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Applications of Permanent Magnet Shaft Generator in Marine Industry

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Applications of Permanent Magnet Shaft Generator in Marine Industry

This master’s thesis focuses on studying the applications of the permanent magnet shaft generator in the marine industry. The work has two objectives. First is to assess the number of applications of direct drive permanent magnet shaft generators in marine applications today and in the future. The second is to determine how the applications of diesel mechanical propulsion systems and diesel electric propulsion systems differ in the marine industry.

The analysis of the number of applications started by finding suitable ship types based on previous references of the commissioner, technological requirements, and a literature review. A 1MW or more auxiliary power limitation was used as a primary selecting criteria for the ship types included into the analysis. EEDI auxiliary power calculation equations were used to investigate the impact of 1 MW or more auxiliary power limitation on the total propulsion power. The effect of total propulsion power on ship size was evaluated in terms of IHS database. The number of ships for the selected ship types and sizes were collected from the 2022 World Merchant fleet statistics from equasis report.

Based on the results, the suitable ship variations are very large gas tankers, large and very large container ships. The percentage of applications according to the 2022 merchant ship statistics is 3,1%. Lowering the auxiliary power limitation from 1MW to 0,75MW would increase the percentage of applications to 7,1%. No potential applications for a diesel-electric propulsion system were found from the selected suitable ships due to their size and their purpose in the marine industry.

Keywords:

Energy Efficiency Design Index, International Maritime Organization, Shaft generator, Auxiliary engine power

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KESTOMAGNEETTIAKSELIGENERAATTORIN KÄYTTÖKOHTEET MERITEOLLISUUDESSA

Insinöörityössä tutkitaan kestomagneettiakseligeneraattorin käyttökohteita meriteollisuudessa. Työllä on kaksi tavoitetta. Ensimmäisenä tavoitteena oli arvioida suoravetoisen kestomagneettiakseligeneraattorien käyttökohteiden lukumäärä meriteollisuuden sovelluksissa nykypäivänä ja tulevaisuudessa. Toinen tavoite on selvittää kuinka diesel mekaanisen propulsiojärjestelmien ja diesel sähköisen propulsiojärjestelmien käyttökohteet eroavat meriteollisuudessa.

Käyttökohteiden lukumäärän selvitys aloitettiin löytämällä sopivat alusvariaatioita aikaisempien toimeksiantajan referenssien, teknologisten vaatimusten ja kirjallisuus selvityksen perusteella. Rajauksessa käytettiin 1MW tai yli apukonetehorajoitusta valituille alustyypeille. Apukonetehon rajoituksen vaikutus kokonaispropulsio tehoon selvitettiin EEDI säännöksen apukoneteho laskentakaavoille. Kokonaispropulsiotehon vaikutus aluksen kokoluokkaan haettiin IHS database tietokannasta. Tilastotiedot valituista alustyypeistä ja kokoluokista kerättiin 2022 World Merchant fleet staticstics from equasis report dokumentista.

Tulosten perusteella soveltuvat alusvariaatiot ovat erittäin suurissa kaasutankkereissa, suurissa ja erittäin suurissa konttialuksissa. Käyttökohteiden prosentuaalinen osuus 2022 vuoden kauppa-alus tilastojen mukaan on 3,1%. Tutkimuksessa selvisi aputehon rajoituksen 1MW laskemisen 0,75MW nostavan käyttökohteiden prosentuaalisen määrän 7,1%. Diesel-sähköpropulsion järjestelmän mahdollisia käyttökohteita ei löytynyt soveltuvista alustyypeistä pääasiassa niiden koon ja käyttötarkoituksen takia.

Asiasanat:

Energy Efficiency Design Index, International Maritime Organization, Akseligeneraattori, Apukoneteho

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Appendix 1. Short-, medium-, and long-term plans in the IMO Strategy

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List of abbreviations

Abbreviation	Explanation of abbreviation
C_{FAE}	Carbon factor for fuel for auxiliary engines [g_{CO2}/g_{fuel}]
C_{FME}	Carbon factor for fuel main engines [g_{CO2}/g_{fuel}]
DWT	Deadweight tonnage is a measurement of ships carrying capacity, 1ton =1000kg
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
FPP	Fixed Pitch Propeller
GHG	Greenhouse gas
GT	Gross Tonnage
HFO	Heavy Fuel Oil
ECA	Emission Control Areas
ICCT	International Council on Clean Transportation
EEOI	Energy Efficiency Operational Indicator
IMO	International Maritime Organization
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	Maximum continuous rating of engine, maximum continuous rated power output. [kW]
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MFO	Marine Fuel Oil

MGO	Marine Gas Oil
NO_X	Nitrogen Oxide
P_{AE}	Power of auxiliary engines [kW]
PM	Particulate matter
P_{ME}	Power of main engine [kW]
P_{TI} / P_{TO}	Power take-in/Power take-out. [kW]
SECA	Sulphur Emission Control Area
SEEMP	Ship Energy Efficiency Management Plan
SFC_{AE}	Specific fuel consumption for auxiliary engines as per NOx certification [g/kWh]
SFC_{ME}	Specific fuel consumption for main engines as per NOx certification
SO_X	Sulfur Oxide
V_{ref}	Reference ship speed attained at propulsion power equal to P_{ME} and under calm sea and deep-water operation at summer load line draught
f_c	Correction factor for capacity of ships with alternative cargo types that impact the deadweight-capacity relationship
f_{eff}	Correction factor for availability of each innovative energy efficiency technologies
fi	Correction factor for capacity of ships with technical/regulatory elements that influence ship capacity

f_w	Correction factor for speed reduction due to representative sea conditions
n_{ME}	Number of main engines
n_{PTI}	Number of power take-in system
n_{eff}	Number of innovative technologies

1 Introduction

The maritime industry is undergoing an energy-technology revolution, and these changes will have a greater impact on costs, asset values and earnings than previous energy-technology revolutions in the marine industry. There is growing pressure on shipowners to reduce greenhouse gas emissions from shipping. There are three main drivers of this pressure: regulations and practices, investors and access to capital, and the expectations of shippers and consumers.

One of the greatest drivers for the change is the revised 2023 International Maritime Organization Greenhouse Gas Strategy (2023 IMO GHG Strategy). The strategy aims to reduce carbon intensity from international shipping by 40% by 2030 compared to 2008 and for fuels or energy sources zero or near-zero GHG emission technologies at least 5% and striving for 10% for the energy used by 2030. For year 2050 international shipping GHG emissions reach to net zero (IMO.2023).

To meet these demands, shipowners in the maritime industry need to adopt new technologies and fuels to reduce greenhouse gas emissions from the maritime industry. Unfortunately, the availability of the necessary quantities of new fuels is still limited today, and the space requirements and costs of new fuels are generally higher. This drives the shipowners to seek new designs for the maritime ships to obtain fuel savings and lower greenhouse gas emissions while making their products more energy efficient (IMO.2023).

1.1 Topic and background

The study aims to identify current merchant ship auxiliary power system requirements in the marine industry, while considering the possible impact of new propulsion technologies on marine propulsion systems. The commissioner is The Switch Engineering Ltd.

Due to the transformation in energy and technology in the marine industry, the demand for different technologies that reduce energy efficiency or greenhouse gas emissions in the marine industry has increased. The commissioner of the thesis offers technological solutions for electric power systems in the marine industry. The commissioner's shaft generators are capable of improving the overall efficiency of marine industry ships and reducing greenhouse gas emissions (Woud, H.; Stapersma, D. 2002,107).

The aim of the thesis is to determine more precisely the applications and number of marine industry applications for commissioner's permanent magnet generator. The aim is also to determine the future trend for the number of these applications. The work examines the impact of environmental regulations on applications. The second objective of the work is to investigate the impact of technological changes in propulsion systems in the applications of shaft generators.

