18,000 to 75,000 deadweight tons.

### 2.1.2 LNG carrier

A liquefied natural gas (LNG) carrier is a vessel type that falls under tankers, although there are some special requirements for various features of the vessel. The concept of an LNG carrier is shown in Figure 3. Natural gas is a widely used energy source, providing energy for households and fuelling power plants and vehicles.



**Figure 3.** Small LNG carrier (Molland, 2008).

According to Molland (2008), LNG together with liquefied petroleum gas, a by-product of natural gas production, are the most common gas products transported worldwide. Natural gas is projected to grow the most among fossil fuels and is anticipated to increase by 0.9 per cent annually from 2020 to 2035 (McKinsey & Company, 2021). Furthermore, it is the only fossil fuel that is predicted to continue growing beyond 2030, reaching its peak in 2037.

Natural gas is carried in vessels in liquefied form due to its smaller volume compared to gaseous form; thus, in liquid form, vessels can transport larger amounts of natural gas. Molland (2008) states that natural gas needs to be held under the temperature of approximately  $-162\text{ }^{\circ}\text{C}$  in atmospheric pressure to maintain its liquid form. Typically, LNG carriers are designed to store LNG in tanks at atmospheric pressure. Molland notes that LNG carriers have steadily increased in capacity. Nowadays, the typical LNG capacity is around  $170\ 000\ \text{m}^3$ .

## **2.2 Mechanical power generation in ships**

Power generation in ships can be divided into propulsion power for manoeuvring and auxiliary power for hotel load and other ship operations requiring electricity (Molland, 2008). This chapter discusses propulsion power. The most suitable propulsion system and auxiliary power plant system are individual for each vessel. According to Molland (2008), the solution is affected by the purpose and operational profile of the vessel, as well as the available machinery options and lifetime costs.

Among large cargo vessels such as tankers and container vessels, the power for propulsion is generated mainly by direct-coupled low-speed two-stroke MEs due to their superior efficiency. Molland states that smaller size vessels such as small cargo vessels, cruise ships, ferries, smaller RoRo vessels and other special vessels prefer medium-speed four-stroke engines for propulsion power generation. Unlike the large two-stroke powered vessels, the propulsion concepts can vary largely.

According to Molland (2008), four-stroke propulsion engines are generally not direct-driven but equipped with gearboxes. For vessels equipped with medium speed ME, gearbox is preferred since the best propulsion efficiency from the propeller point of view is achieved with low rotation speeds. Molland states that geared drive enables the possibility of father-and-son layouts. This is a configuration of two different cylinder number

engines coupled to a common gearbox, and as a result, vessels can be efficiently flexible in propulsion power generation. Propulsion can be carried out with a father or son engine solely or both together.

Diesel-electric propulsion is a form of indirect-drive that uses several medium-speed main gensets for propulsion powering (Molland, 2008). Diesel-electric propulsion is widely used in vessels such as cruise ships and ferries. According to Molland, Diesel-electric systems deliver smooth and accurate speed control and low noise and vibration. Diesel-electric propulsion requires large electric motors to drive the propellers and gensets to supply the power. A large number of main gensets ensures efficient power control of the propulsion system since the number of engines running in the grid can be changed. Therefore, running gensets can be operated within their most efficient load all the time, Molland concludes. Moreover, a redundant system comprising several gensets, with a surplus of parallel units relative to the requisite performance, ensures that the failure or maintenance of any single unit does not compromise the operational functionality of the system.

### **2.2.1 Marine internal combustion engines**

Internal combustion engines are vital in vessels since they produce the required ship-specific propulsion and auxiliary power. Internal combustion engines are often categorised in two different ways the first being the cycle type of the engine, two-stroke or four-stroke (Heywood, 2018). Generally, two-stroke engines are used in the largest and preferably low-speed applications around less than 250 rpm, while four-stroke engines are used in medium-speed and high-speed applications. The two types of engines are distinguished by their different combustion cycles. Heywood states that in the two-stroke engine, the air-fuel mixture's compression, combustion, exhaust gas removal and fresh charge intake is done in one crank-shaft revolution, while in a four-stroke, this is done during two revolutions. According to Heywood, the second way of categorising engines is the fuel ignition type, either spark ignition (SI) or combustion ignition (CI). Conventionally, marine engines are diesel engines, which use CI technology.

According to Heywood (2018), five main characteristics of internal combustion engines need to be considered in the case of engine operation in different conditions and uses: ensuring maximum performance throughout the full speed range, fuel consumption optimizing in the full speed range, minimising engine pollutant emissions and harmful noise, initial cost of the engine and its installation, and reliability of the engine including maintenance requirements. Heywood states that these are the factors of which the engine operating costs consist of. Lifetime costs and emission values guide the user's choice of engine. Table 1 shows the characteristics of some of the largest marine engines from different manufacturers.

**Table 1.** Technical data of various main engine types

Engine	Wärtsilä 16V46F ME	MAN V32/40 (FPP)	MAN B&W G95ME-C10.5	WinGD X92-B
Cycle type	four-stroke	four-stroke	two-stroke	two-stroke
Rated engine speed [rpm]	600	750	80	80
Cylinder output [kW]	1,200	500	6,870	6,450
SFOC 100 % load [g/kWh]	180.6	187.0	162.0	162.8
SFOC 85 % load [g/kWh]	173.0	183.0	N/A	N/A
SFOC 75 % load [g/kWh]	176.4	189.0	157.5	154.3
SFOC 50 % load [g/kWh]	179.3	190.0	158.5	156.7

As seen in the table above, the large-size two-stroke engines are significantly more efficient in terms of specific fuel oil consumption (SFOC). Technical data for all engines has been collected from product guides provided by the manufacturers. The SFOC is given for each engine with fuel oil having a lower heating value of 42,700 kJ/kg, which is roughly equivalent to marine diesel oil.

As the large two-stroke engines are the most efficient stand-alone machines, they also have another advantage over the medium- and high-speed engines when used as the

main engine of a vessel. According to Molland (2008), a critical factor in the choice of the ship's main engine is the fact that the propulsion shaft, and thus the propulsion engine, should be able to be turned at low enough speed to rotate the large diameter propellers. As a basic rule, the larger the propeller's diameter, the lower the rotational speed required to be operated efficiently. Molland states that medium and high-speed engine types can also be used as main engines in large applications, but they also require a large step-down gearbox for efficient use. It should be noted that the gearbox always introduces additional losses in the transmission. It is essential to note that the SFOC of two-stroke engines decreases at partial loads, as can be seen in Table 1.

According to Molland (2008), the most popular propulsion mode for large deep-sea vessels is a direct-drive of a fixed-pitch propeller by a low-speed two-stroke engine. With the long-stroke and super- and ultra-long-stroke engines, the slight loss of propulsive efficiency that was previously in history accepted for the sake of simplicity has been removed. Molland states that the longer-stroke engines now available can produce their rated power at speeds ranging from as low as 55 rpm to around 250 rpm for the smallest bore models. This allows for the specification of a direct-drive propeller shaft operation that yields close to the optimum propulsive efficiency for a given ship design. According to Molland, the large bore low-speed engines with fewer cylinders influence the size of the engine and the machinery space, the maintenance workload, and the number of spare parts needed to be held in stock. In most deep-sea vessels, a larger bore engine with fewer cylinders underwrites a shorter engine room and more space for freight.

However, a direct-coupled two-stroke ME requires service pumps for cooling and lubrication, fuel, as well as lube oil handling and treatment systems (Molland, 2018). These auxiliary devices need electrical power, which is usually provided by medium- or high-speed gensets. Molland states that it is now an industry standard for genset suppliers to offer designs capable of burning the same heavy fuel grade as the main engine and marine diesel oil or blended bunker fuel.

## **2.3 Overview of maritime emissions and emission regulations**

The main emissions from maritime traffic caused by combustion of internal combustion engine fuels are carbon dioxide (CO<sub>2</sub>), sulfur oxide (SO<sub>x</sub>), nitrogen oxide (NO<sub>x</sub>) and particulate matter (Patel, 2021). According to Patel (2021), the maritime industry has steadily reduced fuel consumption of vessels mainly due to the increase in energy prices, but also from the perspective of reducing emissions. However, due to significant increase in shipping, total emissions have also increased steadily.

This thesis focus solely on CO<sub>2</sub> emissions in the empirical part. However, it is important to acknowledge other maritime emissions that are harmful to the environment and human health in addition to CO<sub>2</sub> emissions. Also, an important feature is also the fact, in particular, that regulations regarding limiting SO<sub>x</sub> emissions have a major impact on fuel solutions for shipping and hence on fuel costs.

### **2.3.1 International Maritime Organization**

The International Maritime Organization (IMO) is a specialized agency under the United Nations responsible for the safety, security, and emission regulations of the international maritime industry (IMO, n.d. -a). IMO's main objective is to produce fair and effective regulations for the maritime industry that are worldwide adopted and implemented. According to IMO, today, the organization consists of 175 member states and three associate members.

In 2019, the International Maritime Organization (IMO) introduced new limits on sulfur oxide (SO<sub>x</sub>) emissions, known as IMO 2020. Reducing sulfur emissions is expected to prevent diseases such as asthma, strokes, cardiovascular and pulmonary diseases, and lung cancer (IMO, 2019). IMO (2019) states also that the new limitations aim to prevent acid rain and ocean acidification, benefiting forests, farming, and ocean life. The global sulfur regulation now requires ships operating outside designated Emission Control Areas (ECAs) to limit sulfur content in fuel oil to 0.50%, down from the previous limit of 3.50%.

Within ECAs, the limit is even stricter at 0.10%. According to IMO, the implementation of IMO 2020 is projected to reduce total SO<sub>x</sub> emissions by approximately 77%, equivalent to about 8.5 million tonnes annually.

IMO's latest amendment on nitrogen oxide (NO<sub>x</sub>) emissions on ocean-going vessels is from 2021 (IMO, n.d. -c). This regulation applies to all vessels with diesel engine power of 130 kW or above, with one exception being engines solely used for emergencies. IMO states that NO<sub>x</sub> regulations have been divided into three tiers, and all of them are tied to vessel engine speed  $n$ , which corresponds to engine rounds per minute (rpm). The required tier for individual ships is determined by the construction date. The list of the Tiers for the limitation of NO<sub>x</sub> emission is shown in Table 2. The vessels built between 1 January 1990 and 31 December 1999, which are equipped with engines with over 5,000 kW output power and more than 90 liters of volume per cylinder are mandated to follow the minimum of tier 1 (IMO, n.d. -c).

**Table 2.** MARPOL Annex VI NO<sub>x</sub> emission limits (IMO, n.d. -c)

Tier	Date	No <sub>x</sub> limit (g/kWh)		
		$n < 130$	$130 \leq n < 2000$	$n \geq 2000$
Tier 1	1 January 2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier 2	1 January 2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier 3	1 January 2016	3.4	$9 \cdot n^{-0.2}$	2.0

Tiers 1 and 2 for NO<sub>x</sub> regulations are global, while Tier 3 is applied to specified ECA areas. IMO (n.d. -c) further states that vessels constructed on or after 1 January 2016 must comply with Tier 3 when operating in the North American ECA and the United States' (US) Caribbean Sea ECA. Vessels that were constructed on or after 1 January 2021 and that operates in the aforementioned US coastal or sea areas or in the Baltic Sea or the North Sea, must also meet Tier 3 requirements.

IMO (2022) has introduced two new indicators, the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII), to reduce shipping's GHG emissions in the short term. These measures aim to enhance energy efficiency and monitor carbon emissions in the shipping industry. From 1 January 2023, all vessels affected by the regulations have to be certificated for vessel-specific EEXI requirements and annually report their CII to IMO. IMO states that the EEXI certification requirement applies for all vessels of 400 gross tonnage and above, and the annual CII reporting requirement applies to all vessels with 5 000 gross tonnage and above.

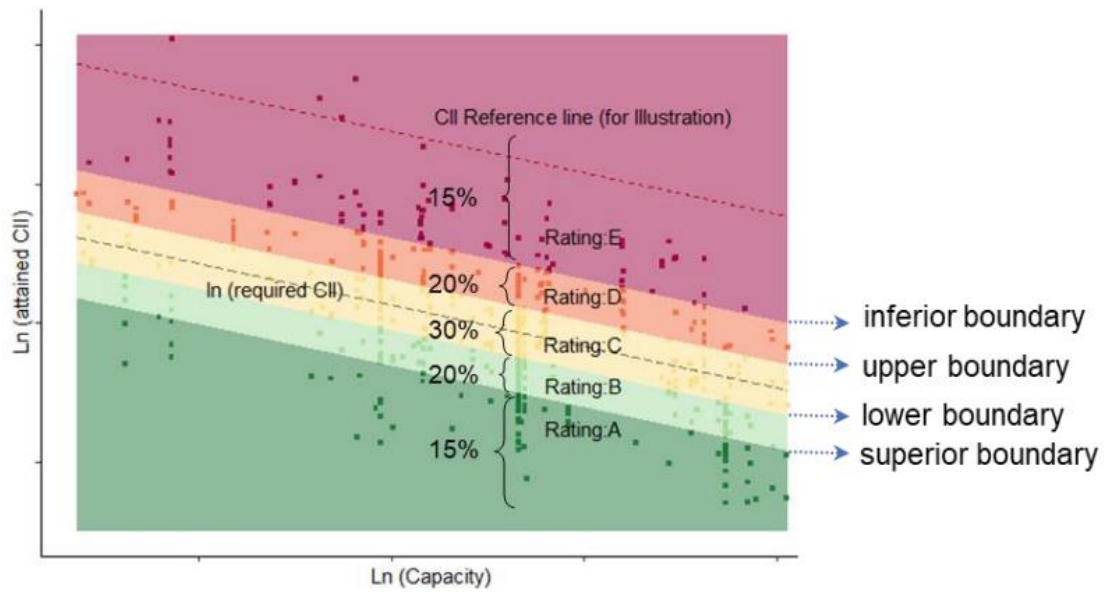
The new EEXI regulation is related to an already existing Energy Efficiency Design Index (EEDI) (Ghosh, 2022). According to Ghosh, EEDI has set a minimum level of energy efficiency for newly constructed ships from January 2013 onward based on their type and size, while EEXI aims to improve the emission level and propulsion efficiency of all existing ships, based on type and size. The attained EEXI must be less than or equal to the required benchmark equal to EEDI baseline. If the attained value exceeds the required value, the vessel is deemed unfit for operating in the seas in terms of energy efficiency (Ghosh, 2022). Ship operators are required to calculate and report their own attained EEXI using Equation 1 (IMO, 2022).

$$EEXI = \frac{\text{Main engine emissions} + \text{Auxiliary engine emissions} + (\text{PTI-Innovative electrical energy technologies}) - \text{Innovative propulsion energy technologies}}{\text{Capacity} + \text{Reference speed} + \text{Reduction factor}} \quad (1)$$

Both main and auxiliary engine fuel consumption is directly proportional to the emissions when calculating EEXI and EEDI. Therefore, by cutting fuel consumption attained EEXI drops. Innovative electrical energy technologies can have both direct effects on attained EEXI as well as indirect effects in the form of potential fuel consumption cuts (Tadros et al., 2023).

CII rating connects a vessel's GHG emissions to the amount of cargo carried for a total distance travelled (IMO, 2022). The rating system of CII is carried out with a five-grade rating mechanism defined on a scale of A to E, A being the greatest rating (MEPC, 2022a).

According to the MEPC resolution, the first ratings are set based on 2019 CII baseline statistics. Ratings are determined as follows: A rating is achieved by vessels that are among the global top 15 % of smallest CII rating, 20 % of vessels that are above the lowest group are assigned with B rating, C rating is assigned for the middle 30 %, D rating for 20 % of above the middle group, and E for the upper 15 %. The rating mechanism is illustrated in Figure 4.



**Figure 4.** CII rating mechanism (MEPC, 2022a).

As shown in the figure above, the maximum attained CII for an individual ship is a C rating. IMO (2022) states that statistics of attained CII are collected from vessels yearly, and the performance ratings are recorded into a statement of compliance to be further elaborated in the vessel's Ship Energy Efficiency Management Plan (SEEMP), which aims to ensure continuous improvement of energy efficiency and lower carbon intensity. Equation 2 shows how the attained CII is calculated for specific vessels.

$$CII_{Ship} = \frac{FC \cdot C_F}{C \cdot D_t}, \quad (2)$$

where  $FC$  is total mass of consumed fuel,  $C_F$  is fuel consumption and  $CO_2$  factor,  $C$  is deadweight and  $D_t$  is distance in nautical miles.

According to IMO (2022), vessels rated D for three consecutive years or E for one year must submit a corrective action plan to achieve the required C rating. Also, it is suggested that entities such as governmental organisations, port authorities, and the other relevant groups offer incentives to vessels that have received a rating of A or B.

### **2.3.2 Marine fuels**

According to King (2022), the maritime industry is currently responsible for approximately 3% of global  $CO_2$  emissions, which initially does not seem relevant compared to other emitting sectors. However, maritime emissions could increase by up to 250 % by the year 2050 due to the projected significant continuous growth in world trade, (Cames et al., 2015). This will inevitably lead to the fact that, without strict actions, the global  $CO_2$  emission share of the maritime industry will increase significantly. Cames et al. (2015) state in their study that the maritime industry could eventually be responsible for up to 17% of global  $CO_2$  emissions in 2050 without strict regulations.

GHG emissions from the maritime sector are caused by the fuels used, which are still today mainly oil-based or other fossil fuels. MEPC (2022b) produces an annual report, which collects data on fuel consumption from all vessels with 5 000 dwt and above. These vessels produce approximately 85% of the total  $CO_2$  emissions from the maritime industry. The 2022 report reveals that 28 171 vessels have rightly reported their 2021 annual fuel consumption, totalling 212 million tonnes of fuel. The report states that 99.89% of the fuel used was either heavy fuel oil (HFO), light fuel oil (LFO), diesel/gas oil (MDO/MGO) or LNG. The remaining 0.11 % consists mostly of ethane, biofuel, propane, butane, methanol and ethanol.