1.2 Research problems

The research problems in this work are summarized into two main questions:

- “*How are the number of merchant ships applications of auxiliary power 1 MW or over is likely to used present day and in the future?”*

The first objective is to determine the number of merchant ships that can use auxiliary engine power 1 MW or over at the present day. Based on this auxiliary engine power limit, different types of ships are considered, and the total number of suitable merchant ships is then calculated. The study also examines the trends of changes in the number of quantities between the years 2010-2022 of suitable merchant ship variations, the aim is to find ship types with a positive change in number of quantity trend. With this information, the commissioner will be able to better assess the existing marine industry product portfolio in relation to applications.

- "*How do the applications of an electric propulsion system and a mechanical propulsion system in the marine industry differ?"*

The second objective of the work is to determine how the applications of marine diesel-mechanical and diesel-electrical systems differ and whether the Maritime Organization Greenhouse Gas Strategy measures have a direct impact on the choice of propulsion system type.

1.3 Limitations

The research questions are approached by reviewing the relevant literature available from the public sources e.g. library and general data-base systems, such as Google scholar. Besides the above-mentioned public sources, one commercial data-source, namely IHS-database Sea-web™ demo version, was used. This selection of data sources naturally has an impact on the data available for answering the above-mentioned research questions.

The scope of the first research question is limited to the size classes of merchant ships that can use auxiliary engine power 1MW or over, while smaller ship types are excluded from the scope. Work is limited to the diesel-mechanical propulsion system. Propulsion system component costs and ship electronic circuit specifications are not included in the study.

In the second research question, the scope is limited into the potential applications diesel-electric propulsion systems and the Maritime Organization Greenhouse Gas Strategy in a literature review. Work will be limited to the general propulsion system and marine industry merchant ship variation level.

1.4 Outline of the work

Chapter 2 presents literature review sources and previous studies. Chapter 3 presents the types, intended use, and examples of the types of merchant ships introduced in the work. Preliminary ship types and size classes have been applied for on the basis of previous studies and the commissioner's reference cases. Chapter 4 sets out environmental requirements for merchant ships. The technological solutions for the selected merchant ship types are presented in Chapter 5. Chapters 6,7 and 8 describe the study methods, results, reliability of results, recommendations made on the basis of the study results, and topics for further study.

2 Literature review sources and previous studies

This chapter describes the essential parts of the sources used in the literature review and previous studies. The study also uses sources from the register database of merchant ships, merchant ship statistics and marine legislation. Literature sources were also used from marine component and system integrator suppliers including MAN, Kongsberg, Wärtsilä, We Tech Solutions and The Switch Engineering.

The book *Laivatekniikka* by Pekka Räisänen and book *Laivan yleisuunnittelu* by Jussi Alanko, provides type descriptions of merchant ship variants including intended use information and more detailed ship type specific characteristics. *Laivan yleisuunnittelu* provide estimates of the range of electrical power for different ship types, estimation values Table 1 based on SIGNIFICANT SHIPS publication. The book also shows the calculation of the electricity balance for finding out the electrical power produced by the auxiliary machines. Electricity balance is calculated for operational environments, at sea, manoeuvring, loading, discharging, anchor, and emergency. The electricity balance of the systems has been calculated:

1. auxiliary machines for propulsion
2. auxiliary machinery for ship
3. heating, ventilation, and air conditioning (HVAC)
4. galley, laundry, workshops
5. cargo, deck, and hull
6. lighting
7. navigation and radio.

Table 1. Electrical power range of different ship types (Alanko, J. 2011.).

Ship type	Electric power range (kW)
Dry cargo ship	150 - 3000
Container ship	1000 - 15000
Ro/Ro ship	800 - 3500
Bulk carrier	1100 - 3000
Oil tanker	800 - 4600
Chemical tanker	1300 - 5300

Book *Design of Propulsion and Electric Power Generation Systems* by Hans Klein Woud and Douwe Stapersma provides propulsion systems concept information and their applications. The book also provides more detailed information on the characteristics of propulsion systems including power plant concepts, electric power systems, main application types and propulsion system components. Book *New Technologies for Emission Control in Marine Diesel Engines* by Masaaki Okubo and Takuya Kuwahara also presents the classifications and characteristics of the marine main engine systems. *Marine Propellers and Propulsion* 4th edition by John Carlton describes the types of propellers and propulsors used in different types of marine ships, also *Design of Propulsion and Electric Power Generation Systems* describes propeller and propulsion solutions used in the marine industry.

A previous study *PREEDICT- EEDI power correction factors fj for ice class ships* by Mattson Tom is also used as a literature source. The study has collected the average engine power levels for the variants of merchant ships, tankers, bulk carriers, general cargo ships, container ships, Ro-Ro ships and LNG carriers. The engine power levels have been retrieved by regression analysis using the Maritime IHS database. The ship search has been limited to ships commissioned between 2000 and 2017.

The regression analysis was used to retrieve the average engine power for the ship types under open water conditions. Table 2 shows the average engine power in open water conditions in relation to deadweight tonnage (DWT).

Table 2. Regression equations on average engine power (Mattsson.T.2020).

Ship type	**Average engine power (kW)**	**Regression analyses number of ships (pcs)**
Tanker	$17{,}444 \cdot DWT^{0{,}5766}$	2594
Bulk carriers	$17{,}207 \cdot DWT^{0{,}5705}$	6692
General cargo ships	$1{,}974 \cdot DWT^{0{,}7987}$	3463
Container ships	$1{,}919 \cdot DWT^{0{,}8867}$	2594
Ro-Ro ships	$790{,}42 \cdot DWT^{0{,}3080}$	147
LNG carriers	$8{,}524 \cdot DWT^{0{,}7220}$	418

3 Scope of ships

A ship is a transport system which sails on water supported by buoyant force. There are many different types of ships suitable for different uses. The classification of ships is influenced by where the ship moves and what the ship carries. Classification methods are e.g. waterways, operation mode, construction material of the ship, the structure of the ship and the machinery of the ship. According to usage, the ships can be divided into merchant ships, special ships, yachts, and warships (Alanko, J. 2011).

Merchant ships can be categorized according to *2022 World Merchant fleet staticstics from equasis report*, Figure 1. The total number of merchant ships is approximately 126947 pcs. Figure 1 below shows how the total number of units is divided by percentage among the different merchant ship variations (EMSA.2023).

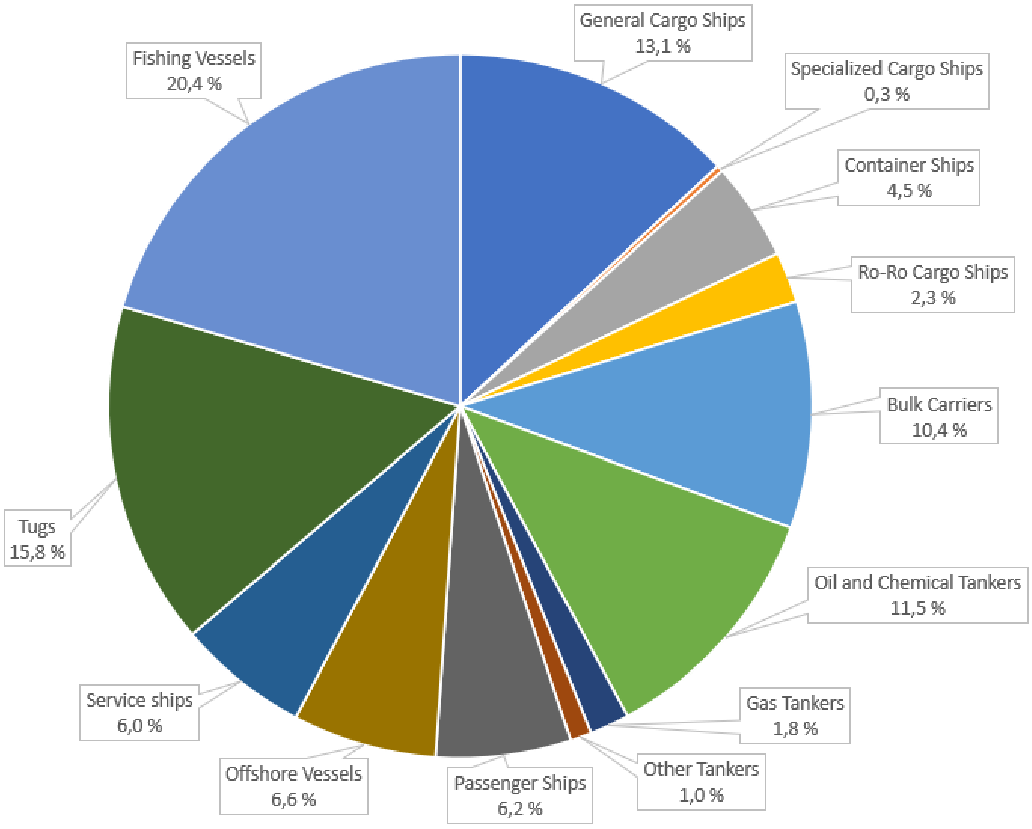


Figure 1. The world merchant fleet in 2022 (EMSA.2023).

In statistics, the Gross tonnage (GT) value is used to determine the size of merchant ships. Gross tonnage describes the total tonnage of the ship and practically includes the entire volume of the ship. According to the *International Convention on Tonnage Measurement of Ships* (ICTM*)*, 1969, there is a standardized numerical value with a logarithmic Equation 1 for the internal space of the ship. There is also no definition of a ton in the regulation, because the value per volume unit is lower on a smaller volume ship than on a larger volume ship (ICTM.1969). Gross tonnage is calculated:

$$GT = K_1 V \tag{1}$$

Where V is total volume of all enclosed spaces of the ship in cubic metres and K_1 is $0.2+0.02\log_{10}V$(ICTM.1969).

According to *2022 World Merchant fleet staticstics from equasis report*, ship types are divided into four categories by size: small GT<500, medium 500≤GT<25000, large 25000≤GT<60000 and very large GT≥60000. The size classification of the ships was used to define the work, and the work covers medium, large, and very large merchant ship sizes. The merchant ship types presented below were selected based on the commissioner's references and the previous study in Chapter 2. Data for each ship examples was obtained from the *Maritime IHS database* (EMSA.2023).

3.1 General Cargo Ships

General Cargo or multi-purpose ships may include multi-purpose and multi-deck cargo ships which do not belong to a clearly defined type of ship. General cargo ships usually have more than one deck and are capable of carrying cargo in various forms, including boxed, palletized, refrigerated, and can also receive bulk goods, including grain. The size of the ship is best described by the DWT value (Raisanen.P.2000).

According to *The world merchant fleet in 2022*, the total number of medium-sized, large and very large ships is 12469 pcs, of which 12181 pcs ships in the medium-sized class 500≤GT<25000, 288 pcs in the large class 25000≤GT<60000 and 0 in the very large class GT≥60000. The largest number of units in the medium and large general cargo ship sizes is concentrated on medium-sized ships 500≤GT<25000 (EMSA.2023).

Example, Medium size general cargo ship *"IMARI"* Picture 1, build 2012. Total length 145m, GT=14122. Main engine: 1x 2 stroke combustion engine 6480 kW. Auxiliary engine power: 3x 544 kW diesel generator set (Maritime IHS database).

Picture 1. Medium size general cargo ship "*IMARI*" (FleetMon.2022).

Second example, large size general cargo ship "*HOLLAND PEARL"* Picture 2. Build 2016. Total length 183m, GT=27460. Main engine: 1x 2 stroke combustion engine 9960 kW. Auxiliary engine power: 3x 680 kW or 860 kW diesel generator sets (Maritime IHS database).

Picture 2. Large size general cargo ship "*HOLLAND PEARL*" (FleetMon.2022).

3.2 Container Ships

Container ship focuses only on describing special ships for container transport. Goods carried on container ships are placed in a container. The most common container size is 20 feet, 6 feet (about 6,1m) in length, 8 feet (about 2,4m) in width, and 8 or 8.5 feet (about 2.6 m) in height. Also, 40 feet and between size containers are used. The size of the ship is best described by the Twenty feet Equivalent Unit (TEU). Container ships are open or with cargo hatch types (Raisanen.P.2000).

According to *The world merchant fleet in 2022*, the total number of container ship medium-sized, large and very large ships is 5717 pcs, of which 2409 pcs ships in the medium-sized class 500≤GT<25000, 1684 pcs in the large class 25000≤GT<60000 and 1624 pcs in the very large class GT≥60000. The largest number of units in the medium, large, and very large container ship sizes is concentrated on medium-sized ships 500≤GT<25000 (EMSA.2023).

Example, Medium size container ship" *A LA MARINE"* Picture 3, build 2009. Total length 170m, GT=16023. Main engine: 1x 2 stroke combustion engine 12640 kW. Auxiliary engine power: 3x1065 kW diesel generator set (Maritime IHS database).

Picture 3. Medium size container ship "*A LA MARINE*" (FleetMon.2022).

Second example, large size container ship "*OOCL BELGIUM"* Picture 4. Build 1998, total length 245m, GT=39174.

Main engine:1x 2 stroke combustion engine 24027 kW. Auxiliary engine power: 3x1580 kW diesel generator set (Maritime IHS database).

Picture 4. Large size container ship *"OOCL BELGIUM"* (FleetMon.2022).

3.3 Ro-Ro Cargo Ships

Ro-Ro cargo ships differ from other cargo ships in that the cargo is brought horizontally from the stern port of the ship. Ferry cars or road trailers with wheels are used to bring cargo. Ferry trailers or road trailers remain on board after transport. In large Ro-Ro ships, the cargo is usually container cargo, which is brought onto the ship horizontally by forklifts or locks and loaded directly onto the deck of the ship (Raisanen.P.2000).

According to *The world merchant fleet in 2022*, the total number of Ro-Ro cargo ship medium-sized, large and very large ships is 1941 pcs, of which 1111 pcs ships in the medium-sized class 500≤GT<25000, 553 pcs in the large class 25000≤GT<60000 and 277 pcs in the very large class GT≥60000. The largest number of units in the medium, large, and very large Ro-Ro cargo ship sizes is concentrated on medium-sized vessels 500≤GT<25000(EMSA.2023).

Example, Medium size Ro-Ro cargo ship” *BLUE CARRIER 1”* Picture 5, build 2000. Total length 142m, GT=4650. Main engines: 2x 4 stroke combustion engines 10740 kW. Auxiliary engine power: 2x1250 kW generators and 2x754 kW generators (Maritime IHS database).

Picture 5. Medium size Ro-Ro cargo ship "*BLUE CARRIER 1*" (FleetMon.2022).

Second example, large size Ro-Ro cargo ship *"BORE SONG"* Picture 6. Build 2011, total length 195m, GT=25586. Main engine: 1x 4 stroke combustion engine 12000 kW. Auxiliary engine power: 2x 1270 kW diesel engines and one shaft generator 3750 kW (Maritime IHS database).

Picture 6. Large size Ro-Ro cargo ship *"BORE SONG"* (FleetMon.2022).

3.4 Bulk Carriers

Bulk carriers carry solid bulk goods. Loading is done by means of grapples connected to cranes or continuous belt loaders. The cranes can be either in port or on board. The most important cargoes are ores and other minerals and their concentrates, cereals, coal, fertilisers, cement, and wood chips. The size of the ship is best described by the DWT value (Raisanen.P.2000).

According to *The world merchant fleet in 2022*, the total number of Bulk Carrier medium-sized, large and very large ships is 12941 pcs, of which 3901 pcs ships in the medium-sized class 500≤GT<25000, 7103 pcs in the large class 25000≤GT<60000 and 1937 pcs in the very large class GT≥60000. The largest number of units in the medium, large, and very large bulk carrier sizes is concentrated on large ships 25000≤GT<60000 (EMSA.2023).

Example, Medium size Bulk carrier” *NH ELIF”* Picture 7, build 2009. Total length 160m, GT=14909. Main engine: 1x 2 stroke combustion engine 5180 kW. Auxiliary engine power: 3x 440 kW diesel generator set (Maritime IHS database).

Picture 7. Medium Bulk carrier "*NH ELIF*" (FleetMon.2022).