MEPC (2022b) report clearly demonstrates the dependence of the maritime industry on fossil fuels and thus world trade is also dependent on them. However, the industry is

being forced to develop new, more environmentally friendly fuels, for example through IMO regulations. Good and already reasonably advanced development with methanol suggest that it has a potential to be an alternative fuel for the future. According to Methanex (n.d.), the use of methanol is supported by a number of factors such as a reduction of up to 95% of SO<sub>x</sub> and PM emissions compared to conventional fuels, up to 80% reduction of NO<sub>x</sub> and a 15% reduction in CO<sub>2</sub> emissions. Table 3 shows the carbon intensity and lower heating value of certain marine fuel types, and Table 4 shows the pricing of common marine bunker fuels.

**Table 3.** Carbon dioxide emission factors for different fuel types (IMO, 2016).

Type of fuel	Carbon content	Specific CO <sub>2</sub> emissions (kg <sub>CO2</sub> /kg <sub>fuel</sub> )
Marine Diesel/Gas Oil (MDO/MGO)	0.8744	3.206
Heavy Fuel Oil (HFO)	0.8493	3.114
Light Fuel Oil (LFO)	0.8594	3.151
Liquefied Natural Gas (LNG)	0.7500	2.750
Methanol	0.3750	1.375

**Table 4.** Bunker fuel prices (Ship & Bunker, n.d.).

Bunker fuel	Date	Price (\$/ton)	LHV (kJ/kg)	Provider
HSFO/IFO380	21.4.2024	486.0	40,200	Port of Rotterdam
MGO	21.4.2024	751.5	42,700	Port of Rotterdam
LNG	21.4.2024	668.0	48,000	Port of Rotterdam
Methanol	21.4.2024	344.0	19,900	Port of Rotterdam

Bunker fuel prices are from Europe's largest port, the port of Rotterdam. Due to the IMO 2020 regulation, fuel oil has been divided into three different categories according to its SO<sub>x</sub> content: HSFO exceeding 0.50%, VLSFO not exceeding 0.50%, and ULSFO not exceeding 0.10%. The port of Rotterdam did not provide the price of ULSFO fuel oil. It is also worth noting the comparison of the price of each fuel with its lower heating value, which is shown in Table 4.

In addition to the IMO's CO<sub>2</sub> emission regulations, the European Union (EU) implements its own measures to reduce carbon emissions of maritime transport within the EU. The European Commission (2023) agreed on 14 July 2021 to revise the EU emission trading system (ETS) directive and explore the inclusion of the maritime transport industry. The ETS directive is currently applied only to factories and power plants.

On December 17<sup>th</sup>, 2022, the EU lawmakers agreed to enhance the EU ETS and implement emissions trading in the maritime transport sector (European Commission, 2023). This agreement must still be officially accepted by both the European Parliament and the Council. Once agreement is officially accepted, the new law will be released in the official journal of the European Union and become effective. Figure 5 shows the European carbon credit market futures for December 2024.



**Figure 5.** European Carbon Credit Market (Carbon Credits, 2024)

As of 2024, ship operators are required to buy EU carbon permits to cover their CO<sub>2</sub> emissions (European Commission, 2023). European Union Allowances (EUA) is the

official exchange-traded futures contract for the EU's emission allowance. One EUA allows the holder to emit one ton of CO<sub>2</sub> or equivalent GHG (Carbon Credits, 2023). The futures shown in Figure 5 illustrate the price of EUA in euros in April 2024.

While EU ETS will be a big driver and pressure maker for the maritime industry to invest in more environmentally friendly technologies, there will be a transition period before the directive is fully implemented. According to the European Commission (2023), ship-owners are required to buy allowances for 40% of their reported CO<sub>2</sub> emissions in 2024, 70% of 2025 and, from 2026 onwards, 100%. The European Commission states that the ETS will encompass all emissions generated by ships traveling within the EU. Half of the emissions produced during trips to or from a non-EU country will also be included in the ETS coverage.

### **3 Permanent magnet shaft generator system**

Today, all electrical power in ships is generated by onboard three-phase alternating current (AC) generators, also known as alternators (Patel, 2021). There are three main concepts for onboard electricity generation, either used individually or in combination (Molland, 2008). These three different auxiliary power generation concepts are shaft generators, standalone generator sets, also known as gensets, and gas turbines. This chapter and thesis focus more on shaft generators from the perspective of permanent magnet (PM) shaft generators; gas turbines are not discussed, as they are also not very common anymore.

Permanent magnet synchronous generators have become more common in the past decade, although as an invention it is nothing new. PM technology is widely used, especially in large slow- and medium-speed applications, due to their greater efficiency compared to electrically excited generators and their simple and robust structure. For example, PM generators in wind power have become the industry standard (Eriksson, 2019). According to Eriksson, also other industries are moving towards PM technology due to global energy demand increase and climate aspects.

#### **3.1 History of the shaft generator system**

As discussed in the second chapter, the first milestone for the electrification of ships occurred in 1880, when the first electric light was installed on SS Columbia. Since then, ship development has continued rapidly. According to Skjong et al. (2016), the first ship to use AC power was SS Canberra in 1960. The introduction of AC power in ships presented the option for onboard alternators for auxiliary power generation for the ship's grid.

As Puranen (n.d.), Head of Product Line—Electric Machines at The Switch, states in his marine blog, the first shaft generator concepts were introduced in the 1960s. In the

1970s and early 1980s, a major development took place in modern solid-state power electronics, whereby, for example, frequency converters became available (Skjong et al., 2016).

Electrically excited shaft generators and their power take-off systems became common in the 1980s both due to the benefits of utilizing the ship's main engine as the prime mover and the latest power electronics to achieve constant-frequency current output on the variable rotational speed of the shaft line (Pringle, 1982). Pringle states that the shaft generators' rise in popularity was due to the ship's two-stroke main engine having higher thermal efficiency and lower SFOC than medium-speed four-stroke gensets. However, at the time, the most important factor for ship operators was the fact that low-speed two-stroke engines used cheap, low-quality fuel oil, which equates savings in fuel costs.

Since electrically excited generators are relatively poor in their efficiency at low rotational speeds and especially at partial loads, step-up gears were introduced for shaft generators in the 1980s. According to Pringle (1982), the efficiency of shaft generators was only around 81% before the utilisation of step-up gears. With the help of a geared system, efficiency was able to be improved significantly up to 91% under ideal conditions, Pringle concludes.

The latest significant developments in marine shaft generator systems are from the middle of the 2010s when permanent magnet technology was introduced for marine shaft generators (Puranen, n.d.). While PM technology was becoming the industry standard in wind power plants, it was noticed that the same technology would also be optimal for direct-driven shaft generators. In ships where the main engines are commonly operated at slow speeds, the direct-driven permanent magnet shaft generator can reach its highest potential with particularly good efficiency, especially at slow rotation speeds and partial loads compared to conventional AC generators, Puranen concludes.

### 3.2 Technical features for variable-speed PM shaft generator system

The purpose of shaft generators is to generate electricity for the ship's grid by the ship's main engine while sailing. The economic attraction for shaft generators is that they make use of the ship's propulsion engine, usually a large two-stroke low-speed engine, which is highly efficient in terms of energy conversion and, therefore, uses less fuel per unit of power generated (Molland, 2008). Additionally, utilization of the main engine for electricity generation means that the auxiliary gensets can be turned off while cruising, resulting in lower fuel consumption, reduced maintenance needs, and lower costs for replacement parts.

#### 3.2.1 Overview of the system's function

The ship's propulsion shaft, also known as the transmission line, transfers the mechanical power for the propeller (Molland, 2008). According to Molland, conventionally, the transmission line as a whole includes the thrust shaft, intermediate shaft, and tail shaft, which are supported by bearings, and finally, the tail shaft, which is connected to the propeller. Figure 6 shows the basic concept of a ship's transmission line.

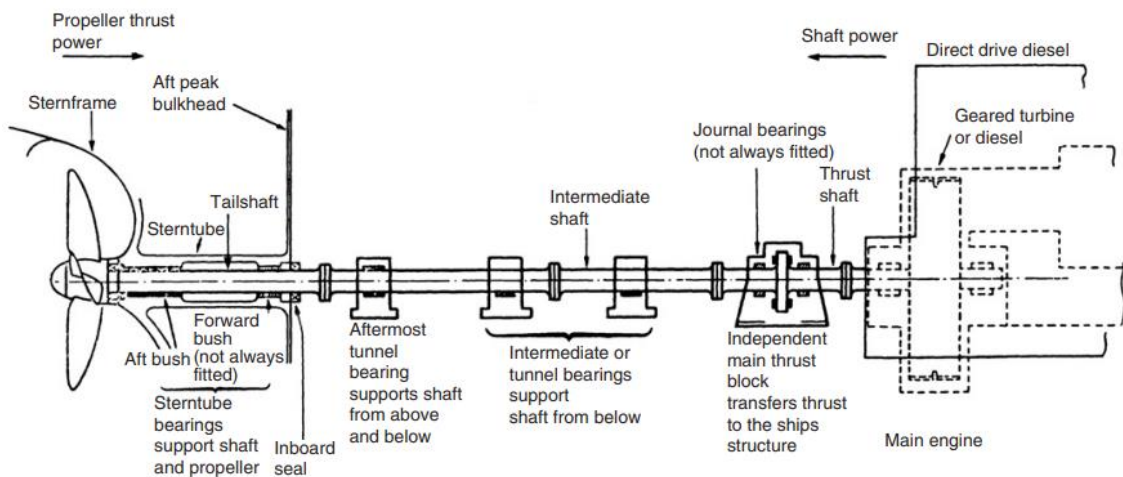
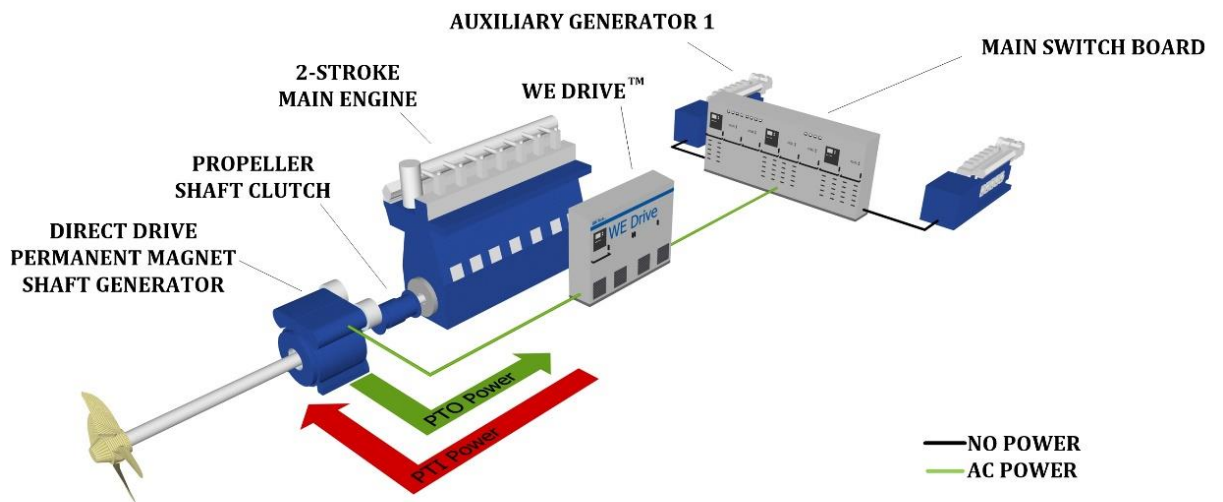


Figure 6. Transmission system (Molland, 2008)

A shaft generator (SG) refers to an AC generator, in which the prime mover is the main engine of the ship (MAN Energy Solutions, 2021). Shaft generators can be divided into two connection types, direct-driven and geared. According to MAN Energy Solutions, in the direct-driven concept, the rotor is fixed with the transmission line, more specifically with the intermediate shaft, and thus, the whole generator sits around the propulsion shaft. In geared applications, the setup is slightly more complex. The main engine runs the gearbox, and the AC generator is connected via step-up gear. In four-stroke main engine applications, the same gearbox can also control the rotation speed of the propulsion shaft with step-down gear.

In an in-line PM shaft generator system, a variable-speed PM generator is directly driven by the main engine, and thus, no gear is required as the generator is mounted to the shaft line (WE Tech, n.d.). Figure 7 shows a concept of an in-line PM shaft generator system. As illustrated, the transmission line can be equipped with a shaft clutch, which allows disconnection of the main engine from propulsion, allowing power-take-home (PTH) mode.



**Figure 7.** Illustration of PM Shaft Generator system (WE Tech, n.d.).

The separation of the main engine from the tail shaft enables the possibility for electrical propulsion by the shaft generator system on board. This brings other advantages in addition to fuel savings and reduction of the operating hours of gensets. As clarified above, the main function of the shaft generator is so-called power take-out (PTO) operation, where the shaft generator produces electricity for the ship's grid. But since an AC generator can also be used as a synchronous motor, it enables the shaft generator system to have the ability for so-called power take-in (PTI) use (Dziuba, 2022). However, if the PTI mode is to be used, the onboard power converter system must allow two-way power flow.

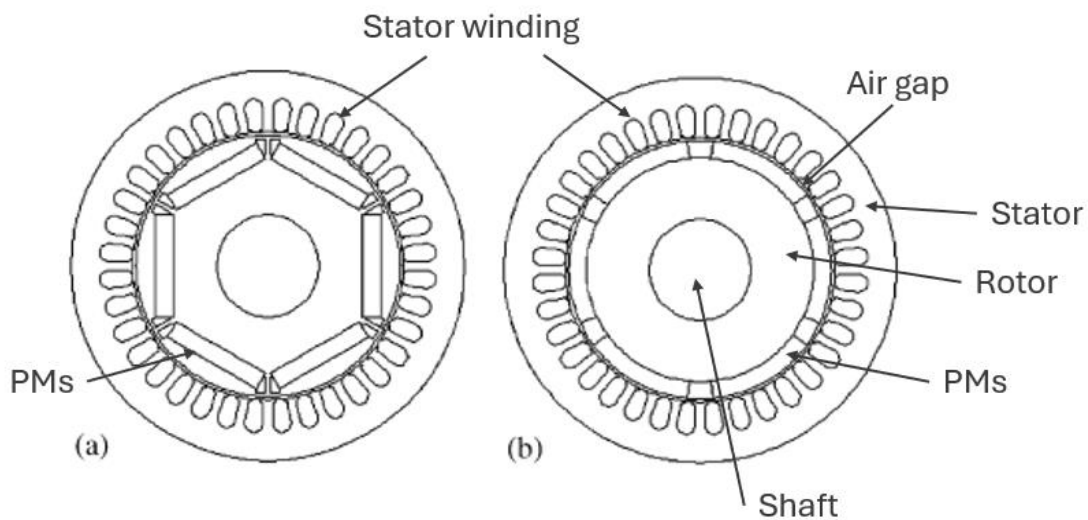
With PTI boost mode, the generator operates as an electric motor providing boost power for the vessel's main engine (Dziuba, 2022). While utilising SG for boost power, the gensets on board, or batteries, produce all the power needed for hotel load and other crucial operations, as well as the power for boost propulsion. According to Dziuba (2022), in general, this type of operation is not commonly used, but for example, in heavy headwind or in rough ice conditions, SG can provide approximately 10–15% of extra power for propulsion. Boost mode can also be used for delay catchup reasons.

With PTI mode, the SG can also be applied for full propulsion, for example, in main engine fault situations (Dziuba, 2022). PTI mode enables safe manoeuvring to the nearest port in situations where ME is out of operation and is in urgent need of service. According to Dziuba, PTI mode requires a shaft clutch between SG and ME to decouple the two. PTI mode also allows full electric propulsion without a combustion engine, for example, to port arrival or departure. This, however, requires installed on-board batteries (MAN Energy Solutions, 2021).

### **3.2.2 PM shaft generator design**

A PM generator's core components and operational principles align closely with those of a conventional synchronous generator. In its simplest configuration, the PMSG comprises three primary parts: the rotor, stator, and frame which includes the requisite

cooling system (Boldea, 2016). Notably, the absence of an excitation system for the rotor distinguishes the PM generator from its conventional counterpart since the utilisation of permanent magnets. However, it is important to note that the specific configuration of the main components can vary significantly on the particular type of generator and its intended application (Patel, 2021). Two main types of rotors are used in PM generators: rotor with surface PMs (SPM) and Rotor with interior PMs (IPM). Figure 8 shows cross-section illustration of a six-pole PM generator for both IPM and SPM configurations.



**Figure 8.** Cross section of (a) IPM and (b) SPM motors.

Currently, the prevailing choice for permanent magnets in large MW class generators consists mainly of rare earth metal based neodymium magnets (NdFeB). This preference is due to NdFeB's superior magnetic properties compared to other available magnet materials (Erikson, 2019).

Research conducted by Baqaruzi et al. (2022) involved a comparative analysis of a PM synchronous generator utilizing three distinct magnet materials: NdFeB 48/11, ferrite magnet (ceramic 11), and samarium-cobalt (SmCo 26/26). Their findings underscored the superior efficiency of NdFeB. In the study, the experimental configuration focused on a 1000 rpm wind generator. Nonetheless, the findings can be considered indicative

of lower nominal rotational speeds. According to the findings NdFeB magnets had the best properties when comparing torque and generator efficiency across various load points for the three different magnet types.

Another major advantage of NdFeB magnets, which argues for their primary use in PM machines, is that they are lighter compared to other available magnet materials. According to Boldea (2016a), when comparing the active material weight of the NdFeB rotor and ferrite rotor, the NdFeB rotor is approximately half of the weight. At the same time, however, the most significant disadvantage of NdFeB is that their price per kg is significantly higher than, for example, ferrite magnets, even though the price has dropped from the peak in recent years (Strategic Metals Invest, 2024). The higher price of the NdFeB magnets compared to the other materials leads to higher initial costs, but guarantees better performance. Noteworthy is also that NdFeB material is further graded by its strength and heat resistance, which also has an impact on the price.