Second example, large size Bulk carrier *“ALANYA-M”* Picture 8. Build 2004, total length 186m, GT=25065. Main engine: 1x 2 stroke combustion engine 8340 kW. Auxiliary engine power: 3x 4 stroke diesel engine each 563 kW and 3x diesel generator sets each 674 kW (Maritime IHS database).

Picture 8. Large size Bulk carrier *"ALANYA-M"* (FleetMon.2022).

3.5 Oil and Chemical Tankers

Tanker ships, as a rule, transport oil industry products. The most essential characteristics of the cargo are density, flash point, boiling point/pour point, transport temperature, cooling/heating need, viscosity, fire safety aspects and hazards to the environment and humans. Tankers can be roughly divided into crude oil tankers, oil tankers, product tankers, chemical tankers, LPG (liquified petroleum gas) tankers and LNG (liquefied natural gas) tankers (Raisanen.P.2000).

According to *The world merchant fleet in 2022*, the total number of Oil and Chemical Tankers medium-sized, large and very large ships is 12631 pcs, of which 7513 pcs ships in the medium-sized class 500≤GT<25000, 2827 pcs in the large class 25000≤GT<60000 and 2291 pcs in the very large class GT≥60000. The largest number of units in the medium, large, and very large Oil and Chemical Tankers ship sizes is concentrated on medium size ships 500≤GT<25000 (Raisanen.P.2000).

Example, Medium size Oil and Chemical Tanker" OTTOMANA*"* Picture 9, build 2006. Total length 169m, GT=18034. Main engine: 1x 2 stroke combustion engine 7650 kW. Auxiliary engine power: 3x970kW diesel generator set (Maritime IHS database).

Picture 9 Medium size Oil and Chemical Tanker "*OTTOMANA*" (FleetMon.2022).

Second example, large size Oil and Chemical Tanker *“HULDA MAERSK”* Picture 10. Build 2010, total length 180m, GT=25723. Main engine: 1x 2 stroke combustion engine 9480 kW. Auxiliary engine power: 3x910 kW diesel generator set (Maritime IHS database).

Picture 10. Large size Oil and Chemical Tanker "*HULDA MAERSK*" (FleetMon.2022).

3.6 Gas Tankers

Gas tankers transport the liquefied gases. As a rule, these ships are of two different styles, LPG (liquified petroleum gas) tankers and LNG (liquefied natural gas) tankers. These ships are complex in structure because gases require low temperature and high pressure for transportation. LPG ships carry e.g. propane, butane, etc. LNG tankers carry methane and ethane, among others (Raisanen.P.2000).

According to *The world merchant fleet in 2022*, the total number of Gas Tankers medium-sized, large and very large ships is 2276 pcs, of which 1182 pcs ships in the medium-sized class 500≤GT<25000, 475 pcs in the large class 25000≤GT<60000 and 619 pcs in the very large class GT≥60000. The largest number of units in the medium, large, and very large Oil and Chemical Tankers ship sizes is concentrated on medium size ships 500≤GT<25000 (EMSA.2023).

Example, Large size Gas Tanker” CORAL *NORDIC”* Picture 11, build 2022. Total length 177m, GT=26234. Main engine: Dual-Fuel engine 1x 4 stroke combustion engine 7800 kW. Auxiliary engine power: 2x1123 kW diesel generator set (Maritime IHS database).

Picture 11. Large size Gas Tanker "*CORAL NORDIC*" (FleetMon.2022).

4 Marine legislation governing engine emissions

The International Convention for the Prevention of Pollution from Ships (MARPOL) contains standards for emissions from ships in the maritime industry, regulated by the UN's International Maritime Organization (IMO). The limits for NOx and sulphur in marine engines and fuels are defined in MARPOL Annex VI: Regulations for the Prevention of Air Pollution from Ships. Compliance is monitored through periodic inspections and surveys by flag states, port states and global control (TransportPolicy.net. 2018).

The IMO emission standards specification is commonly known as Tier. The 1997 version of MARPOL Annex VI defines Tier 1 standards. The 2008 update of Annex VI defines Tier 2 and 3 emission standards. The Engine International Air Pollution Prevention (EIAPP) certification program controls NOx emissions from diesel engines and also the specific requirements of the 2008 Code technical regulations 13.8 and 5.3.2. An emission limit is set for NOx from a diesel engine based on the rated nominal speed (TransportPolicy.net. 2018).

By optimising the combustion reaction of a diesel engine, Tier 2 requirements can be achieved. Combustion response optimisation is used to modify the timing of fuel injection by changing the flow area of the fuel injector in relation to the timing of the exhaust valve in relation to the cylinder compression volume. NOx emissions are controlled by exhaust gas recirculation or selective catalytic reduction to meet Tier 3 requirements (TransportPolicy.net. 2018).

The Sulphur Emission Control Area (SECA) affects ships to have multiple fuels on board. When a ships enters the SECA area, it must switch to low sulphur fuel. Changes in fuel use must be recorded in the logbook, with a record of the change, when the change was made and the amount of fuel used. In SECA areas, an exhaust gas cleaning system may also be used. These systems remove sulphur from the exhaust gas to a level that is compatible with emission control area (ECA) regulations (TransportPolicy.net. 2018).

4.1 Reduction of GHG emissions from ships

To ensure the energy efficiency of ships in the maritime industry, *MARPOL Annex VI, Chapter 4 Regulations on energy efficiency for ships*, published in 2011, set out 2 mandatory methods.

1. Energy Efficiency Design Index EEDI.
2. Ship Energy Efficiency Management Plan (SEEMP).

The application of the regulations applies to all ships with a total capacity of more than 400GT, these regulations have entered into force in 2013. However, there was flexibility in the regulations six and a half years after their introduction. Derogations were made, in particular for ships under construction during the entry into service. In 2018, the IMO's original strategy to reduce greenhouse gas emissions from ships was outlined with the following emission reduction targets:

- Reduce the carbon intensity of international shipping by at least 40% by 2030, compared to 2008 carbon intensity.
- Reducing the carbon intensity of international shipping by 70% by 2050, compared to the carbon intensity in 2008.
- Reaching the peak of greenhouse gas emissions from international shipping as quickly as possible and achieving a 50% cumulative reduction by 2050, compared to 2008. At the same time, the aim is to eliminate greenhouse gas emissions in line with the temperature targets of the Paris Agreement.

The strategy also determined possible short, medium and long-term plans to reach the objectives. Appendix 1 presents the strategy plans.

Revised 2023 IMO GHG strategy aims to keep carbon intensity of international shipping goal by at least 40% 2030 compared to 2008. Take in use zero or near-zero GHG emissions technologies fuels and energy sources at least 5% and striving for 10% of the energy used by 2030. Reach net zero GHG emissions from international shipping around year 2050 (DNV.2024).

4.2 Energy efficiency design index

Energy efficiency design index (EEDI) The mechanism is based on the performance of the ship. This mechanism requires new ships to meet a certain minimum energy efficiency. Ships design stage, it is possible choose the energy efficiency technologies that meet the EEDI requirements for a given ship design.

4.2.1 EEDI regulation

MEPC.308(73) 2018 Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships.

The EEDI regulations apply to new ships of 400 GT or more and also to ships that have undergone major changes. The EEDI achieved must be equal to or less than the required EEDI, according to Equation 2 (IMOrules.2024).

$$attained\ EEDI\ \leq required\ EEDI \tag{2}$$

The refencing line for the different ship types is used in the calculation of the required EEDI, according to equation 3. The reference line definitions for the different ship types can be found in MEPC.231(65) and MEPC.233(65). The reduction is taken into account according to Regulation 4 of Chapter VI of Annex VI to the MARPOL Convention (IMOrules.2024).

$$required\ EEDI = \left(1 - \frac{x}{100}\right) \times reference\ line\ value \tag{3}$$

In Equation 3, *x* is a reduction factor to gradually tighten the EEDI setting over time by increasing the value. The shipping regulation’s goal is to reduce CO_2 emissions by improving energy efficiency. The regulations also aim to encourage innovative implementations to improve energy efficiency, related to the construction of new ships (IMO.2018).

4.2.2 Attained EEDI

The EEDI achieved by new ships measure the energy efficiency of a ship and the unit of measurement is CO_2/ton-mile, below simplified Equations 4 and 5 (IMO.2018).

$$EEDI = \frac{CO_2\ emissions}{transport\ work} \tag{4}$$

$$EEDI = \frac{Engine\ power\ \times\ SFC \times C_F}{DWT\ \times\ speed} \tag{5}$$

In Equation 5, fuel consumption *SFC* per engine, units of g/kWh. In Equation 5, C_F is the non-mean conversion factor between fuel consumption (unit of measure g) and CO_2 emissions based on the carbon content of the fuel. C_F values for different fuels are shown in Table 3. The full EEDI calculation equation is shown in Picture 12 (IMO.2018).

Table 3. Fuels lower calorific, carbon content and emission factors values (IMO.2018).

Type of fuel		Lower calorific value (MJ/kg)	Carbon content	CF (g_{CO2}/g_{fuel})
Diesel / Gas oil		42,700	0,8744	3,206
Light Fuel Oil (LFO)		41,200	0,8594	3,151
Heavy Fuel Oil (HFO)		40,200	0,8493	3,114
Liquefied Petroleum Gas (LPG)	Propane	46,300	0,8182	3,000
	Butane	45,700	0,8264	3,030
Liquefied Natural Gas (LNG)		48,000	0,7500	2,750
Methanol		19,900	0,3750	1,375
Ethanol		26,800	0,5217	1,913

$$\frac{\overbrace{\left(\prod_{j=1}^{n} f\right)_j \left(\sum_{i=1}^{nME} P_{ME} \cdot C_{FME_{(i)}} \cdot SFC_{ME\,(i)}\right)}^{\text{Main engine}} + \overbrace{\left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}\right)}^{\text{Auxiliary engine}} + \overbrace{\left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI\,(i)} - \sum_{i=1}^{neff} f_{eff\,(i)} \cdot P_{AE\,eff_{(i)}}\right) C_{FAE} \cdot SFC_{AE}\right)}^{\text{Shaft generators/motors}} - \overbrace{\left(\sum_{i=1}^{neff} f_{eff\,(i)} \cdot P_{eff\,(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}^{\text{Innovative energy efficiency power generation}}}{\underbrace{f_i \cdot f_e \cdot f_l \cdot f_w}_{\text{Correction factors}} \cdot Capacity \cdot V_{ref}}$$

Picture 12. Full EEDI calculation equation (IMO.2018).

Equation 6 determines the total propulsion power:

$$\sum MCR_{ME(i)} + \frac{\sum P_{PTI(i)}}{0{,}75} \tag{6}$$

The need for auxiliary engine power is calculated for normal maximum sea load conditions, the auxiliary power is supplied to systems such as propulsion machinery/ systems and accommodation, for example the pumps of the main machinery, navigation systems and devices and living on board. Auxiliary power is not calculated for propulsion system equipment/systems such as thrusters, cargo pumps, cargo gear, ballast pumps, maintaining cargo, for example reefers and cargo hold fans (IMO.2018).

For ships with a total propulsion power of 10000 kW or more, the auxiliary engine power P_{AE} is defined by Equation 7 (IMO.2018).

$$P_{AE} = \left(0{,}025 \times \left(\sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI(i)}}{0{,}75}\right)\right) + 250 \tag{7}$$

For ships with a total propulsion power of less than 10000 kW, the auxiliary engine power P_{AE} is defined in Equation 8 (IMO.2018).

$$P_{AE} = \left(0{,}05 \times \left(\sum_{i=1}^{nME} MCR_{ME(i)} + \frac{\sum_{i=1}^{nPTI} P_{PTI(i)}}{0{,}75}\right)\right) \tag{8}$$

4.2.3 Reference line

The reference lines for the EEDI for different ship types depending on size are specified in MEPC.231(65) and MEPC.233(65). MEPC.231(65) is applicable to gas carrier, container ship, bulk carrier, general cargo ship, tanker, refrigeranted cargo carrier, Ro-Ro cargo ship, LNG carrier, Ro-Ro cargo ship for vehicle and Ro-Ro passenger ship. MEPC.233(65) is applicable to cruise passenger ships with unconventional propulsion systems. It should also be noted that the calculation method for the reference line is only published for cruise ships with non-conventional propulsion systems.

Reference line is more like curve showing the average index value as a function of ship size, fitted to the EEDI values of the separately assessed groups of ships. Those in the groups were submitted between 1 January 1999 and 1 January 2010. The estimated index values (EEDI values) for the defined ship groups are calculated using Equation 9, excluding container ships and Ro-Ro cargo ships.

$$Estimated\ Index\ value = 3{,}1144 \times \frac{190 \times \sum_{i=1}^{n} P_{MEi} + 215 \times P_{AE}}{Capacity \times V_{ref}} \tag{9}$$

Capacity is replaced in container ships by 70% of DWT. For Ro-Ro ships, Equation 9 is multiplied by an additional factor f_{jRoRo} or f_{RoRov} Ro-Ro vehicle carrier. For Ro-Ro passenger ships, equation 9 is multiplied by $f_{j\ RoRo}$ and divided by f_{cRoPax}. LNG tankers are affected by whether the ship is dual fuel diesel-electronic, direct diesel or steam turbine, the equations for the different propulsion types can be found in Annex 2 of MEPC.231(65).

The reference line value for ships covering MEPC.231(65) is calculated using Equation 10 (IMOrules.2024).

$$Reference\ line\ value = a \times (100\%DWT)^{-C} \tag{10}$$

Equation 10 *a* and *c* present values get it from the regression curve. Passenger ships with non-conventional propulsion systems reference line is calculated according to equation 11 (IMOrules.2024).

$$Reference\ line\ value = 170{,}84 \times b^{-0{,}214} \tag{11}$$

Value *b* present GT of the ship.

4.3 Required EEDI

Each ship type reference line create base of the required EEDI. In Equation 3 showed reduction factor x reduces required EEDI. Different ship type reduction factors are in three stages, according to Table 4.

Table 4. Different ship type reduction factors (IMOrules.2024).

Ship Type	**Size**	**Phase 0 1 Jan 2013-31 Dec 2014**	**Phase 1 1 Jan 2015-31 Dec 2019**	**Phase 2 1 Jan 2020-31 Dec 2024**	**Phase 3 1 Jan 2025 and onwards**
Bulk carrier	20000 DWT and above	0	10	20	30
	10000 - 20000 DWT	n/a	0-10*	0-20*	0-30*
Gas carrier	10000 DWT and above	0	10	20	30
	2000 - 10000 DWT	n/a	0-10*	0-20*	0-30*
Tanker	20000 DWT and above	0	10	20	30
	4000 - 20000 DWT	n/a	0-10*	0-20*	0-30*
Container ship	15000 DWT and above	0	10	20	30
	10000 - 15000 DWT	n/a	0-10*	0-20*	0-30*
General Cargo ships	15000 DWT and above	0	10	15	30
	3000 - 15000 DWT	n/a	0-10*	0-15*	0-30*
Refrigerated cargo carrier	5000 DWT and above	0	10	15	30
	3000 - 5000 DWT	n/a	0-10*	0-15*	0-30*
Combination carrier	20000 DWT and above	0	10	20	30
	4000 - 20000 DWT	n/a	0-10*	0-20*	0-30*
LNG carrier***	10000 DWT and above	n/a	10**	20	30
Ro-ro cargo ship (vehicle carrier)***	10000 DWT and above	n/a	5**	15	30
Ro-ro cargo ship***	2000 DWT and above	n/a	5**	20	30
	1000 - 2000 DWT	n/a	0-5***	0-20*	0-30*
Ro-ro passenger ship***	1000 DWT and above	n/a	5**	20	30
	250 - 1000 DWT	n/a	0-5***	0-20*	0-30*
Cruise passenger ship*** having non-conventional propulsion	85000 GT and above	n/a	5**	20	30
	25000 - 85000 GT	n/a	0-5**	0-20*	0-30*

* Reduction factor to be linearly interpolated between the two values dependent upon ship size. The lower value of the reduction factor is to be applied to the smaller ship size (IMOrules.2024).