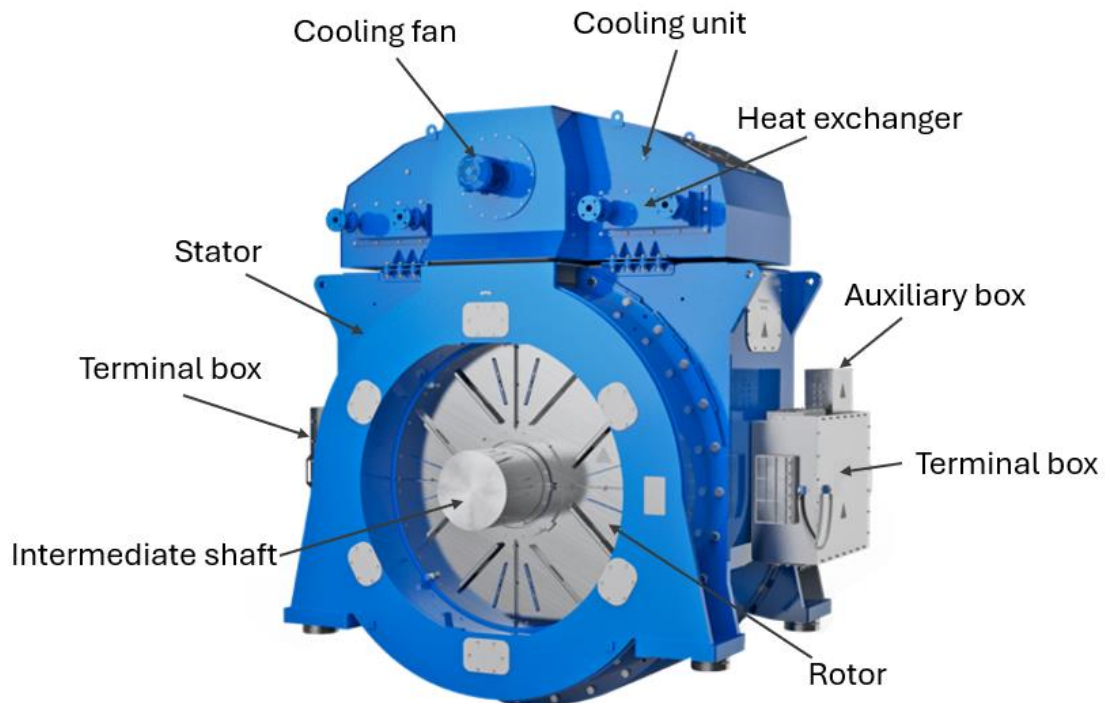
The second main component of the PM shaft generator is the stator, which consists of three-phase winding, which are separated in the stator frame physically by  $120^\circ$  from each other (Patel, 2021). Patel states that the stator coils and rotor are enclosed within ferromagnetic cores and are separated by an air gap that meets the necessary electrical and mechanical specifications. MW class stators are typically made of thin (generally 0.50 mm) silicon steel sheets stamped to create slots for windings (Boldea, 2016a). As explained by Boldea, for larger generators, the stator consists of segments assembled into a circle. The number of segments in a stator is dependent on the size of the stator and can, therefore, vary.

Medium and large generators commonly use either multiturn lap coils or single-turn bar coils for their stator windings (Boldea, 2016a). Multiturn coils offer flexibility in slot arrangement, allowing for a greater choice in the number of slots for a given number of current paths. Boldea further explains that the multiturn coils are limited in

manufacturing for pole pitches less than 0.8–1 meter. The multiturn coils require careful bending to fit into slots without damaging the insulation during installation.

On the other hand, bar coils are suitable for heavy currents, making them ideal for high-power applications (Boldea, 2016a). They have fewer connectors than multiturn coils, reducing costs. According to Boldea, lap-bar coils, a combination of both types, enable short-pitching to minimize electromagnetic force harmonics.

Additional insulation may also be required to protect against voltage impulses during switching (Boldea, 2016a). Accidental short circuits can produce circulating currents in multiturn coil windings with parallel current paths, potentially affecting the circuit balance. However, this issue is less pronounced in bar coils (Boldea, 2016a). When constructing AC windings for generators, they can be arranged in either a single or double layer. Figure 9 provides an illustration of a PMM1500M PMSG along with its primary components.



**Figure 9.** The Switch PMM1500M shaft generator

The direct-driven PM shaft generator is integrated into the transmission line of the ship. An intermediate shaft is attached to the rotor flange, enabling the rotor to rotate within the stator without a bearing system. The rotor and stator are positioned with a designated air gap between them. The PM rotor design of the PMSG incorporates SPM NdFeB magnets, while the stator is composed of double-layer diamond coils. Additionally, the machine frame features a water-circulated cooling unit, terminal boxes for power cable connections, and an auxiliary box for sensors.

### 3.2.3 Technical overview of variable speed PM generator

PM generators have the characteristics of a synchronous generator and heteropolar excitation with a PM rotor (Boldea, 2016a). As stated by Boldea (2016a), the PM generators are commonly used with variable speed input to generate constant voltage and frequency power output with the help of power electronics, which often allows the electric machine to be used as a motor, for example, for marine propulsion applications. The PM generators have fast and safe power control capabilities.

In conventional electrically excited (EE) synchronous generators, the desired magnetic field is produced with a DC coil in which the direct current (DC) excitation current comes from an external exciter via slip rings and carbon brushes or from a separate brushless self-excitation system (Patel, 2021). In PM generator systems, the desired magnetic field comes from permanent magnets, and therefore, no external excitation power is needed.

The generator's rotor properties are crucial in synchronous generators since, by mechanically turning, it generates voltage in each of the three identical stator coils according to Faraday's law of induction (Patel, 2021). These three-phase voltages have the same magnitude but are 120° out of phase with each other. Equation 3 shows how the frequency  $f$  of generated AC power is determined, and Equation 4 how the magnitude of the voltage  $E_{rms}$  induced in a given stator phase is determined (Chapman, 2012).

$$f = \frac{p}{2} \cdot \frac{n}{60} = \frac{n \cdot p}{120} \text{ (Hz)}, \quad (3)$$

where  $p$  is the pole number of the rotor and  $n$  is the rotational speed in rpm of the rotor.

$$E_{rms} = \sqrt{2} \cdot \pi \cdot N_C \cdot \Phi \cdot f, \quad (4)$$

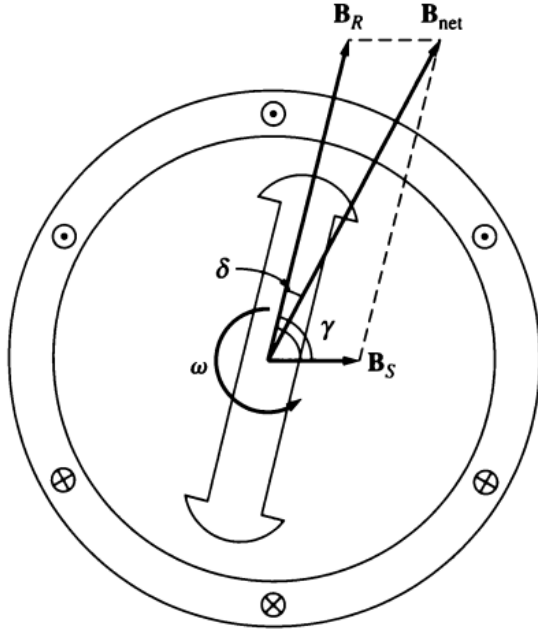
where  $N_C$  is the amount of turns of wire in the stator coil and  $\Phi$  is the magnetic flux passing the coils.

Each time a two-pole rotor completes a full rotation, it produces one cycle of electrical voltage in the stator coil (Patel, 2021). On the other hand, a four-pole rotor generates two cycles of electrical voltage for each full rotation since it has twice as many poles. Patel states that in general, a rotor with  $p$  number of poles rotating at  $n$  generates  $p/2 \cdot (n/60)$  electrical cycles per second. On the basis of Equation 4, it can be concluded that in order to also produce constant frequency, the speed of the rotor needs to be constant. The induced stator phase voltage  $E_{rms}$  is directly proportional to frequency  $f$  and thus the rotation speed of the prime mover (Chapman, 2012). However, the desired voltage is also influenced by rotor characteristics such as the flux  $\Phi$  passing through the coil and the amount of turns  $N_C$  of the coil.

In a generator application, the twisting force of the prime mover and the two magnetic fields creates torque for the machine. Figure 10 shows a simplified representation of a synchronous generator, illustrating its rotor and stator magnetic fields.

A generator in an operating form always has two magnetic fields present: one in the rotor due to PMs or electric magnetisation and the other in the stator windings due to induced current. (Chapman, 2012). These two magnetic fields and their interaction create a natural desire to line them up. According to Chapman (2012), this can easily be comprehensible with an example of two small permanent magnets brought close enough together, and they automatically line up and attach according to their polarities.

Chapman states that this interaction with two magnetic fields creates the induced torque  $\tau_{ind}$  of the generator.



**Figure 10.** Magnetic fields of stator and rotor (Chapman, 2012).

According to Chapman (2012), in synchronous generators, the overall magnetic flux density is determined by the combination of rotor and stator magnetic flux densities, as expressed in Equation 5. The induced torque  $\tau_{ind}$  of the synchronous generator is directly related to both the rotor and induced stator magnetic fields. Consequently, as Chapman states, this enables the calculation of the induced torque in terms of both its magnitude and direction, as outlined in Equations 6 and 7 (Chapman, 2012).

$$\mathbf{B}_{net} = \mathbf{B}_R + \mathbf{B}_S, \quad (5)$$

where  $\mathbf{B}_{net}$  is net vector of magnetic flux density,  $\mathbf{B}_r$  is the vector of rotor magnetic flux density and  $\mathbf{B}_s$  is vector of stator magnetic flux density.

$$\tau_{ind} = k\mathbf{B}_R \times \mathbf{B}_S, \quad (6)$$

where  $\tau_{ind}$  is the induced torque of the generator and  $k$  is quotient of  $K$ , the manufacturer's assigned constant dependent of the machine size and design, and  $\mu$  is magnetic permeability.

$$\tau_{ind} = kB_R B_{net} \sin \delta, \quad (7)$$

where  $\delta$  is the angle between  $B_{net}$  and  $B_R$ .

The synchronous generator's net magnetic flux density  $B_{net}$  is therefore the vector sum of rotor magnetic flux density  $B_R$  and stator magnetic flux density  $B_S$ , while saturation is not taken into account. In Equation 7,  $\tau_{ind}$  is shown only by the magnitude of induced torque.

The generator utilises the mechanical input power of the shaft  $P_{in}$ , which is a factor of torque applied by prime mover  $\tau_{app}$  and its angular velocity  $\omega_m$ , as shown in Equation 8, for power conversion to electrical power. The generator's converted power can be determined by the induced torque  $\tau_{ind}$  and angular velocity  $\omega_m$  of the rotor, as shown in Equation 9 (Chapman, 2012). The real generator output power  $P_{out}$ , however, is expressed in Equation 10, where  $V_L$  is line voltage and  $I_L$  is line current. This is due to the fact that the generator does not work ideally and, therefore, has losses that decrease the power conversion efficiency.

$$P_{in} = \tau_{app} \omega_m, \quad (8)$$

where  $P_{in}$  is the generator's mechanical input power,  $\tau_{app}$  is the torque applied by the the prime mover and  $\omega_m$  is prime mover's angular velocity.

$$P_{conv} = \tau_{ind} \omega_m, \quad (9)$$

where  $P_{conv}$  is generator's converted electrical power.

$$P_{out} = \sqrt{3}V_L I_L \cos \theta, \quad (10)$$

where  $P_{out}$  is output power of the generator,  $V_L$  is line voltage,  $I_L$  is line current and  $\cos \theta$  is the power factor.

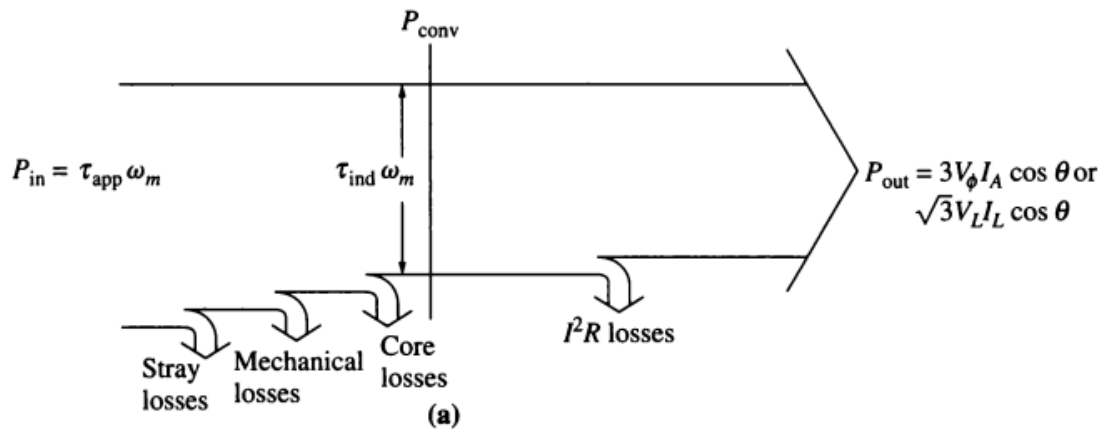
Grid-connected variable speed shaft generator is the optimal choice in ships since it can utilise power from the prime mover in all rotational speeds (Boldea, 2016b). This way, the generator also offers a more flexible power system. However, the ship grid requires constant frequency and voltage for operation, and as noted in Equations 3 and 4, both frequency and induced voltage are proportional to the prime mover's angular velocity. Thus, for thoroughly variable speed operation of shaft generator converter system also known as variable-frequency drive is required as Boldea (2016b) states. The converters utilise power electronics to match the generated power for the desired grid voltage and frequency. Boldea (2016b) states that in grid-connected applications, converters are always designed for the specified power plant capacity.

### 3.3 PMSG benefits and drawbacks compared to conventional systems

The savings potential of PMSGs comes from the fact that PM generators are more efficient in power conversion from mechanical power to electrical power due to fewer losses and the fact that PMSGs are able to utilise the ship's efficient main engine.

The fuel consumption and thus also emissions of a given ship are the result of the operation of internal combustion engines on board. These engines convert energy from fuel into mechanical power, known as brake power ( $P_B$ ), which is then utilized for various purposes (Molland, 2008). The power available for the intended use is termed as delivered power ( $P_D$ ). Molland highlights that each stage of energy transfer from  $P_B$  to  $P_D$  affects the efficiency of the system due to inherent losses. For instance, losses in the shaft generator system contribute to increased ship fuel consumption.

The factors influencing generator efficiency can typically be categorized into four groups: winding or copper losses, core or iron losses, mechanical losses, and stray losses (Chapman, 2012). Figure 11 shows a power flow diagram of a typical AC generator.



**Figure 11.** AC generator power flow diagram (Chapman, 2012).

Stray losses refer to losses that do not fit into any specific category mentioned before. Despite thorough accounting for losses, some do not neatly fit into those predefined categories. These unclassifiable losses are collectively termed stray losses. Typically, for most machines, it is conventionally assumed that stray losses are about one per cent of the machine's full load (Chapman, 2012).

The mechanical losses in an AC machine arise from mechanical actions within the machine (Chapman, 2012). These losses mainly come in two forms: friction and windage. Friction losses occur due to the friction of machine bearings, while windage losses stem from the friction due to the interaction between air and rotor parts. Air resists the rotational movement of the rotor. The windage losses increase as the cube of rotor speed increases (Boldea, 2016a). Bearing losses  $P_{bear}$  and windage losses  $P_{air}$  are shown in Equations 11 and 12.

$$P_{bear} = P_{axial} + P_{guide} \approx (9,81 \cdot G_V \cdot U_{bear} + F_m + F_d \cdot U_{a\,bear}) \cdot \mu_f, \quad (11)$$

where  $G_V$  is the total vertical mass,  $U_{bear}$  is the radial bearing peripheral speed,  $U_{a\ bear}$  is the axial bearing peripheral speed,  $F_m$  is the magnetic pull due to estimated rotor eccentricity and  $F_d$  is the mechanical radial force due to eccentricity and mechanical rotational imbalance. In direct-drive shaft generator systems mechanical losses are meaningless due to slow speed and lack of bearings.

$$P_{air} \approx C_a \cdot (2\pi n)^3 \cdot D_r^5 \cdot \left(1 + \frac{5 \cdot l_p}{D_r}\right), \quad (12)$$

where  $C_a \approx [(1.5-3) \cdot 10^{-3}]$  is a machine constant depending on rotor smoothness,  $n$  is rotor speed,  $D_r$  is rotor external diameter, and  $l_p$  is the total length of rotor poles.

Core losses are the sum of hysteresis losses and eddy current losses occurring in the machine's metal core (Chapman, 2012). Both losses heat the machine core. According to Chapman (2012), these losses are inherent losses of each machine depending on the features of the machine. These losses will vary as the square of the magnetic flux density as well as the speed of the rotor. A machine's mechanical and core losses are often lumped together and called the no-load rotational loss of the machine.