** Phase 1 commences for those ships on 1 September 2015 (IMOrules.2024).

*** Reduction factor applies to those ships delivered on or after 1 September 2019, as defined in paragraph 2.1 of regulation 2 (IMOrules.2024).

4.4 Ship energy efficiency management plan

The Ship energy efficiency management plan (SEEMP) method focuses improve cost-effective way to ship energy efficiency. Ship owner can example use the Energy Efficiency Operational Indicator (EEOI) monitoring system. System helps owners and operators plan better voyage route and more precise scheduled propeller cleaning to get more efficiency ship operations (TransportPolicy.net. 2018).

4.5 Energy efficiency existing ship index

Energy efficiency existing ship index (EEXI) applies to all ships. EEDI and EEXI are both technical measures, but EEDI applies only new ships. Ships must obtain EEXI approval once in their lifetime by 2023 at the latest. The EEXI value is compared to the EEXI value required for the type and size of the ship. Required EEXI value is function of ship speed and engine power. A ship that cannot achieve EEXI requirements need to limit the engine power, it is also possible to install retrofit applications that improve energy efficiency, e.g. wind-assisted propulsion (TransportPolicy.net. 2018).

4.6 Carbon intensity indicator

The carbon intensity indicator (CII) measures the annual greenhouse gas emissions per deadweight tonne and per nautical mile travelled. The CII is responsible for the classification of a ship between A and E, where A is the best and C is the minimum compliance threshold. The use of energy efficiency technologies will be promoted by the CII, which will become more stringent by 2030. Ships with three consecutive years of D or E class must be designed to bring the ship into compliance. The SEEMP system will allow CII to be checked. For A and B class ships, the IMO encourages the provision of incentives to promote the reduction of emissions and fuel consumption of ships. (TransportPolicy.net. 2018).

4.7 Technologies and operations strategies

In 2011, The International Council on Clean Transportation (ICCT) collaborated on an extensive study that recognize 53 different types of ships to which efficiency technologies can be applied. The study estimated that 22 existing technological developments could be implemented now or in the near future. Table 5 below groups the methods into 15 general categories.

Table 5. Technologies and strategies that reduce marine industry's greenhouse gas emissions (TransportPolicy.net. 2018).

Propeller polishing	Hull cleaning	Speed reduction
Autopilot upgrade	Air lubrication	Main engine retrofits
Water flow optimization	Hull coating	Speed controlled pumps and fans
Weather routing	Wind power	High-efficiency lighting
Propeller upgrade	Waste heat reduction	Solar panels

In the IMO's Fourth Greenhouse Gas Study, emission reduction cost curves were derived by taking into account additional reduction technologies. The technologies were divided into four broad categories: renewable energy, energy conservation, alternative fuels and speed reduction. Table 6 below shows the selected reduction technologies.

Table 6. Reduction technologies (TransportPolicy.net. 2018).

	Gr. no.	Abatement technologies and use of alternative fuels and renewable energy
(1) Energy-saving technologies	Group 1 main engine improvements	Main engine tuning Common-rail Electronic engine control
	Group 2 auxiliary systems	Frequency converters Speed control of pumps and fans
	Group 3 steam plant improvements	Steam plant operations improvements
	Group 4 waste heat recovery	Waste heat recovery Exhaust gas boilers on auxiliary engines
	Group 5 propeller improvements	Propeller-rudder upgrade Propeller upgrade (nozzle, tip winglet) Propeller boss cap fins Contra-rotating propeller
	Group 6 propeller maintenance	Propeller performance monitoring Propeller polishing
	Group 7 air lubrication	Air lubrication
	Group 8 hull coating	Low-friction hull coating
	Group 9 hull maintenance	Hull performance monitoring Hull brushingHull hydro-blasting Dry-dock full blast
	Group 10 optimization of water flow hull openings	Optimization of water flow hull openings
	Group 11 super light ship	Super light ship
(2) Use of renewable energy	Group 12 reduced auxiliary power demand	Reduced auxiliary power demand (low energy lighting etc.)
	Group 13 wind power	Towing kite Wind power (fixed sails or wings) Wind engine (Flettner rotor)
	Group 14 solar panels	Solar panels
(3) Use of alternative fuels	Group 15A use of alternative fuels with carbon	LNG + ICE or FC Methanol + ICE Ethanol + ICE
	Group 15B use of alternative fuels without carbon	Hydrogen + ICE or FC Ammonia + ICE or FC Synthetic methane + ICE or FC Biomass methane + ICE or FC Synthetic methanol + ICE Biomass methanol + ICE Synthetic ethanol + ICE Biomass ethanol + ICE
(4) Speed reduction	Group 16 speed reduction	Speed reduction by 10%

5 Concept of propulsion power system

The propulsion system is one of the most important systems on board a ship in the marine industry. The propulsion system provides the thrust for the movement and manoeuvrability of the ship. Propulsion system power plant concepts can be roughly divided into two categories mechanical concept and electrical concept. The propulsion system of a mechanical power plant can be divided into three main components prime mover, transmission and propulsor. The following chapters present the characteristic features of these main components. Electrical concept applications can be found in cruise ships, icebreakers, ferries, shuttle tankers, chemical carriers, and research ships (Wärsilä.2024).

5.1 Mechanical power plant concept

The mechanical power plant concept can be divided into two main categories according to transmission, direct drive and indirect drive. Direct drive transmission is a shaft system between the prime mover and the propeller, keeping the rotational speeds of the prime mover and the propeller the same. In a direct drive system, a low-speed diesel engine is used as the prime mover. The indirect drive system uses a reduction gear between the prime mover and the propeller. Because of the reduction gearing, the prime mover may have a higher rotational speed than the propeller. Indirect drive applications usually use a medium-speed and high-speed diesel engine. The gearbox is also used to connect two prime movers (Woud, H.; Stapersma).

5.2 Prime movers

The main purpose of a prime mover is to provide mechanical energy to the propulsion system. The prime mover converts the chemical energy of the fuel into mechanical energy. As a rule, diesel engines are used in merchant ships due to their low fuel consumption compared to other prime movers. A common classification of diesel engines used in the marine industry is their speed range (Woud, H.; Stapersma).

The rotational speed ranges are divided into low-speed, medium-speed and high-speed diesel engines. In merchant ship applications, low and medium speed diesel engines are used. Medium-speed diesel engines are also used in so-called genset systems, in which the medium-speed diesel engine acts as a diesel generator to produce, for example, the electrical power required for auxiliary equipment (Woud, H.; Stapersma).

5.2.1 Low-speed diesel engines

In low-speed marine diesel engines, the crankshaft speed is usually below 300 rpm. Low-speed marine diesel engines are 2-stroke engines, and these have been identified as economical and readily readable primary movers for large merchant and cargo ships. Other examples of applications include oil tankers, cargo ships and bulk carriers. The design of the low-speed 2-stroke marine diesel engine is considered simple due to the low number of components. Due to the simple design, the engines are larger compared to medium speed and high-speed marine diesel engines. Low-speed 2-stroke diesel engines used HFO and MFO as fuel. (Okubo, M.; Kuwahara, T. 2020, 16).

5.2.2 Medium-speed diesel engines

On medium-speed marine diesel engines, the crankshaft speed is usually between 300 and 1000 rpm. The crankshaft of a medium-speed marine diesel engine operates mostly with a 4-stroke cycle. Applications include ferries, Ro-Ro ships, passenger ships and medium sized cargo ships. Due to the higher speed of the crankshaft, a reduction gear is required between the engine and the propeller. As fuel 4-stroke medium speed diesel engine use MDO, MGO, MFO or HFO fuels (Okubo, M.; Kuwahara, T. 2020, 16).

5.3 Transmission

In the more common mechanical power plant concept of merchant ships, the power transmission can be classified as direct whereby the primary mover is directly coupled to the propeller. In a geared solution, a reduction gear is used to optimize the rotational speeds of the primary mover and propeller. The purpose of the reduction gear is to reduce the speed of the propeller shaft in order to obtain a larger propeller and thus better efficiency, however the addition of gearing also results in additional costs (Woud, H.; Stapersma).