Copper losses refer to the energy consumed as heat due to the resistance in the stator winding (armature) and in conventional synchronous generators in the rotor (field) windings of the machine (Chapman, 2012). The stator copper losses ( $P_{scl}$ ) and rotor excitation copper losses ( $P_{ex}$ ) are given by Equations 13 and 14, where  $R_A$  is the resistance of each armature phase,  $I_A$  is the current flowing in each armature phase,  $R_F$  is the resistance of field winding and  $I_F$  is the current flowing in the field winding.

$$P_{scl} = 3 \cdot I_A^2 \cdot R_A \quad (13)$$

$$P_{ex} = I_F^2 \cdot R_F \quad (14)$$

In conventional generators the total excitation system losses are the combination of  $P_{ex}$  and Brush-slip ring losses  $P_b$  as shown in Equations 15 and 16 (Boldea, 2016a).

$$P_b = 2 \cdot \Delta V \cdot I_F \quad (15)$$

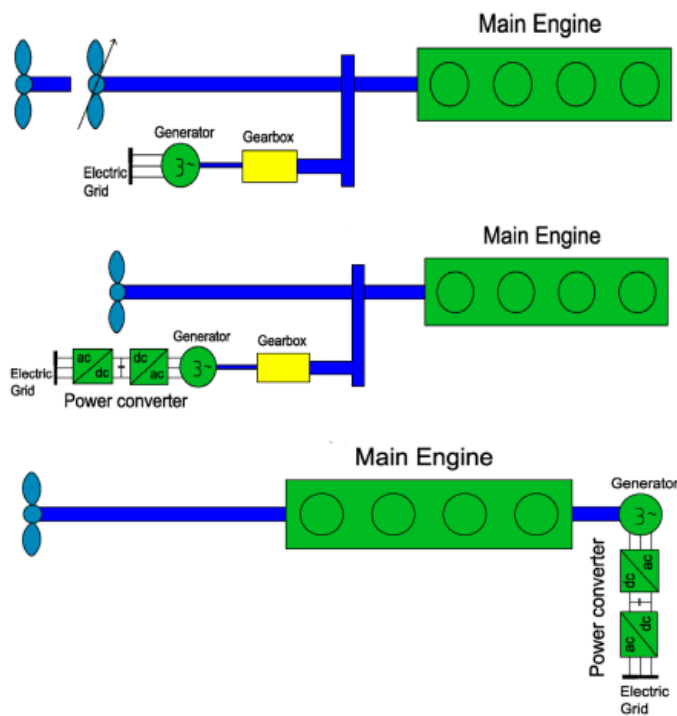
$$P_{exsh} = \frac{R_F \cdot I_F^2 + 2 \cdot \Delta V \cdot I_F}{\eta_{ex}}, \quad (16)$$

where  $\eta_{ex}$  is the total efficiency of the exciter system.

In the instance of a static exciter,  $\eta_{ex}$  represents the efficiency of the static exciter. In the scenario of a brushless exciter, the losses incurred by brushes and slip rings are substituted with rectifier losses, typically of comparable percentages (Boldea, 2016a).

### 3.3.1 Different shaft generator configurations

Conventionally there are three principal configurations of EESG systems commonly employed in marine vessels (Sarigiannidis et al., 2016). The first configuration is PTO/gear constant ratio (PTO/GCR) or PTO/constant frequency mechanical (PTO/CFM) SG, where step up a gear provides the generator with a frequency proportional to the main engine speed. According to Sarigiannidis et al. (2016), this indicates that maintaining a consistent frequency output is achievable solely during the ship's navigation at sea. To achieve this stability, the installation of a controllable pitch propeller is required or with only a constant rotational main engine speed. The second configuration is PTO/constant frequency electrical (PTO/CFE), which consists of a step-up gear, synchronous generator, and power converter, which allows variable speed utilisation of the main engine. Finally, the third solution is direct-driven EESG without gearing. Sarigiannidis et al. (2016) state that in direct-driven EESG applications, a higher number of poles are to be selected due to low rotation speed. Also, a power converter is mandatory for grid connection. Different conventional SG system topologies are shown in Figure 12.



**Figure 12.** Schematic of the main SHG system topologies (Sarigiannidis et al., 2016).

As seen from the Figure 12, both PTO/CFE and direct-driven applications offers variable speed operation due to power converters of the system. These are the two most commonly applied SG systems nowadays.

### 3.3.2 PMSG vs EESG and auxiliary genset

PMSG system offers distinct advantages over conventional auxiliary gensets. The biggest advantage of PMSG compared to gensets comes from situations where a two-stroke main engine runs PMSG; thus, electricity is produced by less fuel consumption compared to the vessel's four-stroke gensets (Andtfolk et al., 2023). A comparison between the SFOC of different two- and four-stroke engines is presented in Table 1 of Chapter 2.

When comparing the PMSG system to normal synchronous SG systems, the benefits do not come from the prime mover properties as in comparison with auxiliary gensets, since the ship's main engine drives shaft generators. The inherent advantages of the PMSG

system compared to the conventional ones are power density, efficiency, output power quality, and manufactory simplicity (Sarigiannidis et al., 2016). In conventional SGs, the required magnetic flux in the rotor is created by power flow in conductors (Dziuba, 2022). These electromagnets create significant losses (copper losses), which add up the total generator losses and reduce the generator efficiency. To supply current to the rotor, the generator either requires a brushless exciter, a small internal generator, or a slip-ring unit, which demands regular maintenance and is susceptible to malfunctions (Sarigiannidis et al., 2016). Additionally, EESG systems always require an automatic voltage regulator (AVR) for current control in the rotor. These factors decrease generator efficiency and add mechanical complexity to the system, leading to larger physical dimensions and decreased reliability. In the PMSG systems, electromagnets, internal excitation generators or sliprings, and the AVR systems become obsolete.

In slow speed direct-driven applications, such as a two-stroke main engine as prime mover, the PMSGs have an even bigger advantage over conventional EESGs. The PMSG has characteristics of great operating efficiency at partial loads and speeds (Zhang et al., 2011). According to the analysis by Zhang et al. (2011), the slow-speed PM generators reach their optimal efficiency approximately at power loads of 30–60% of nominal load and reaches efficiency of over 90% straight from zero load even with total drive train losses included, whereas the EESG do not perform as well in lower end of partial loads. The same goes for partial rotational speed; PM generator operates with great efficiency straight from the start and peaks at 30–60% of the nominal speed when conventional machines reach optimal operation closer to the nominal speed. This is particularly relevant in situations where the ship is slow-steaming during a voyage to save fuel.

The PMSG system offers not only PTO mode but with some shaft line modifications also PTI mode for powering the ship propellers, which cannot be done directly with auxiliary generators (Andtfolk et al., 2023). In PTO mode, the PMSG system allows fully variable speed drive, with high efficiency and full torque immediately from zero rpm. This comes

in as an important factor since ships prefer slow steaming to optimise fuel consumption and EEDI.

Another benefit of PMSGs over auxiliary gensets is the fact that utilisation of PMSGs can significantly save space in a ship's power plant, compared to situations where utilising only gensets. The lifetime of shaft generators, in general, has been proven to be longer than auxiliary gensets (Prousalidis et al., 2012). Also, shaft generators have proven to be more reliable than auxiliary generators when it comes to fulfilling their function effectively over time. All this is mostly due to the simpler build with fewer components. The gensets require components such as bearings, gearing and power electronics in an AVR; all this ends up in more losses and requirements for maintenance. On top of all this, gensets are affected by the rotor excitation losses.

A drawback of the shaft generator systems compared to conventional gensets utilized in ships is that shaft generators can generate electricity only when the ship is moving. Consequently, ships equipped with shaft generator systems do not have electricity available in port. Also, as discussed in Chapter 3.1, the PMSG systems are fairly new in ships, so compared to diesel generators or conventional shaft generators, there is not so much information about their use and reliability. However, the available data indicate their excellent reliability. In addition, there is always a risk of magnet demagnetization, due to, for example, incorrect operational conditions. But when this risk is taken into account at the design phase, the risk is almost zero.

## 4 Research methods

This chapter introduces the research methodology and research process. First, the theory behind the selected research method is discussed. Later, the collected data are introduced and finally the practical implementation of this study is discussed.

This thesis aimed to establish total savings and CO<sub>2</sub> emission reduction potential with a permanent magnet shaft generator system compared to a conventional electrically-excited shaft generator system and a standalone diesel generator system. The anticipated savings were calculated from the decrease in fuel consumption and the subsequent decrease in EU carbon tax (ETS). The research was conducted on two vessel types: LNG carrier and product tanker. Quantitative data analysis was selected for the empirical approach. The hypothesis of the research was that the PMSG system would introduce clear advantages in savings compared to the conventional marine power plant systems.

### 4.1 Collected research data

The primary data for this study pertained to the operational profile of the vessels under examination. For this thesis, it was collected via questionnaires for the parties involved. The questionnaires were open-ended questions gathered via email. The necessary secondary data for the research was gathered from research carried out by The Switch, literature on the subject, and data sets provided by different manufacturers.

The collection of primary data was accomplished through the distribution of questionnaires via email to two distinct groups. The first group comprised of experts, which operates in the vessel system integration sector. System integrators play a pivotal role in assembling various systems for especially new build ships, including for example the complete electrification system and propulsion system.

In addition to the system integrator, data was also gathered from two different ship operators. The first operator managed a LNG carrier with a capacity of 174,000 cubic meters, while the second operated a chemical tanker with a 22,500 dwt. This data collection strategy ensured a comprehensive understanding of the subject matter.

The primary data was collected in both written and numerical ways. Written data explained the trends and tendencies of new-build vessels and their typical operation and power demand. The numerical data was collected from a reference voyage about the vessel's main switch board (MSB) load, PMSG load, genset load, and annual main engine running hours. This information allowed to determine the operational profile of the vessel with sufficient accuracy. Below are the questions that were addressed to the parties. First, general info about the vessel's power generation was determined (1–3), and afterwards, the more specified questions about the operation profiles were determined (4–6). When the function of time was cited, it discussed certain voyages for example, port-to-port voyages:

1. What is the main propulsion engine type (model, rated rpm and rated output power)?
2. What are the auxiliary genset types (model, rated rpm and rated output power)?
3. What is the PMSG type (Preferably info of the generator name plates)
4. Main propulsion engine/engines running hours as a function of time?
5. Operating profile of PMSG (electric output of PMSG as a function of time)?
6. Vessel's main switchboard load as a function of time?

The secondary data regarding the efficiency difference between generators were collected from The Switch's internally generated research and from the literature on the subject, as well as data provided by the generator manufacturers. Engine-specific fuel consumption was collected from data sets provided by the manufacturer. The needed fuel bunker prices were collected from Rotterdam Port. Lower heating values and

specific CO<sub>2</sub> emissions for the studied marine fuels were collected from IMO regulations. ETS price was gathered from its exchange price at the time of the study.

Collected data allowed precise numerical calculations and data analysis and thus made the quantitative data analysis method relevant for the empirical study in this thesis. The methods of empirical data analysis can be found in chapter 4.2. To ensure objectivity in the analysis of EESG systems, the efficiencies of various generator systems were gathered and examined using predefined variables. This data was sourced from two independent references: a prior research study of a similar nature and a study conducted by The Switch. The research results are represented in Chapter 6 through various graphs. This research sought to give the general conclusion of the data sample used and thus identify and provide predictions of the benefits of the PMSG system in the relationship between vessel-specific variables. This study can later be replicated both for the same type and for other types of vessels.

## **4.2 Research approach**

The objective of this thesis was to discover the potential for vessel lifetime fuel savings and emission reductions by employing a PMSG system, in contrast to conventional systems such as EESG or gensets. The study was conducted on two distinct types of ships: a 174,000 m<sup>3</sup> LNG carrier and a 22,500-dwt product tanker. Both fuel savings and emission reductions would result in cost savings for ship operators due to a decrease in the need for fuel supply and the acquisition of carbon credits according to the EU ETS system. The obligation to purchase carbon credits is determined by the specific CO<sub>2</sub> emissions of the vessel. However, it only applies to ships sailing within Europe or to and from Europe. For the purpose of this study, it was assumed that the ships were sailing to or from the European Union. The calculations for savings and emission reductions were performed for three different types of fuel: LNG, MGO and HFO.

A tool was created using Excel to present the findings as clearly and simply as possible. The primary function of this tool was to compute all the desired outcomes from the collected data. This approach made it straightforward to replicate the research with varying input data. The tool automatically generated a graph concerning the desired variables, such as the cumulative cost difference between the three studied generator systems in terms of fuel consumption and carbon emission credits.

The research was conducted under the assumption that the lifespan of a vessel is 25 years in total. The average power measured at the MSB, the annual sailing hours, and the operational profile of the main engine were all expected to remain constant throughout the entire projected lifespan of the vessels. In addition, the current prices at the time of the study were used for fuel bunker prices and ETS prices.

The difference in total fuel use for electricity production in the three selected systems demonstrates potential savings and emission reductions. The results are presented only regarding costs due to efficiency-related factors. Looking only at the energy consumed by generator systems directly demonstrates the financial and environmental benefits of a better-performing system without considering issues unrelated to the energy production system.

The tool has been configured with fundamental information about the specific types of vessels under consideration. This includes the type of main engine and its SFOC values, which have been obtained from manufacturer data sheets or data provided by the ship operator. The SFOC of internal combustion engines varies with operation at different load points, but for the purpose of this study, the vessels were assumed to be operated at constant load points.

The selected fuels' lower heating value and carbon content were configured according to the IMO standards. Annual ME running hours were calculated from the data provided by the ship operators. The collected data was given for a specific time period, which was

used to estimate the full year's ME running hours. ME running hours are proportional to the SG power generation availability.

Fuel losses linked to the generator system, which are consequent upon generator and engine efficiency, were based on the information received concerning the typical power load during sailing. The efficiency of the generator in general, and hence the fuel losses, are influenced by the drawn load relative to the available load. The efficiency of the generators chosen for the tool was established by the average load percentage in relation to the available load. This information was subsequently compared with secondary data of efficiency comparison between different generator systems at a constant speed with varying torque. These secondary data points were gathered from The Switch's internal data and relevant literature to determine the overall efficiency of the generator system.

With the average MSB load ( $P_{MSB}$ ) and the chosen generator system efficiency ( $\eta_g$ ) the total average power delivered by the shaft line to the generator could be determined. Subsequently, when the annual main engine, and hence the availability of SG PTO, running hours ( $t_{ME}$ ) were identified, the total annual energy ( $E_{tot}$ ) in  $kWh$  needed for power generation could be calculated.

The annual fuel consumption ( $m_{tot}$ ) in tons for power generation was determined by multiplying the *SFOC* constant of the engine of the system under consideration with the calculated  $E_{tot}$  and further multiplying the outcome by  $10^{-6}$ . The total annual  $CO_2$  release from the total fuel consumption for power generation could then be calculated with the help of the fuel-specific  $CO_2$  factor ( $CO_2$  intensity) when multiplying the  $CO_2$  factor (ton/ton) with the total fuel consumption  $m_{tot}$ . Annual energy used for power generation and annual fuel consumption is given in Equations 17 and 18.

$$E_{tot} = \left( \frac{P_{MSB}}{\eta_g} \right) \cdot t_{ME}, \quad (17)$$

where  $E_{tot}$  is total annual energy consumption,  $P_{MSB}$  is annual average of the MSB load,  $\eta_g$  is generator efficiency and  $t_{ME}$  is annual generator running hours.

$$m_{tot} = E_{tot} \cdot SFOC \cdot 10^{-6}, \quad (18)$$

where  $m_{tot}$  is annual fuel consumption.

Further, consequent annual total costs of fuel consumption and CO<sub>2</sub> emissions were calculated using fuel bunker prices (\$/ton) and carbon credits (\$/ton) according to the EU ETS system. To estimate the results for the whole life cycle of the ship, costs and emissions were calculated cumulatively over 25 years. The prices for used fuel bunkers are presented in Table 4, while the price of EUA carbon credits in Euros is shown in Figure 5.

## **5 Data analysis and creation of operating profiles for different vessel types**

This chapter introduces the operating profiles of the ships in the study. Both electricity generation and engine operating profiles are discussed. The study was carried out based on the presented profiles. The following factors had to be determined to define the operational profiles and thus carry out the study: ME and shaft generator annual running hours, ME SFOC for selected fuels, AE SFOC for selected fuels, average MSB load, PMSG efficiency, EESG efficiency and genset efficiency. This section discusses the factors mentioned for both vessel types.

The first vessel to be considered in the study is a 2023-built 174,000 m<sup>3</sup> capacity LNG carrier. The vessel has a total length of 299 m and a gross registered tonnage of 114,180 tons. The second vessel is a 2021-built 22,500 dwt product tanker. The ship has a length of 167.3 m, a gross tonnage of 18,636 tons, and a net tonnage of 6,821 tons.

### **5.1 LNG carrier**

Data for the LNG carriers was acquired via a questionnaire. A professional from the system integrator addressed the first three points of the survey, which was presented in Chapter 4.2. In addition to the comments, operational data was obtained from a real operating ship. This combined data allowed the study to obtain a general operational profile of the ship type in question. The responses to questionnaire items 1–3, which pertain to the general vessel type information on the prevailing power generation trends in the maritime sector for LNG carriers, are presented below.

1. For an LNG carrier the main engine and propulsion system have been very different. The first generation had steam powered propulsion, meaning LNG boil-off was burned and as a result steam was produced. The issue with these

was that efficiency was very poor and as a consequence they were replaced about 20 years ago with electric propulsion solution with 4-stroke main engines from for example Wärtsilä.

The third generation is what we have today with two pcs of 2-stroke dual-fuel main engines. Examples are WinGD X-DF 72 bore and MAN ME-GA 70 bore. These main engines when running in gas mode injects the gas during the compression stroke, and thus they run in the otto cycle (not diesel cycle) in gas mode. The reason low pressure 2-stroke engines are used is because the boil off can quite simply be directly injected into the main engine.

In some cases, the high-pressure main engine from MAN, ME-GI 70 bore is used. These vessels typically have higher power for the shaft generator because the LNG boil off needs to be deliquesfied, as it cannot be injected directly to the main engine during the compression stroke. Instead it is injected via a traditional injector like with diesel. This main engine runs in the diesel cycle also in gas mode.

Both of today's used two-stroke main engines have benefits and drawbacks. From an environmental aspect one can say generally the low gas injection pressure have higher methane slip than high pressure, but high pressure produces more NO<sub>x</sub> than low pressure.

For an LNG carrier propulsion power is relatively high as we need to keep quite high speed. If we were to reduce the speed the trip becomes longer, and we would get excess LNG boil-off. This is one of the reasons they go fast, and speed reduction as seen for other vessel types becomes more difficult. Example of the propulsion power is: 2x 12 MW at 75 rpm (WinGD 5X72DF or MAN 5G70ME GA or GI) two-stroke.

2. Typically, 4x Medium Speed (720 rpm) Dual fuel. Wärtsilä or Hyundai Himsen. In case Wärtsilä; 2x 6L34DF and 2x 8L34DF.
3. Typical Shaft Generator: 2x approximately 2100kW 60 – 75 rpm. Generally, LNG carrier tends to be close to 100 % load while sailing.

According to the survey answers to questions 1–3, newly built LNG carriers generally prefer large, slow-speed, two-stroke main engines for propulsion power. The main engines are preferably dual fuel configurations, where boil-off gas can be utilised for propulsion power. LNG carriers maintain a fast speed while sailing.

The answers to questions 4–6 of the questionnaire were mainly collected by the data provided by the ship operators. The LNG carrier from which the data was collected was equipped with two WinGD 5X72DF main engines. No information was provided for the auxiliary engines. Therefore, in the study, the calculations are done with Wärtsilä 6L34DF, which, as indicated by the survey responses, is a common solution for this type of vessel.

Performance data for the ME and AE are shown in Table 5. The data has been collected from data sheets provided by the manufacturers. For the HFO, the manufacturers did not report the engine-specific SFOCs. Therefore, it was assumed that HFO's SFOC was inversely proportional to MGO when considering SFOC and energy content. The LNG carrier was equipped with two The Switch's PMM1500J00 PMSGs. The performance data of equipped PMSGs is shown in Table 6.

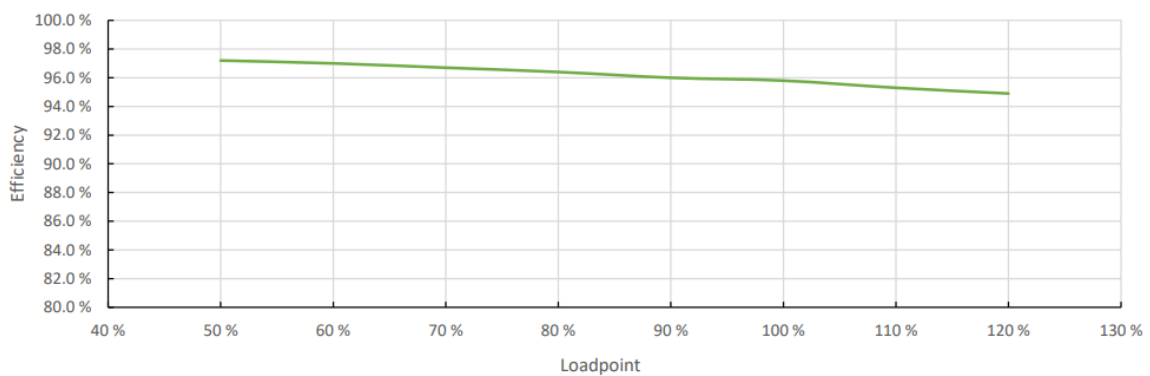
**Table 5.** ME and AE data for a LNG carrier with a capacity of 174,000 m<sup>3</sup>

Engine	WinGD 5X72DF	Wärtsilä 6L34DF
Cycle type	two-stroke	four-stroke
Rated speed	79 rpm	750 rpm
Nominal power	11,900 kW	3,000 kW
SFOC (MDO/MGO)	173 g/kWh	184 g/kwh
SFOC LNG	133 g/kWh	156 g/kwh
SFOC HFO	184 g/kWh	195 g/kWh

**Table 6.** The Switch PMM1500J00 data

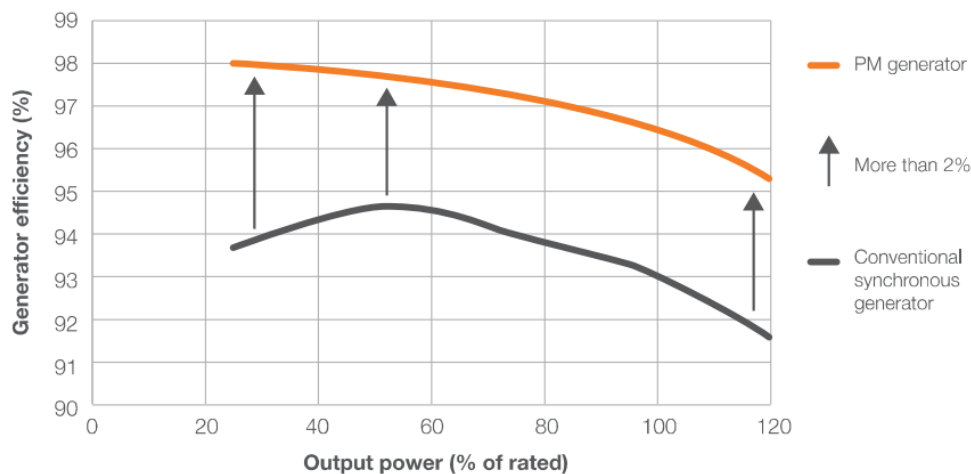
Generator	Rated power (PTO)	Rated speed	Efficiency
The Switch PMM1500J00	1,894 kW	65–77 rpm	95.8%

The efficiency of the equipped PMSG for the studied vessel could be determined from the factory acceptance test (FAT) report. As shown in Table 6, the machine's efficiency was 95.8% based on rated speed and output power. As the answers to the questionnaire showed, LNG carriers operate with close to 100% load on shaft generators while sailing; therefore, in the study for the PMSG, this machine efficiency was used. Figure 13 shows FAT data of the machine efficiency at different load points while speed was constant 65 rpm.

**Figure 13.** The Switch PMM1500J00 efficiency at different loads.

A prior study was utilised to define the corresponding efficiency of the EESG system. The study was an efficiency comparison between two different shaft generators: a direct-drive PMSG and EESG. The nominal power for the machines in the prior study was in the 1.5 MW range. Measured efficiency was done at constant speed with varying loads. Although the machines in the prior study were slightly smaller in terms of power compared to the machines covered in this thesis, they provide a sufficiently accurate efficiency for an EESG machine with a nominal power of 1,894 kW. It should be noted that, according to the FAT report of the PMSG machine used in this thesis, the efficiency was slightly lower (95.8%) compared to the reference (96.4%) shown in the Figure 14.

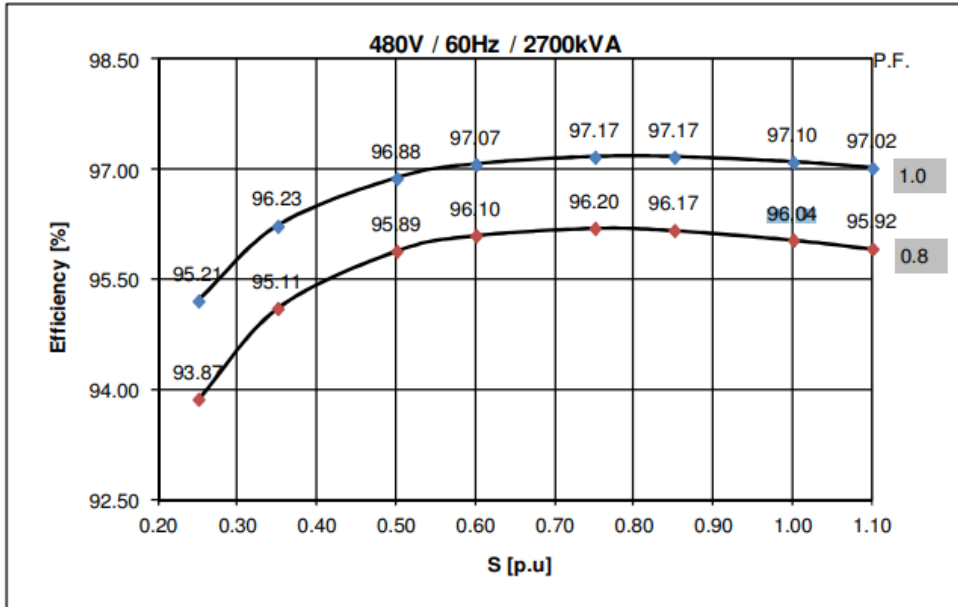
In this thesis, efficiency for the EESG at 100% load was determined to be 93.0%. This is also supported by another independent research by Zhang et al. (2011), where for an EESG, in slightly different use, efficiency of 93.6% was presented. Figure 14 shows the efficiency comparison between a PM and an EESG machine.



**Figure 14.** An efficiency comparison between a PM and EESG machine (The Switch)

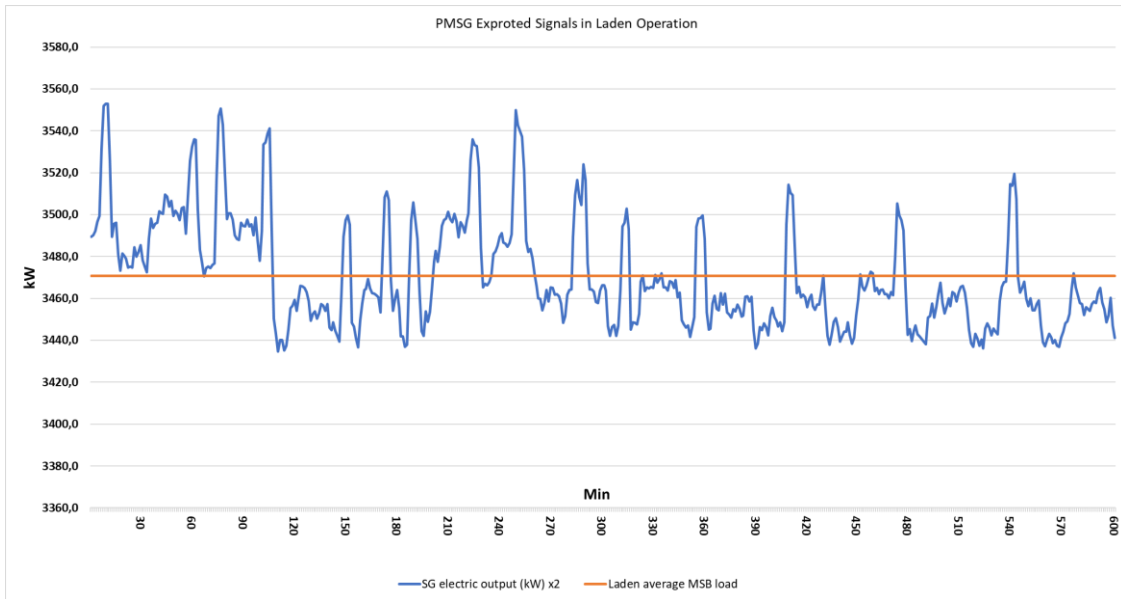
For the auxiliary genset generator, an ABB's synchronous generator AMG0450DD04 was used. The details of the machine's technical specifications were gathered from the manufacturer's shared online library. Figure 15 shows the efficiency graph of the machine at different loads. The technical specification specifies the AMG 0450DD04 generator for diesel/gas engines used for industrial applications. However, this is expected to also give

a sufficiently accurate estimate for marine use. The efficiency of the generator at 100% load was determined to be 96.0%.



**Figure 15.** ABB's AMG 0450DD04 efficiency curves (ABB, 2012).

The ship operator has shared fleet analytics data for a certain voyage; the raw data consists of two different 10-hour coverages of PMSG load at one-minute intervals in both with laden and ballast conditions. The data did not include any manoeuvring or stops at ports. Extracted fleet analytics considered only data from one PMSG on board, so the load has been duplicated. While sailing, all the MSB power was generated by the shaft generators. According to the data, the ship held an average speed of 18 knots, and the shaft generator had an average speed of 67.2 rpm during the observation period. Figure 16 shows two PMSG's load of the LNG carrier during the observation period, also average MSB load is displayed.



**Figure 16.** PMSG operational profile in Laden condition

As can be seen on the chart, the LNG carrier maintains a high power demand even during sailing. For the fleet analytics, the same raw data of ballast condition was also provided. For the determination of the average MSB load on all conditions, research by Deng (2018) was utilised. According to Deng (2018), an average LNG carrier operates 60% of the time in laden conditions and 40% of the time in ballast conditions. The average MSB load could be determined for the ship covered in this study by this information. The total average MSB load was determined for 3,260 kW.

The annual sailing hours, and therefore PMSG utilisation hours, of the ship, could not be determined with sufficient accuracy from the provided fleet analytics. Therefore, a prior study by Poljak et al. (2020) was utilised for the determination of common yearly operating hours. According to the study, the LNG carrier's main steam turbine had accumulated running hours of 63,204 hours in the period from the year 2001 until the end of 2010. Hence, the annual running hours were approximately 6,300 hours. This study assumes the main engines and shaft generators annual operating hours to be 6,300 hours.

## 5.2 Product tanker

The data for the product tanker was collected via questionnaire. In the survey, a specialist within the system integrator company addressed the first three points. In addition to their responses, operational data was collected from real ship operation data. These questions allowed to reach the general operational profile of the ship type in question. The responses to questionnaire items 1–3, which pertain to the general vessel type information on the prevailing power generation trends in the maritime sector for product tanker, are presented below.

1. No clear winner for the main engine. But the trend is towards 4-stroke main engine, and we can see Wärtsilä 31 is a popular choice. These vessels hold quite low speed, about 12 knots so the propulsion power is fairly low. Fuel can be conventional or more exotic. As this is a tank vessel and if this vessel were to carry methanol we would see a dual fuel main engine running on methanol. Other popular options are DF with LNG, or to some extent DF Ammonia ready.

Examples of common main engine choice for these types of vessels: 1x 6MW at 102 rpm (MAN 5S50 ME) or 1x Wärtsilä 6.1 MW 10V31

When it comes to main engine selection this is not black and white. Many factors have an impact on selection. For example, if you want 2-stroke DF methanol, the only option is 50 bores from MAN, there are no other models available. The commodity you carry have a great impact.

2. Typically, 4x high speed (1800 rpm) with conventional fuel. Mitsubishi or similar.
3. Typical Shaft Generator: 1500 kW between 75-102 rpm for 2-stroke or 1500kW between 840-1200 rpm for PTO shaft on gearbox for 4-stroke.

Load profile depends on electrical consumption onboard of the vessel, which can vary over time. Generally, the product tanker will be close to 50 % during sailing (avg SG load/available load) on open water, then to reach close to 100% load on SG during manoeuvring when the bow thruster is operated.

As can be seen from the survey answers, product tankers generally prefer slow steaming while sailing and within the industry, there is no ultimate choice for main engines. The main engine of the ship involved in the study is 1x Wärtsilä 10V31 DF, and the auxiliary gensets are 2x Wärtsilä 8L20DF. The data for these engines is shown in Table 7. The data for the main engine was collected from FAT report provided by the shipowner, and the data for the auxiliary engines was collected from the manufacturer's data specification sheets. For the HFO, the engine-specific SFOCs were not reported by the manufacturers or ship owner. Therefore, it was assumed that HFO's SFOC was inversely proportional to MGO when considering SFOC and energy content.

**Table 7.** ME and AE data for a product tanker of 20,500 dwt

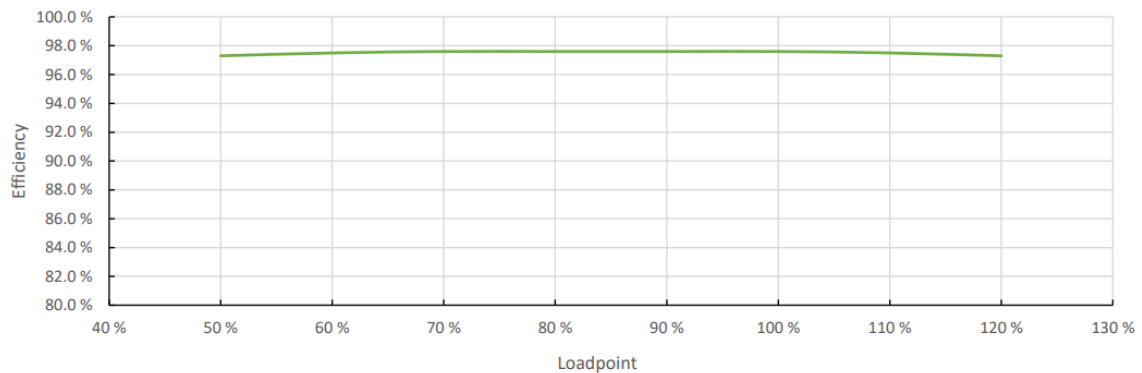
Engine	Wärtsilä 10V31 DF	Wärtsilä 8L20DF
Cycle type	four-stroke	four-stroke
Rated speed	750 rpm	900 rpm
Nominal power	5,500 kW	1,405 kW
SFOC MDO/MGO	179 g/kWh	197 g/kWh
SFOC LNG	153 g/kWh	171 g/kWh
SFOC HFO	190 g/kWh	209 g/kWh

For the ship's shaft generator, the product tanker has been equipped with three-phase permanent magnet synchronous generator: 1x The Switch PMM0500E01. The data of the gear-connected shaft generator is shown in Table 8.