5.4 Propulsor

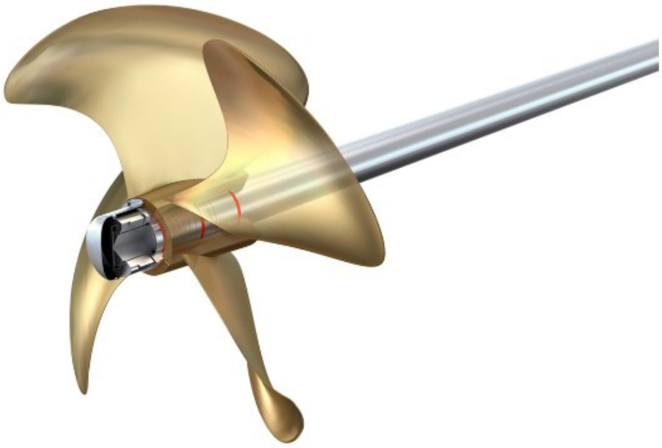
By far the most common propeller solutions for merchant ships are Fixed Pitch Propellers (FPP) and Controllable Pitch Propellers (CPP). These propeller solutions are described in more detail in the sections below. It is also good to mention Podded and Azimuthing propulsors. The main difference between Podded and Azimuth propellers is found in the location of the motor that drives the propeller. If the engine is located in the hull then it is an Azimuth propeller, these are mechanically driven by either a Z or L propeller shaft arrangement. Usually, the vertical and horizontal shafts are connected by a rotating gear system. In the case of a Podded propeller, the propeller system includes an electric motor directly connected to the propeller shaft (Carlton, J. 2019, 16).

5.4.1 Fixed pitch propellers

The fixed pitch propeller (FPP) has for many years be the basis of propeller production, either in one piece or assembled from several pieces. Most common type of propeller today single piece, the so-called monobloc propeller. A "built-up" propeller assembled from several pieces has individually casted bolt fixed blades, this type of construction is rarely used for low markets. However, this has not always been the case, in the early years of the last century built-up propellers were very common, the reason being that at that time it was not possible to produce large, good quality castings. Another thing that also drove the manufacture of separate blades was the determination of the correct blade angle at that time. With the separate bolt-on pallets it was relatively easy to adjust the angle of the blades. Despite the advantages, built-up propellers assembled from several parts also have a larger blade mounting point on the propeller hub. This can cause cavitation problems in the root area of the wing and limit the efficiency of the propeller (Carlton, J. 2019, 11).

One-piece monoblock propellers cover a wide range of design types and sizes. Examples include propellers weighing a few kilograms, which can be found in small motorboats, as well as those used in specialised vessels such as container ships. In these container ships the propeller can weigh up to 100 tonnes and require considerably more metal than a single ladle to produce the casting. Materials used in the manufacture of propellers vary considerably depending on size and model. For larger propellers, over 300 mm in diameter, the materials used are mostly non-ferrous.

High-alloy brass-manganese alloys, including nickel-aluminium bronzes, are the most popular material types, with nickel-aluminium bronze consumption being higher. Stainless steel has also seen limited use in the niche market, with cast iron material used in the past to make spare propellers, but now virtually disappearing. Polymers, aluminium, nylon, and carbon fibre composites are also used in smaller propellers. These materials offer new opportunities, in the design of hydro elastic propeller blades, to improve propeller performance in terms of both efficiency and cavitation performance. Picture 13 shows Kongsberg FPP model (Carlton, J. 2019, 11-12).



Picture 13. Kongsberg maritime Fixed pitch propeller (Kongsberg. 2023).

5.4.2 Controllable pitch propellers

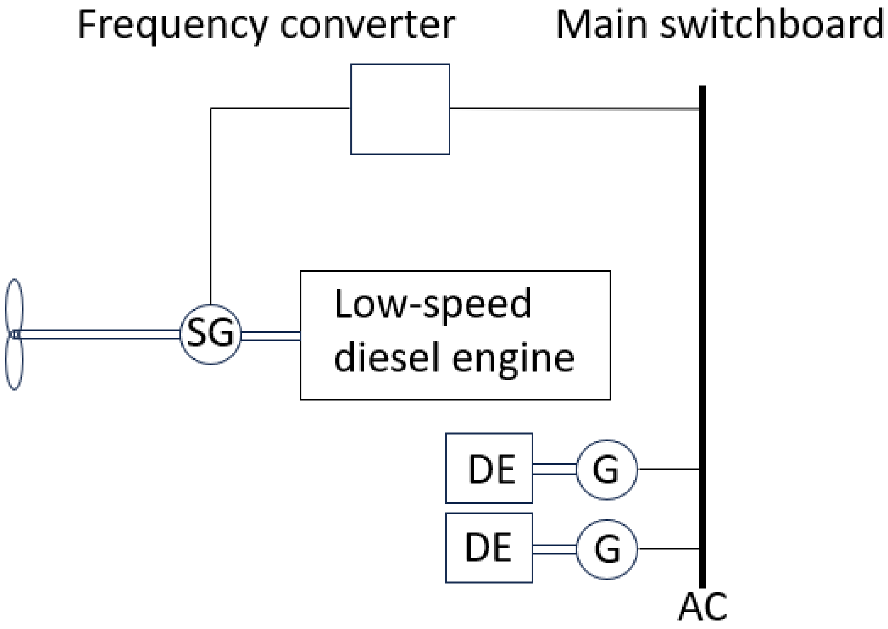
The controllable pitch propeller (CPP), Picture 14, is able to change the pitch of the propeller blades. This brings variation freedom compared to fixed pitch propellers. However, in some propulsion applications using propeller shaft driven generators, these are designed to keep the shaft speed constant, reducing the number of variable features from the dual number of propeller speed and blade pitch to one again. The above approach is convenient for power generation but can also cause problems with the cavitation characteristics of the propeller under different propulsion conditions (Carlton, J. 2019, 19-20).

Since the 1950s, the demand for controllable pitch propellers has grown to its current position of a significant market share. Today, the market share of controllable pitch propellers is about 35% compared to fixed pitch propeller systems. Applications where this application is seen are on board ferries, general cargo, tugs, and trawlers. One advantage of a controllable pitch propeller is manoeuvrability. Propulsion control can be achieved by adjusting the pitch of the propeller blade, this also allows other operational changes in the steering to be adjusted so that the propulsion system does not need to be accelerated or decelerated. This can also achieve the precision control of thrust required in situations where the vessel experiences multiple repeated moorings, for example in short distance ferry traffic (Carlton, J. 2019, 19-20).

Picture 14. Controllable pitch propeller (Anish. 2019).