**Table 8.** The Switch PMM0500E01 data

Generator	Rated power (PTO)	Rated speed	Efficiency
The Switch PMM0500E01	1,530 kW	840–1,200 rpm	97.6%

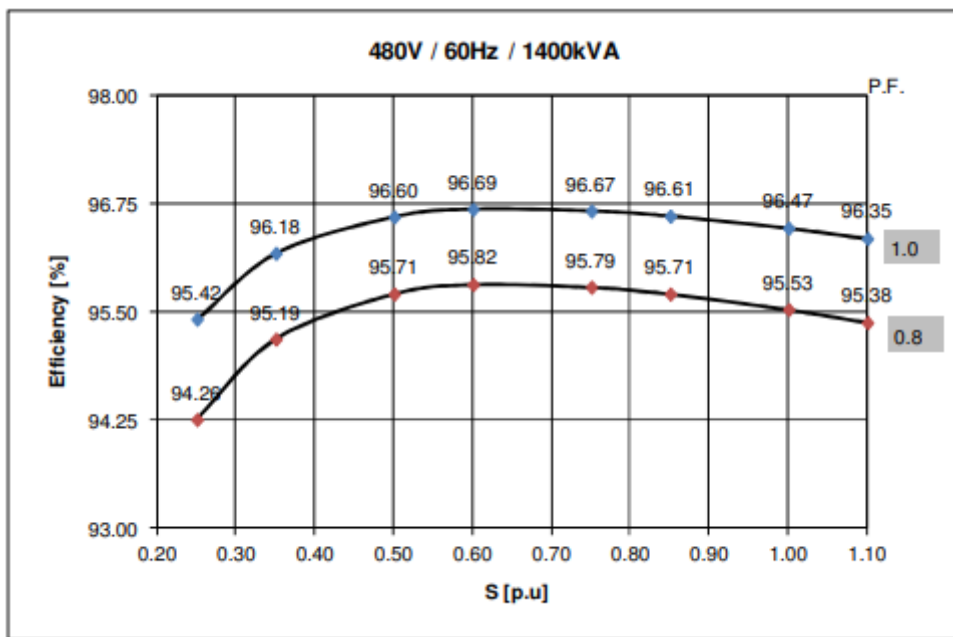
The efficiency of the existing generator on board affecting the fuel consumption could be determined from the manufacturer's FAT report. As shown in Table 6, the calculated rated efficiency for PMSG in use was 97.6%. However, as determined in the questionnaire answers, product tankers are assumed to operate SG at 50% load, and thus, PMSG efficiency for the studied machine was determined to be 97.3%. Figure 17 shows the efficiency graph of the machine at different loads. In the ship's real configuration, the PMSG is connected via a one-stage step-up gear which was assumed to have a decreasing effect of 1% for the power generation (Molland, 2008). Thus, the real power generation efficiency was determined to be 96.3%.

**Figure 17.** The Switch PMM0500E01 efficiency at different loads.

In order to calculate the differences between the systems, the efficiency of the EESG and auxiliary genset had to be determined. The efficiency for EESG and AE genset was assumed to be the same for this particular ship type. As a reference for the study, an ABB's synchronous generator was used. The generator considered was ABB AMG 0400DD04, and the details for the machine were retrieved from technical specifications available in the manufacturer's online library. This specific generator was chosen since it has similar

output power characteristics as the ship equipped PMSG. Figure 18 shows the efficiency graph of the machine at different loads. The technical specification specifies the AMG 0400DD04 generator for diesel/gas engines used for industrial applications. However, this is expected to also give a sufficiently accurate estimate for marine use.

In the study, the power factor of 0.8 was used, and when the efficiency loss due to the step-up gear was considered, the real power generation efficiency for EESG was determined to be 94.7%. In the genset configuration, efficiency was determined to be 95.7%. The identified difference in efficiency was 1.6% between the PMSG and EESG, and 0.6% between the PMSG and genset. These results are also supported by previous research by Zhang et al. (2011), where efficiency of one-stage gear connected EESG had efficiency of 96.7% with power factor of 1.0 at 50% load.

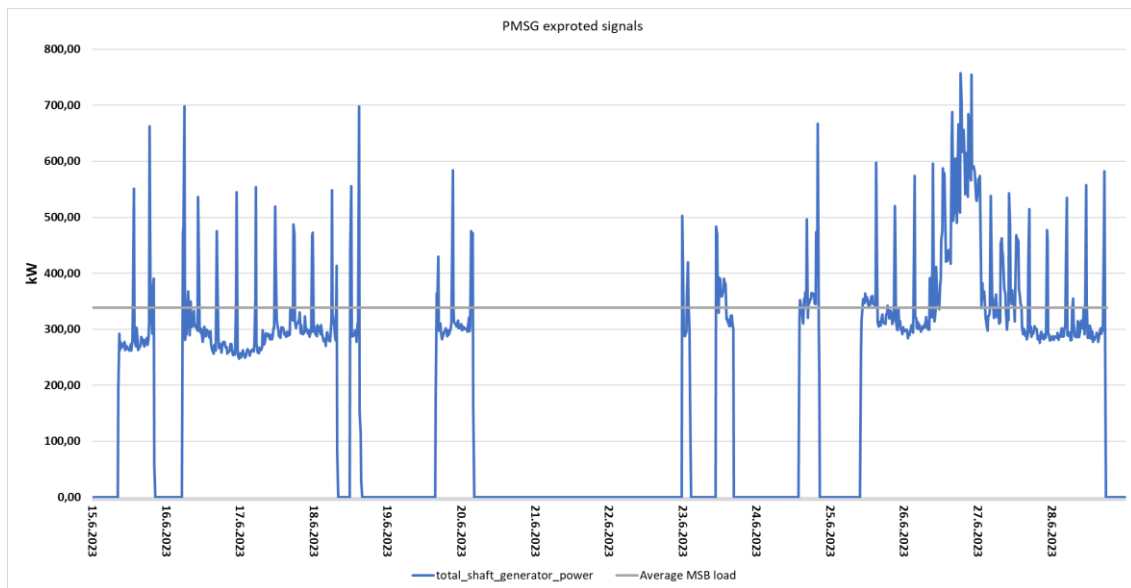


**Figure 18.** ABB's AMG 0450BB04 efficiency curves (ABB, 2012).

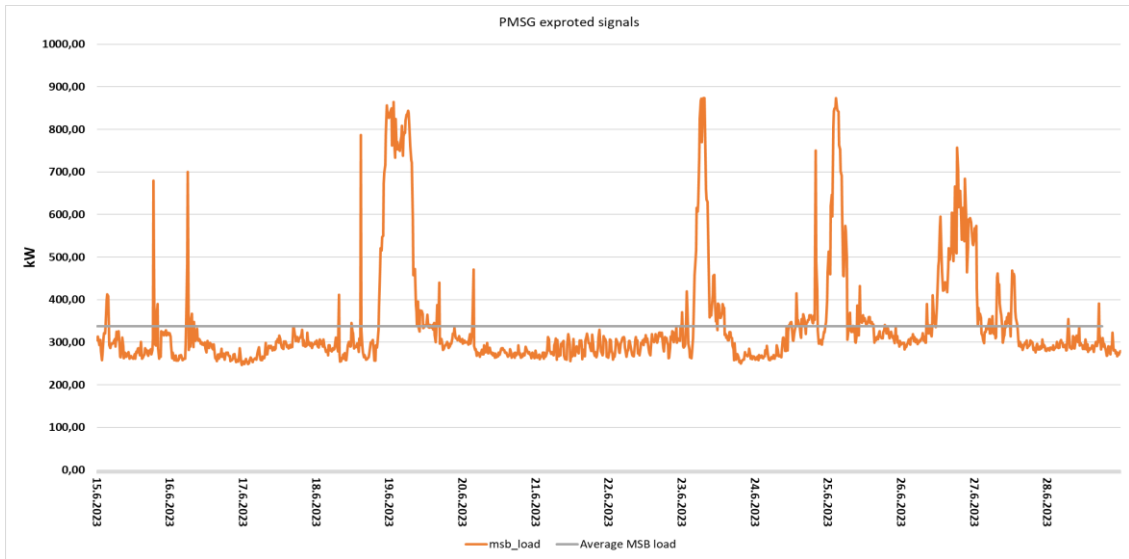
The ship operator shared fleet analytics data from a voyage that occurred in June 2023. The data covers a period between June 15, 2023, and June 28, 2023. The provided data sample spans precisely 336 hours. During this voyage, the ship made a total of six stops at various ports. Extracted fleet analytics data considered ME running hours, MSB load,

PMSG load and auxiliary generator load. The variables in raw data were presented at 15-minute intervals.

The annual operating hours and MSB load relevant to this work have been calculated as an average from the voyage in question. The main engine running hours and PMSG running hours were equivalent. In the given data sample, the total running hours of ME and PMSG were 174 hours, which equals approximately 52% of the covered time period. The study assumed this to be the annual average, thus yearly running hours were 4,555 hours. The ship's average MSB load was calculated to be 338.14 kW, which was also used to calculate the yearly average. Figure 19 shows the PMSG operational profile and Figure 20 the MSB load during the whole voyage.



**Figure 19.** Product Tanker PMSG operational profile



**Figure 20.** Product Tanker MSB load

As the Figures 19 and 20 show, electricity consumption remained fairly stable most of the time during the reference period. However, the manoeuvring periods can clearly be noted from the graphs, while the electricity demand was high. For consumption spikes, the vessel had to use both PMSG and genset simultaneously for electricity production.

## 6 Results

This section introduces the results of potential fuel savings for the different generator systems and the consequent costs due to the engine fuel supply and EU ETS system carbon credits for the whole expected vessel's lifetime operation. First, the lifetime cumulative costs are presented, and last, the total savings when comparing the PMSG system to both EESG and genset is shown. Further, the total CO<sub>2</sub> emissions reductions consequent to the fuel consumption for power generation are presented.

First, the research results regarding the fuel consumption and consequent costs for the studied LNG carrier are presented, followed by the results of the product tanker. A comparison of the three different systems is shown for all the fuels selected for the study. Later, lifetime CO<sub>2</sub> emission reductions are presented for both vessel types and all fuels selected.

### 6.1 Fuel savings with PMSG vs EESG vs fixed speed Genset

#### 6.1.1 LNG carrier

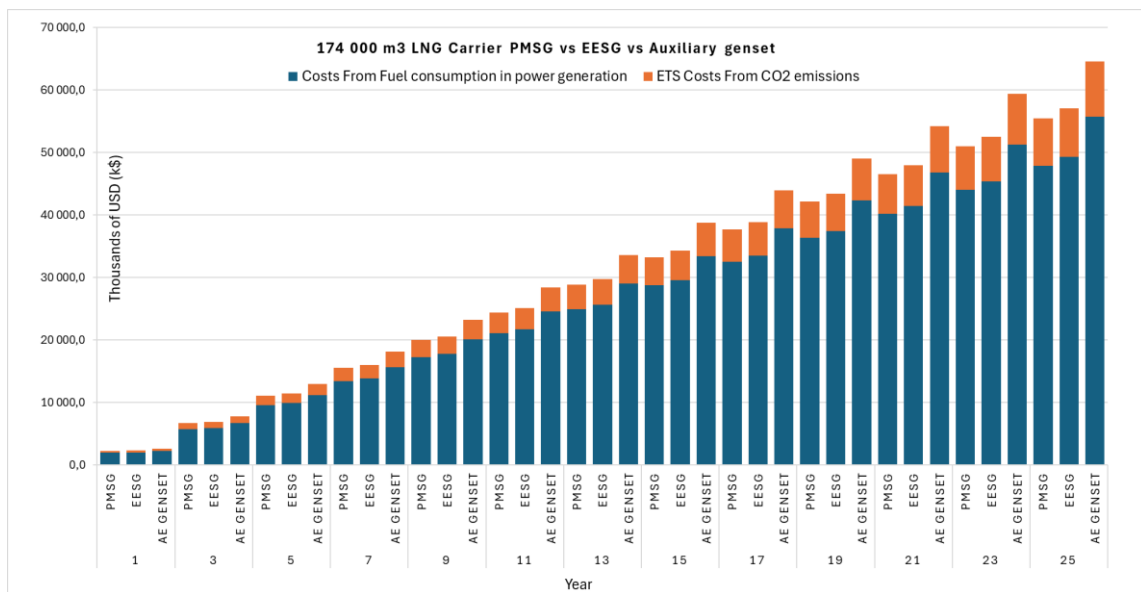
Figures 21–23 show the LNG carrier's cumulative costs resulting from fuel consumption and carbon credits for all three studied marine fuels. The charts cover the results for the expected 25-year lifetime, which have been presented in two-year intervals. Chart bars have been divided in two: costs from fuel consumption due to power generation and EU ETS carbon credits due to the emissions from consumed fuel.

For the LNG fuel configuration, the PMSG system consumes yearly 2,864.5 tons of fuel for power generation, whereas the EESG system consumes 2,950.8 tons and the Genset system 3,336.4 tons. The fuel consumption equals consequent yearly CO<sub>2</sub> emissions of 7,877.4 tons, 8,114.6 tons and 9,175.2 tons for the different systems in the same order as mentioned above. The total yearly costs for fuel consumption and ETS allowance

acquisition for the systems were PMSG: 2,216.8 kUSD, EESG: 2,283.5 kUSD and genset: 2 582.0 kUSD.

For the MGO configuration, the yearly fuel consumption for the PMSG system was 3,715.7 tons, and the consequent CO<sub>2</sub> emissions were 11,912.6 tons. For the EESG system, the figures were 3,827.6 tons and 12,271.3 tons, and for the genset system, the same figures were 3,939.6 tons and 12,630.3 tons. These figures resulted in costs as follows: PMSG: 3,251.0 kUSD, EESG: 3,348.9 kUSD, and genset: 3,446.9 kUSD.

In the HFO configuration, the PMSG system consumed 3,947.3 tons of fuel and emitted 12,291.9 tons of CO<sub>2</sub> emissions. The EESG system consumed 4,066.1 tons of fuel and emitted 12,662.0 tons of CO<sub>2</sub> emissions. Lastly, the genset system consumed 4,185.5 tons of fuel and emitted 13,033.7 tons of CO<sub>2</sub> emissions. These figures resulted in costs of 2,391.6 kUSD for PMSG, 2,463.6 kUSD for EESG, and 2,536.0 kUSD for the genset.



**Figure 21.** LNG Carrier cumulative costs comparison with LNG as used fuel.

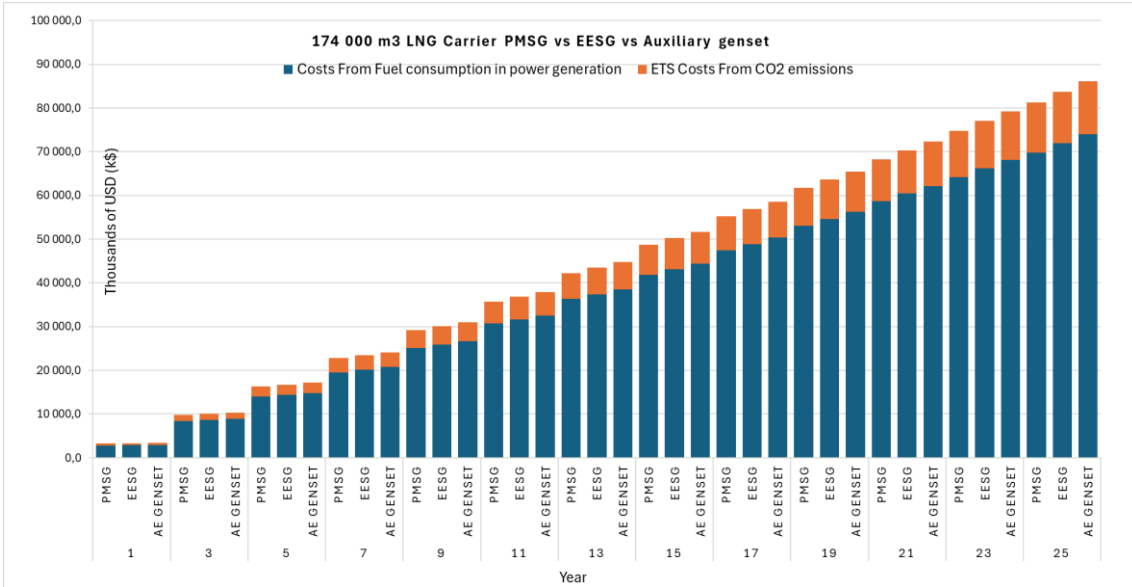


Figure 22. LNG Carrier cumulative costs comparison with MGO as used fuel.

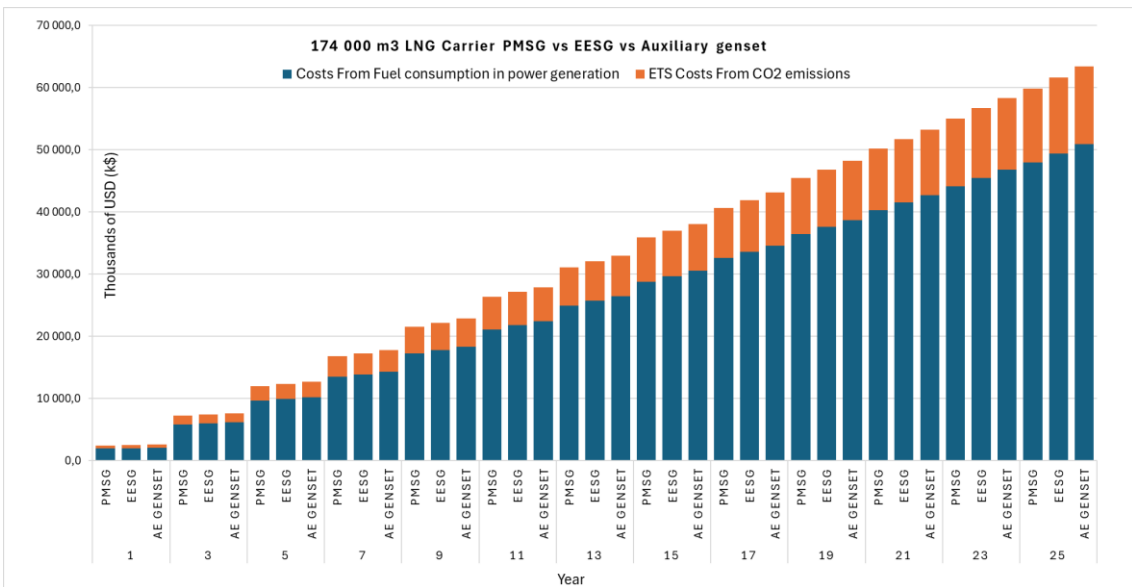


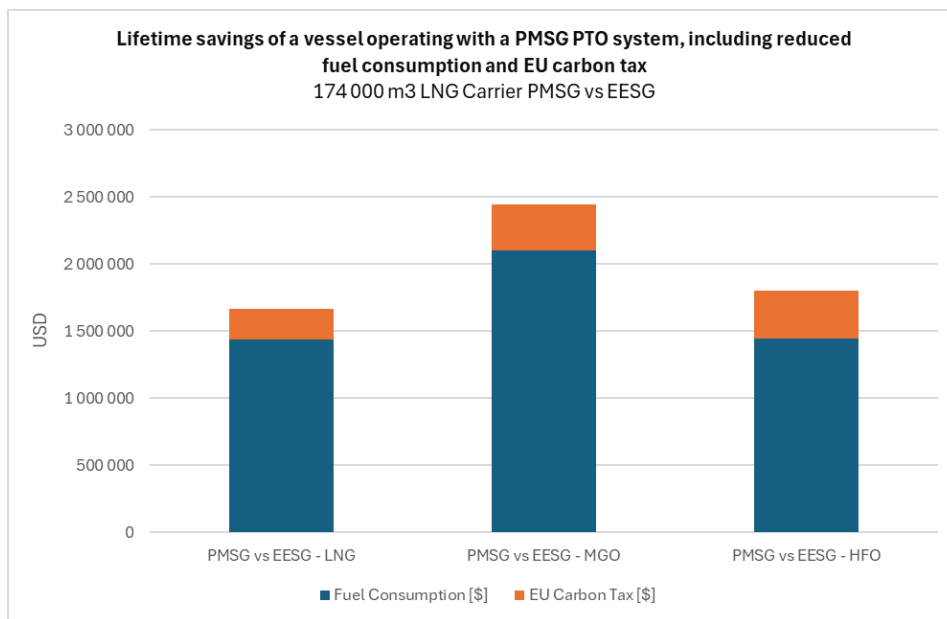
Figure 23. LNG Carrier cumulative costs comparison with HFO as used fuel.

As can be seen from the results, the PMSG system is the most efficient in power generation, followed by the EESG system, and the genset is the least favourable system. Utilisation of the PMSG system results in the least fuel consumption and CO<sub>2</sub> emissions. When comparing PMSG and EESG with different fuels, the biggest advantage comes

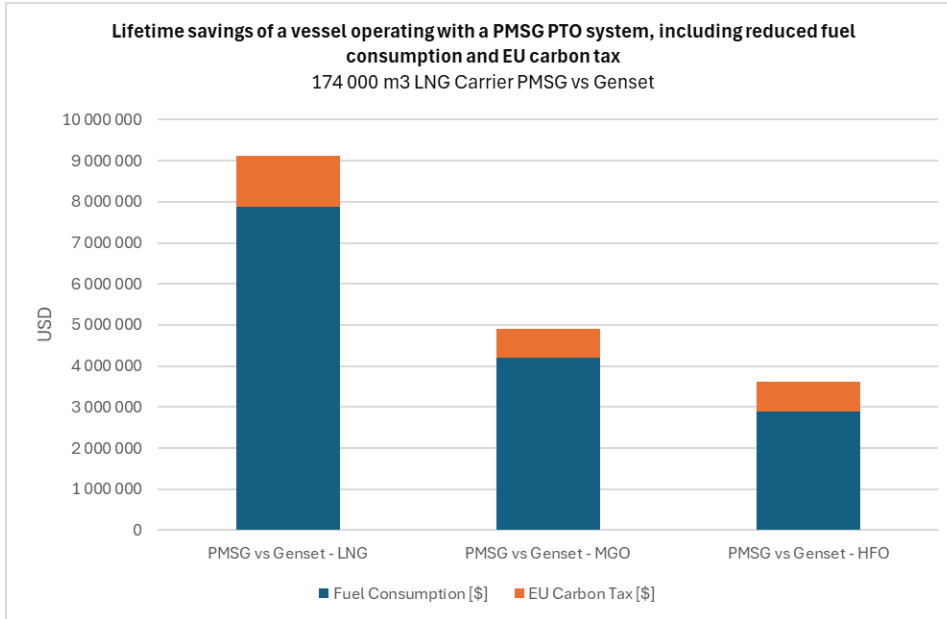
when the ship ME operates with MGO. Whereas when comparing PMSG and genset, the biggest advantage comes when both MEs and AEs operate with LNG.

As the data analysis showed, the genset had the best generator efficiency of 96.04% compared with PMSG's 95.8% and EESG's 93.0%. However, the results clearly show how great an impact the main mover of the system has on the end result. This is due to the fact that large two-stroke engines can convert the energy more efficiently from the fuel into motion. In this case, the four-stroke auxiliary engine had 16.8% higher fuel consumption on LNG and 6.3% for both MGO and HFO.

For the shaft generator configurations all the benefits come from the technology used in the PMSG machine and its lower power losses. Figures 24 and 25 show in more detail the full life-cycle benefits when comparing the PMSG system with the two conventional generator systems.



**Figure 24.** LNG Carrier lifetime savings potential PMSG vs EESG



**Figure 25.** LNG Carrier lifetime savings potential PMSG vs Genset

In the PMSG vs EESG comparison with the LNG carrier, the expected lifetime savings are 1.67 million USD if only LNG were used as fuel, 2.45 million USD if only MGO were used, and 1.80 million USD if HFO were the only fuel used. In the PMSG vs genset comparison, the expected savings are 9.13 million USD for LNG use, 4.90 million USD for MGO use, and 3.61 million USD for HFO.

The major share of costs comes straight from fuel consumption. However, ETS allowances also have an explicit impact on the total lifetime costs for power generation. Also, if the vessel sailed only within the EU, the share of ETS costs would be double the amount currently shown in the charts. In conclusion, both the choice of the power generation system and the choice of the fuel used for the engine powering have great impact on the lifetime costs for the vessel in question.

### 6.1.2 Product tanker

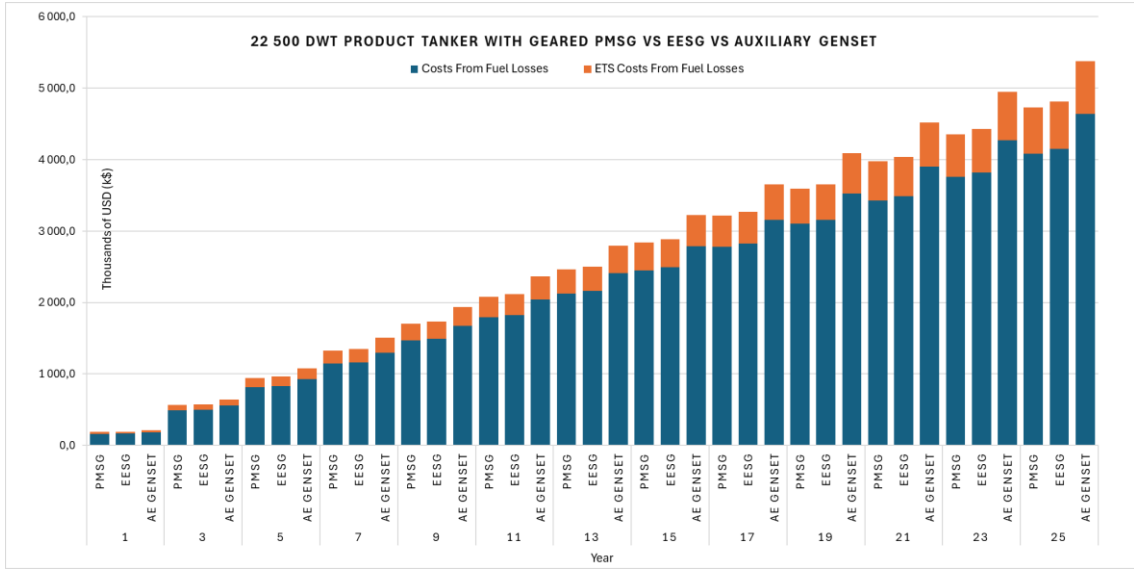
Research results for the cumulative costs resulting from fuel consumption and carbon credits for the studied product tanker with all three marine fuels are shown in Figures 26-28. The charts show the results for the expected 25-year lifetime, and the results have

been presented in two-year intervals. The chart bars have been divided into two: costs from fuel consumption due to power generation and EU ETS carbon credits due to the emissions from consumed fuel.

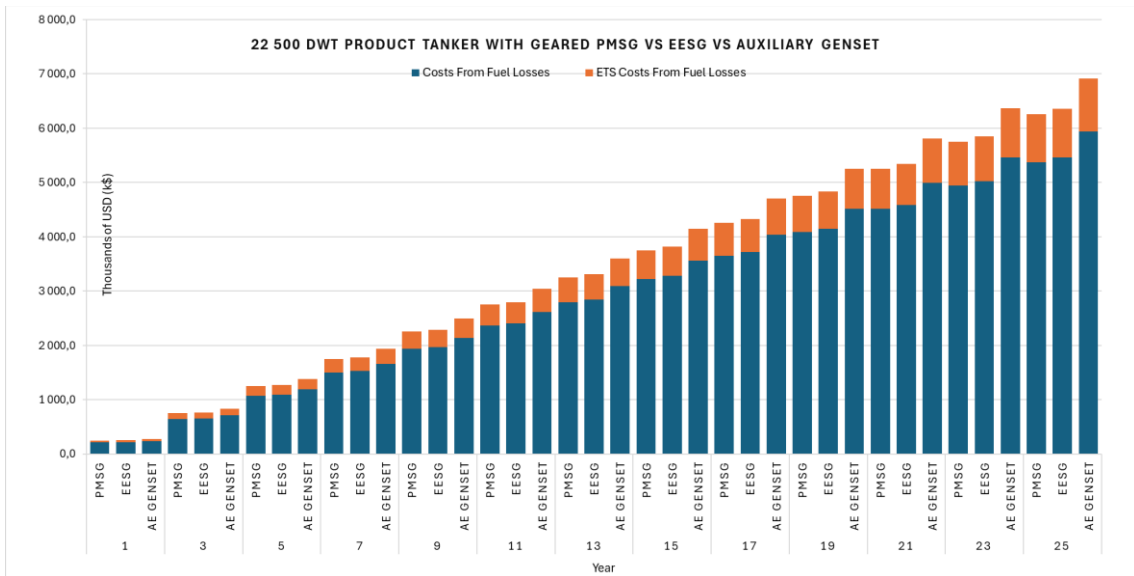
For the LNG fuel configuration, the PMSG system consumes 244.5 tons of fuel annually for power generation, while the EESG system consumes 248.7 tons, and the genset system consumes 277.9 tons. The fuel consumptions correspond to the yearly CO<sub>2</sub> emissions of 672.5 tons, 683.8 tons, and 764.3 tons for the different systems. The total annual expenditures for fuel consumption and ETS allowance acquisition for the systems were PMSG: 189.3 kUSD, EESG: 192.4 kUSD, and generator: 215.1 kUSD.

For the MGO configuration, the yearly fuel consumption for the PMSG system was 286.0 tons, and the consequent CO<sub>2</sub> emissions were 916.8 tons. For the EESG system, the figures were 290.8 tons and 932.2 tons, and for the genset system, the same figures were 316.2 tons and 1,013.8 tons. These figures resulted in PMSG's costs being 250.2 kUSD, EESG's 254.4 kUSD, and genset's cost of 276.7 kUSD.

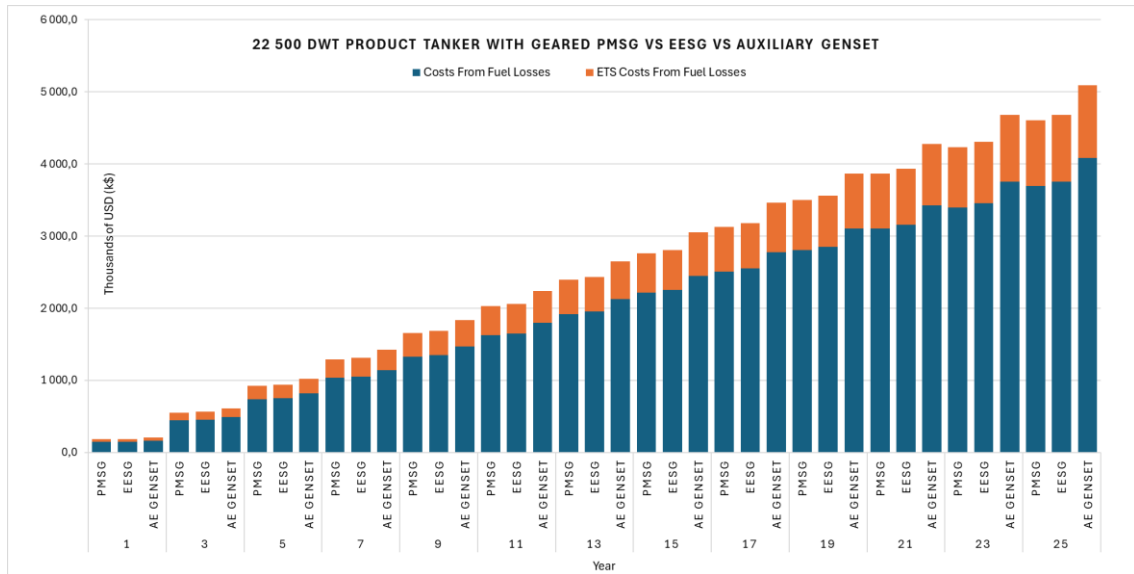
In the HFO configuration, the PMSG system consumed 303.7 tons of fuel and emitted 945.8 tons of CO<sub>2</sub>. The EESG system consumed 308.8 tons of gasoline and emitted 961.7 tons of CO<sub>2</sub>. Finally, the genset system consumed 335.9 tons of fuel and emitted 1,045.8 tons of CO<sub>2</sub>. These statistics resulted in the following costs: PMSG 184.0 kUSD, EESG 187.1 kUSD, and genset 203.5 kUSD.



**Figure 26.** Product Tanker cumulative costs comparison with LNG as used fuel.



**Figure 27.** Product Tanker cumulative costs comparison with MGO as used fuel.

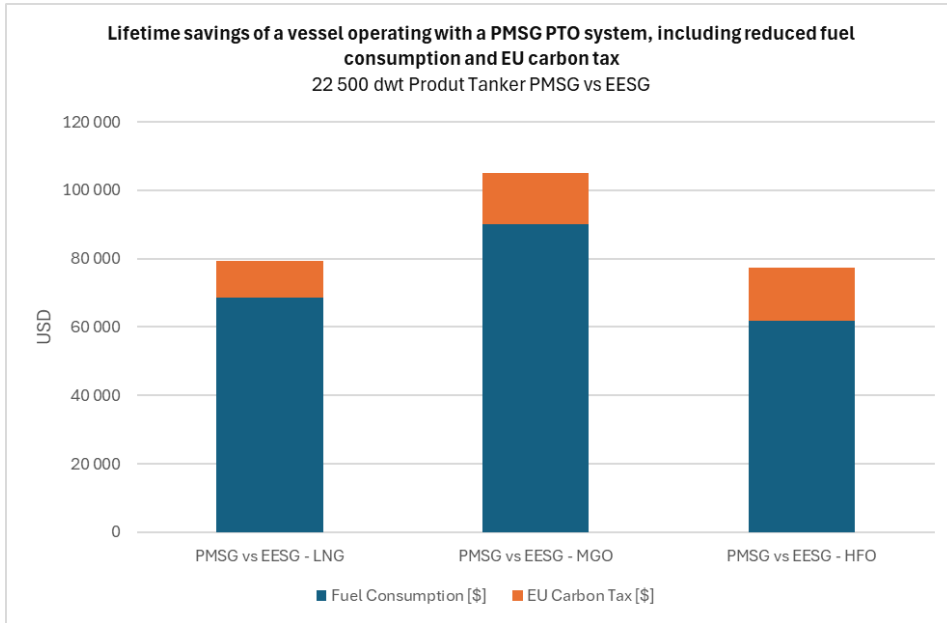


**Figure 28.** Product Tanker cumulative costs comparison with HFO as used fuel.

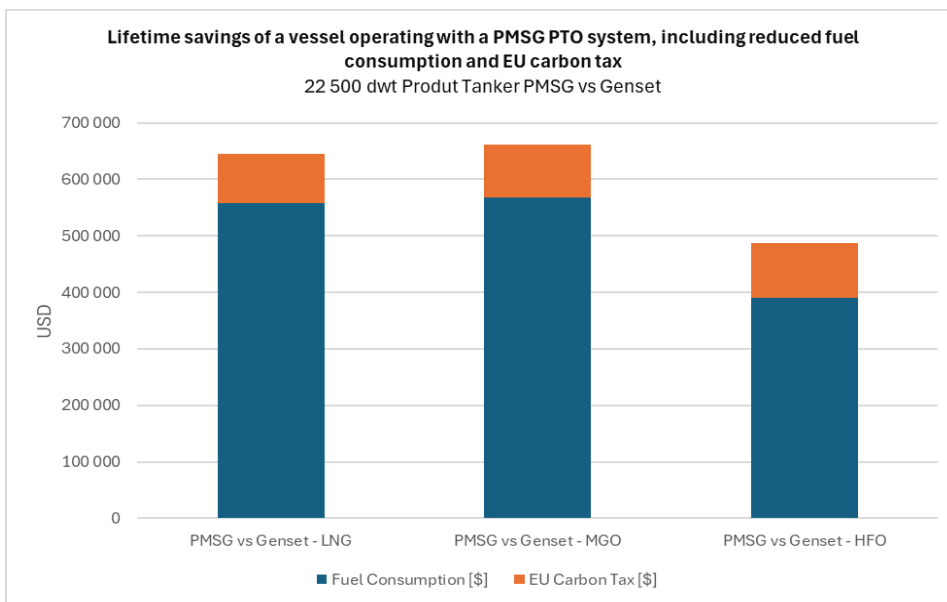
The results highlight the superiority of the PMSG system compared with the two other systems. Also, in the product tanker case, it can be noted that utilisation of the PMSG system results in the least fuel consumption and CO<sub>2</sub> emissions. Regarding the different fuels, also in this case, in the comparison of the PMSG and EESG systems, the biggest difference comes when ship ME operates with MGO. In the comparison of the PMSG and genset, the biggest difference comes from LNG operation. However, the pure advantages in terms of cost are not even close to the LNG carrier advantages. This is due to the fact that the ship has explicitly lower power consumption and the main engine of the ship does not operate at as high an efficiency as the ones in the LNG carrier. Also, the generator efficiencies are more equal.

As was shown in the data analysis, the PMSG had the best generator efficiency of 96.3% compared with EESG's 94.7% and gensets 95.7%. Again, when comparing the PMSG and EESG, all the benefits originate from the technology used in the PMSG machine and its lower power losses. In the production tanker case, when comparing PMSG and genset, the benefits come both from the better generator efficiency as well as the better engine efficiency. The auxiliary engine had 12.9% higher fuel consumption in LNG mode and 6.2% for both MGO and HFO mode when compared to the ship's main engine. Figures 29 and

30 show in more detail the full lifecycle benefits when comparing the PMSG system with the two conventional generator systems.



**Figure 29.** Product Tanker lifetime savings potential PMSG vs EESG



**Figure 30.** Product Tanker lifetime savings potential PMSG vs Genset

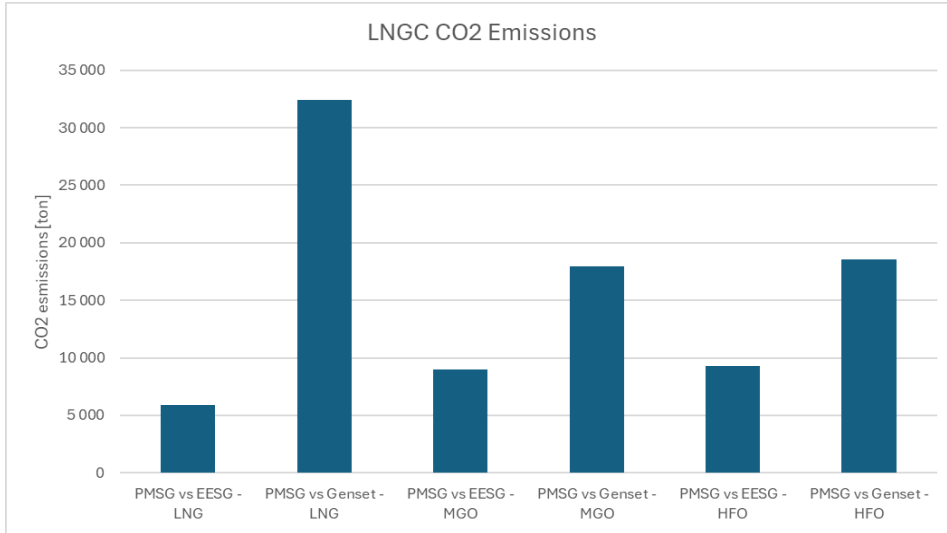
In the comparison of PMSG and EESG to the Product tanker, the expected lifetime savings are 79.4 kUSD if LNG is the sole fuel used, 105.0 kUSD if MGO is the sole fuel used, and 77.2 kUSD if HFO is the only fuel used. In contrast, in the PMSG versus genset comparison, the expected savings are 645.6 kUSD for LNG, 661.6 kUSD for MGO, and 486.6 kUSD for HFO consumption.

Fuel consumption accounts for the vast majority of the product tanker's costs. However, ETS allowances also impact the overall lifetime cost of power generation. Furthermore, if the vessel operated just within the EU, the share of ETS costs would be twice what is now shown in the charts. In conclusion, both the power generation system and the fuel used in the engine have a significant impact on the vessel's lifespan expenses.

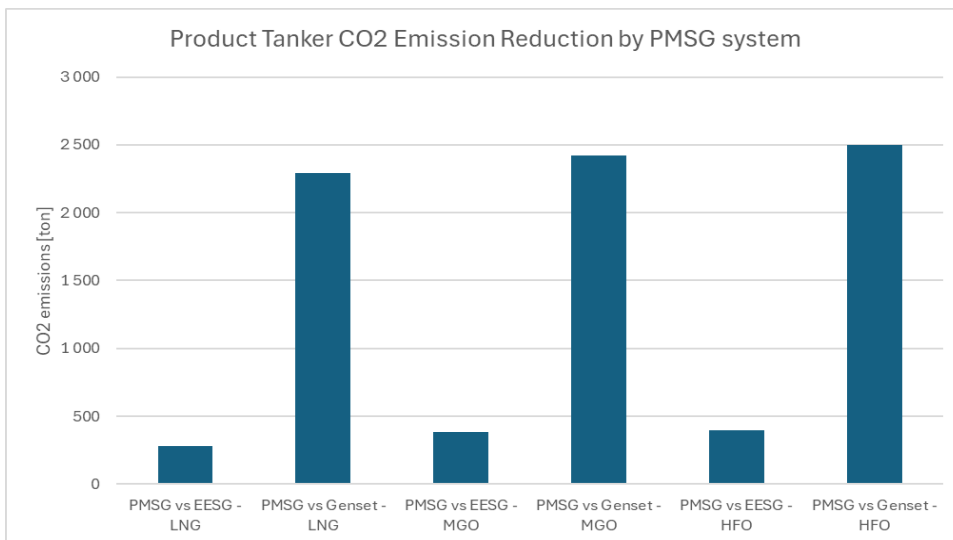
## **6.2 Consequent CO<sub>2</sub> emission reduction with various fuel types**

Engine fuel consumption has a direct impact on the vessel's CO<sub>2</sub> emissions. Figures 31 and 32 illustrate the expected 25-year lifetime's CO<sub>2</sub> emission reduction potential, achievable by the PMSG system for both studied vessel types.

The results show that for the LNG carrier, the CO<sub>2</sub> reduction potential is higher than the product tanker. This is because power demand is higher in the LNG carrier, and also, the PMSG system utilised in the LNG carrier has more edge on efficiency over its rival systems. In the product tanker case, the PMSG system does not introduce as big benefits for the total power system efficiency. However, CO<sub>2</sub> reduction is also here evident by the utilisation of the PMSG system.



**Figure 31.** LNG Carrier CO<sub>2</sub> reduction potential by utilising PMSG system



**Figure 32.** Product Tanker CO<sub>2</sub> reduction potential by utilising PMSG system

With an LNG carrier, the potential CO<sub>2</sub> emission reduction compared with the EESG system is 5,929 tons with LNG, 8,967 tons with MGO and 9,252 tons with HFO. When comparing to the genset power generation system, the potential is 32,445 tons with LNG, 17,941 tons with MGO and 18,546 tons with HFO.

For the product tanker, the potential CO<sub>2</sub> emission reduction with PMSG compared to the EESG system is 282 tons with LNG, 385 tons with MGO and 397 tons with HFO. The

same comparison with the genset shows a reduction potential of 2,294 tons with LNG, 2,424 tons with MGO and 2,501 tons with HFO. For both vessels, the biggest CO<sub>2</sub> reduction potential comes from HFO use followed by MGO and LNG with the EESG comparison. For genset comparison in the LNG carrier case, the biggest benefits come from LNG use followed by HFO and MGO, while in the product tanker case the biggest benefits come from HFO use followed by MGO and LNG.

## 7 Conclusions

The study aimed to determine the potential fuel savings and CO<sub>2</sub> emission reductions by using a PMSG system with three different marine fuels for two different vessel types. In the study the PMSG system were compared with conventional marine power generation systems by the help of created vessel specific operational profiles.

The PMSG system provides considerable long-term fuel savings and, thus, emission and cost reduction potential across various fuel options for LNG carrier and product tanker compared to conventional power systems such as EESG and genset systems. However, the results show that the fuel choice significantly impacts potential savings. For both vessel types, when comparing PMSG and EESG systems, the most significant cost savings potential in fuel consumption came from MGO operations. When comparing PMSG and genset systems, the most significant cost savings potential in fuel consumption for both vessel types came in LNG operation.

The study showed that the larger the ship and the more electricity it consumes, the greater the benefits of the PMSG system are, both in fuel savings and emission reduction. The PMSG system is most effective when directly coupled and driven without gearing with a two-stroke main engine. The results revealed that this combination resulted in the biggest savings in fuel consumption and therefore the biggest reductions in CO<sub>2</sub> emissions.

For future studies, the same study could be repeated for other vessel types, such as container vessels. In addition, if more precise data gathering were available, for example, a data set of a full year from a LNG carrier, it could be compared with the results given in this thesis. As discussed at the beginning of the theory part of the thesis, the diesel-electric propulsion system is widely used in addition to diesel-mechanical propulsion technology. The same type of research could be conducted in a case where the diesel-electric propulsion would be conducted by a PM engine and compared to conventional electrically excited propulsion motors.

## 8 Summary

The purpose of the thesis was to establish fuel saving and CO<sub>2</sub> emission reduction potential with a permanent magnet shaft generator (PMSG) system compared to a conventional electrically-excited shaft generator system (EESG) and a standalone generator system (genset). The importance of the topic is underlined by the fact that the maritime sector is in rapid transition towards lower emissions due to environmental aspects as well as various tightened standards and guidelines for ship operators worldwide from organisations such as IMO and EU. This thesis concentrated on the PMSG system's benefits in terms of emission reductions and lifetime savings for ship operators with real ship operation data.

The research was conducted on two vessel types: LNG carrier and product tanker. The fuel savings and emission reduction results were calculated for three different fuels: LNG, MGO and HFO. Quantitative data analysis was selected for the empirical approach. The hypothesis of the research was that the PMSG system would introduce clear advantages in savings compared to the conventional marine power plant systems for all fuel types chosen for the study.

Key findings from the research results were that the PMSG system is able to introduce evident savings in fuel consumption and emission reduction, yielding notable cost savings for ship operators. However, the scale of the benefits is mainly the result of the ship's power consumption profile, yearly sailing hours and the main engine type. For the large 174,000 m<sup>3</sup> LNG carrier, the power demand for the vessel was high, and therefore, both the fuel savings, emission reduction potential and lifetime cost savings with the PMSG system were fairly high. Also, for the 22,500 dwt product tanker, the benefits were noticeable, but since the ship was smaller, operation profile was different and its average power demand was significantly lower, the results showed lower total fuel savings and emission reduction. Also, the main engine choice did not provide as big an advantage for the fuel energy conversion efficiency as in the LNG carrier case.

For LNG carriers, the PMSG system introduced potential lifetime cost savings over the EESG system, varying from 1.7 million USD to 2.5 million USD depending on the fuel choice. In comparison with the genset system, the PMSG system introduced cost savings varying from 3.6 million USD up to 9.1 million USD depending on the fuel choice. The introduced total emission reduction potential over the EESG system ranged from 5,900 tons up to 9,300 tons, and with comparison over the genset system, reduction potential ranged from 18,900 tons up to 32,500 tons.

In the production tanker case PMSG system did not introduce as big total savings and emission reduction potential as in the LNG carrier case. When comparing, the vessel-mounted PMSG system and EESG system, the lifetime cost savings varied between 77,000 USD to 105,000 USD and introduced CO<sub>2</sub> reduction from 280 tons up to 400 tons depending on the Fuel choice of the vessel. When the PMSG system was compared with the genset, the cost savings varied between 490,000 USD to 660,000 USD, and CO<sub>2</sub> reduction varied between 2,300 tons to 2,500 tons, dependent on the used fuel. The fuel prices were based on port of Rotterdam bunker fuel prices, these fuel prices are shown in Table 4.

This research encountered certain limitations that may have influenced the results and conclusions drawn of the study. In the research, secondary sources had to be used; in the example, all used generator efficiencies and engine consumption profiles, with the exception of PMSGs and product tanker ME, had to be retrieved from manufacturers-provided data or from earlier studies in the sector with certain assumptions of the used machine types. This may have some small effects on the accuracy of the results. Also, in the case of the LNG carrier, the yearly main engine running hours could not be determined from the data provided by the ship operator, and therefore, an earlier study on the same type of vessel had to be utilised for the determination of average running hours. In addition it is important to note that this study considered only the generator and engine efficiencies of the power system, not the drive train as a whole. For example, shaft

generators require converter systems for variable frequency drive, which has some effects for the whole drive train efficiency.

It is also important to highlight that the PMSG system introduces other advantages over the compared systems in addition to the cases studied in this research. Shaft generators, in general, are able to provide the opportunity to ship for PTI operation. In PTI operation, the machine operates as an electric motor, and the needed power is solely generated by on-board gensets. With the help of this operation, ship can for example provide boost power for the main engine in rough weather conditions or in schedule-catching situations. In addition, if the shaft line and main engine have been separated by a shaft clutch, the shaft generator can provide the full propulsion power for the ship. This feature can be used to ensure that the ship is driven to the nearest port in the event of the ship's main engine failure or for fully electrical port arrival. In addition, the PMSG has a simple and robust construction, which leads to low maintenance needs. As a result, the PMSG system delivers better power generation efficiency and indirect positive cost effects of lower maintenance needs.

Based on the research results for both vessel types, the choice of PMSG system for the vessels' power generation seems to be beneficial since it can bring cost savings and emission reductions. The results can be seen as an indicator for the overall marine industry, not only limited to the two certain vessel types but especially for large-sized vessels with big power consumption. PMSG system introduces the biggest advantages when coupled with low-speed, highly efficient two-stroke marine engines. The PMSG system can help the industry with the transition towards fewer emissions and, at the same time, reduce vessel operator's costs.

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## Appendices

### Appendix 1. Illustration of calculation tool for LNG carrier

Vessel Type	LNG Carrier	Expected Lifetime for Vessel (years)	25
Main Engine	WinGD 5X72DF	AVG SG Load/Available while sailing	100 %
Auxiliary Engines	Wärtsilä 6L34DF	AVG power on MSB while sailing (kW)	3260,40
Annual running hours of ME	6300	<b>PMSG In ship</b>	
ME Fuel used	LNG	PMSG efficiency	95,8 %
AE Fuel used	LNG	AVG power on Propulsion shaft while sailing (kW)	3 403,3
		Annual PMSG Power (losses included) (kWh)	21 441 043,8
ME SFOC (g/kWh)	133,6	Annual Fuel consumption for power generation (ton)	2 864,5
AE SFOC (g/kWh)	156	Total Annual Costs from Fuel used for power gen. (k\$)	1 913,5
		Total annual CO2 released from Fuel used for power gen. (ton)	7 877,4
ME Fuel Lower Heating Value (kJ/kg)	48000	Total annual ETS price from Fuel used for power gen. (k\$)	303,3
AE Fuel Lower Heating Value (kJ/kg)	48000		
		<b>EESG compared with real system</b>	
ME Fuel specific CO <sub>2</sub> emissions (ton/ton)	2,75	EESG efficiency	93,00 %
AE Fuel specific CO <sub>2</sub> emissions (ton/ton)	2,75	AVG power on Propulsion shaft while sailing (kW)	3 505,8
		Annual EESG Power (losses included) (kWh)	22 086 580,6
ME Fuel Price (\$/ton)	668	Annual Fuel consumption for power generation (ton)	2 950,8
AE Fuel Price (\$/ton)	668	Total Annual Costs from Fuel used for power gen. (k\$)	1 971,1
		Total annual CO2 released from Fuel used for power gen. (ton)	8 114,6
EU carbon tax in EU (\$/ton)	77	Total annual ETS price from Fuel used for power gen. (k\$)	312,4
EU carbon tax to or from non-EU country (50 %)	38,5		
		<b>AE Genset compared with real system</b>	
		Genset efficiency	96,04 %
		AVG power on Propulsion shaft while sailing (kW)	3 394,8
		Annual Genset Power (losses included) (kWh)	21 387 463,6
		Annual Fuel consumption for power generation (ton)	3 336,4
		Total Annual Costs from Fuel used for power gen. (k\$)	2 228,7
		Total annual CO2 released from Fuel used for power gen. (ton)	9 175,2
		Total annual ETS price from Fuel used for power gen. (k\$)	353,2

### Appendix 2. Illustration of calculation tool for Product Tanker

Vessel Type	Product Tanker	Expected Lifetime for Vessel (years)	25
Main Engine	Wärtsilä 10V31DF	AVG SG Load/Available while sailing	50 %
Auxiliary Engines	Wärtsilä 8L20DF	AVG power on MSB while sailing (kW)	338,14
Annual running hours of ME	4555	<b>PMSG system In ship</b>	
ME Fuel used	LNG	PMSG efficiency (gear loss included)	96,3 %
AE Fuel used	LNG	AVG power on Propulsion shaft while sailing (kW)	351,1
		Annual PMSG Power (losses included) (kWh)	1 599 405,7
ME SFOC (g/kWh)	152,9	Annual Fuel consumption for power generation (ton)	244,5
AE SFOC (g/kWh)	172,7	Total Annual Costs from Fuel used for power gen. (k\$)	163,4
		Total annual CO2 released from Fuel used for power gen. (ton)	672,5
ME Fuel Lower Heating Value (kJ/kg)	48000	Total annual ETS price from Fuel used for power gen. (k\$)	25,9
AE Fuel Lower Heating Value (kJ/kg)	48000		
		<b>EESG system</b>	
ME Fuel specific CO <sub>2</sub> emissions (ton/ton)	2,75	EESG efficiency (gear loss included)	94,71 %
AE Fuel specific CO <sub>2</sub> emissions (ton/ton)	2,75	AVG power on Propulsion shaft while sailing (kW)	357,0
		Annual EESG Power (losses included) (kWh)	1 626 256,7
ME Fuel Price (\$/ton)	668	Annual Fuel consumption for power generation (ton)	248,7
AE Fuel Price (\$/ton)	668	Total Annual Costs from Fuel used for power gen. (k\$)	166,1
		Total annual CO2 released from Fuel used for power gen. (ton)	683,8
EU carbon tax in EU (\$/ton)	77	Total annual ETS price from Fuel used for power gen. (k\$)	26,3
EU carbon tax to or from non-EU country (50 %)	38,5		
		<b>Genset system</b>	
		Genset efficiency	95,71 %
		AVG power on Propulsion shaft while sailing (kW)	353,3
		Annual Genset Power (losses included) (kWh)	1 609 265,2
		Annual Fuel consumption for power generation (ton)	277,9
		Total Annual Costs from Fuel used for power gen. (k\$)	185,7
		Total annual CO2 released from Fuel used for power gen. (ton)	764,3
		Total annual ETS price from Fuel used for power gen. (k\$)	29,4