6 Electric power system

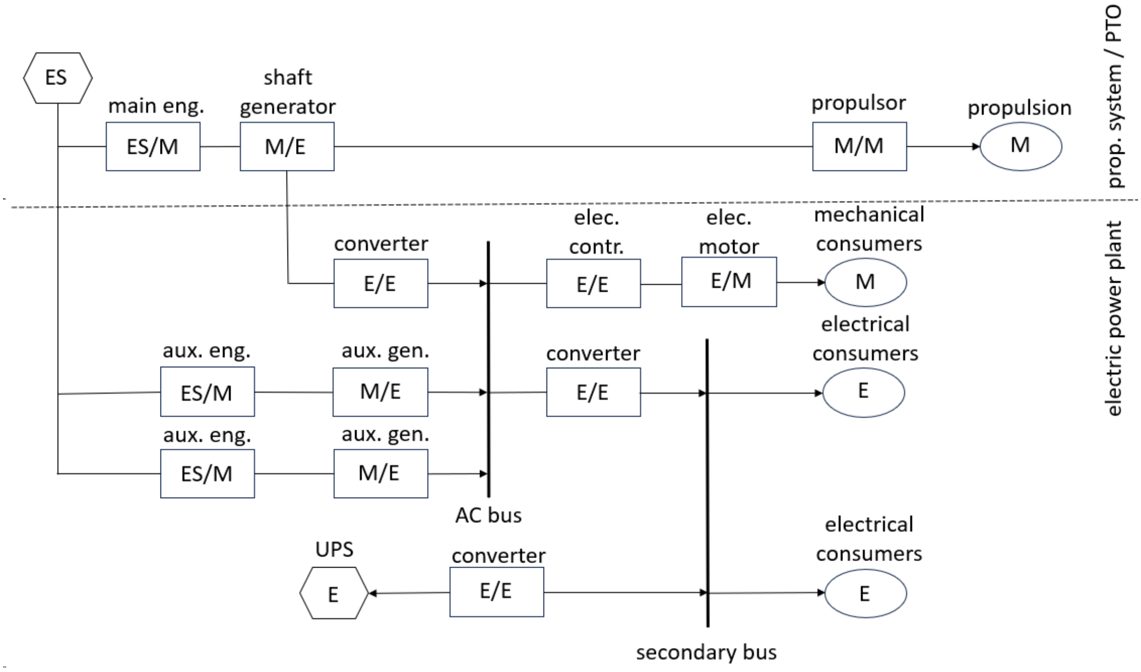
The electric power system produces the auxiliary power needed for the ship, among other things, for the prime mover auxiliary systems, the ship's auxiliary systems, ventilation, lighting, navigation, and cargo. The electricity production of merchant ships is affected by the ships' operating environments and mission. The most common operating environments of merchant ships are at sea, manoeuvering, loading, discharging, at anchor and emergency. The direct drive power plant concept of merchant ships usually includes an FPP or CPP propeller connected directly via the shaft system for low-speed diesel engine, diesel generator sets and shaft generators as auxiliary machinery. Picture 15 below shows a conventional direct drive power plant concept (Woud, H.; Stapersma, D. 2002,106).



Picture 15. Simplified direct drive electrical power system.

6.1 Auxiliary power in direct drive power plant concept

The electrical power system includes auxiliary machinery and generators. The link between the propulsion system and the electric power system can be connected to the main propulsion shaft system via a shaft generator power take out (PTO). The shaft generator can be installed in the propulsion system through the gearbox or directly on the main shaft line. The auxiliary power system, which is part of the power system package, operates in an autonomous system, except for the additional input from the shaft generator. Where some functions of the electrical power system are vital, energy storage in the form of electric batteries provides an uninterrupted power supply (UPS). Picture 16 shows a mechanical direct drive energy flow diagram (EFD) (Woud, H.; Stapersma, D. 2002,105).



Picture 16. EFD of mechanical direct drive with shaft generator PTO.

In the diagram, ES stands for energy source, M for mechanical energy and E for electrical energy. In the direct drive power plant concept, electricity generation is usually carried out by diesel generator sets and shaft generators. The shaft generator with frequency converter covers partly the power generation needs in an at sea environment with various sailing speeds and ship can use example slow steaming method which reduce fuel consumption and carbon emissions. Considering variable sailing speed and direct operation the FPP, shaft generator produces a potentially variable voltage, therefore the voltage must be converted before connection to the grid using converters. (Woud, H.; Stapersma, D. 2002,106).

A major decrease in the rotational speed of the main drive can also make it difficult to maintain the nominal power of the shaft generator, in which case the generator sets provide the electrical power. Generator sets should be at least two pieces due to the redundancy requirement. A shaft generator is not installed for redundancy but to improve overall efficiency and to achieve lower carbon emissions and operating costs (Woud, H.; Stapersma, D. 2002,107).

6.2 Marine shaft generators

Shaft generators for the merchant ships can be used in either PTO, PTI or PTH mode, depending on the purpose of the application. In PTO mode, the shaft generator operates in generator mode to generate electricity for auxiliary systems. In PTI mode, the electric generator is used as an electric motor to boost the main engine. PTH mode present state that you can use shaft generator as electric motor and main engine is decoupled from the shaft line. PTH mode is usually used smaller hybrid propulsion systems (MAN.2021).

It is possible to install the shaft generator either on the propeller side of the main engine (aft-end) or on the front side of the main engine (front-end). Mounted on the front side of the main engine can be mount directly to the main engine or on the tank top. Shaft generator can be roughly divided into direct driveshaft driven or gearbox driven. The main difference between the two is the rotational speeds; shaft generators directly coupled to the main drive shaft generally have rotational speeds in the 0-200 rpm range, while gearbox driven shaft generators have much higher rotational speeds (MAN.2021).

Shaft generators connected directly to the drive shaft of the main drive are generally suitable for slow speed marine diesel engines due to the speed limitation, while shaft generators connected through the gearbox are generally suitable for slow and medium speed marine diesel main drives. Shown below is the The Switch Engineering Oy permanent magnet shaft generator Picture 17, directly connected to the main drive shaft, typically used in 4-12 MW slow speed direct drive power plant concept (The Switch Engineering.2023).

Picture 17. PMM2000M shaft generator (The Switch Engineering.2023).

7 Merchant ships with over 1MW auxiliary power

The purpose of this chapter is to identify the number of ships in the maritime industry for the commissioner's shaft generator applications. The commissioner's direct drive permanent magnet shaft generators are suitable for applications using a direct drive mechanical power plant concept including a low speed 2-stroke diesel engine. Based on previous studies, references of commissioner's and technological suitability, the study was limited to marine variants for merchant cargo ships in the marine industry.

The effect of the auxiliary power limitation on the amount of total propulsion power can be determined from the maritime regulations regarding emissions from the maritime industry. The total propulsion power value is used to search for the applicable size classifications of merchant ships variations. Based on this, aim is to get an overall picture of the number of applicable merchant ships variations in relation to the total number of merchant ships.

7.1 Study method

The study uses a quantitative product research method. In study are used calculation equations of existing regulations, the number of ships from *World Merchant fleet statistics from equasis report* and the ship registry *Maritime IHS database*, *Sea-Web*™ for the applicable parameters of the ships. The research method is used to find out the percentage share of the applicable ship types from the total number of units selected and the trends in the number of units of the applicable ship types.

For the auxiliary engine power *MEPC.308(73) 2018 Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships* regulation instructions was used. Auxiliary engine power Equations 7 and 8 was used to determine the required maximum continuous rating of the total propulsion power MCR_{ME} for 1 MW of auxiliary engine power. After the calculation, the data of actual ships of the selected ship types and medium, large, very large size classes are retrieved by extraction, based on the Maritime IHS database data. The search results are used to determine the appropriate size class limits for the selected merchant ship types. The next step is to compare the number of units of each ship type and size class obtained as a proportion of the merchant ships total number.

The study also aims to investigate the trend in the amount of the selected ships size classes and types. For the analysis of the trends in ships amount, 12 years of ships quantity data will be selected according to the *World Merchant fleet statistics from equasis report*. A linear trend of the change in numbers of selected merchant ship types and size classes was investigated.

7.2 Data for research

To answer the first research question, the data used in the study is divided into four categories. The first category is the calculation equations, the calculation Equations 7 and 8 used in the study are the equations used to determine the auxiliary engine power of *MEPC.308(73) 2018 Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for new ships* (IMO.2018)*.*

As reference for calculation is used in the year 2021 *Procedure for calculation and verification of the Energy Efficiency Design Index (EEDI)* published in the year 2021 by Nippon Kaiji Kyokai ship classification society (ClassNK.2021).

The second category is the *Maritime IHS database* used to retrieve ship parameters for the selected merchant ship types, more specifically the *Sea-web*™ application demo version was used to retrieve individual ship capacity and main engine power parameters. The search parameters used were the merchant ship types and size categories as described in Chapter 3 (Maritime IHS database. Sea-web™).

The third category is the number of merchant ships according to *The world merchant fleet - statistics from Equasis* reports generated by the European

Maritime Safety Agency (EMSA) for the period 2010-2022. The search data limitation is the merchant ship types and size categories presented in Chapter 3. (EMSA.2023).

In the fourth category, a comparison is made between the ship types that are applicable based on study and the commissioner’s reference ship types. The reference data was obtained from the WE Tech solutions reference website (WE Tech Solutions.2023).

A literature review for the second research question based on *The International Council on Clean Transportation* (ICCT) year 2011 published *Reducing Greenhouse Gas Emissions from Ships* report (icct.2011), *International Maritime Organization's Fourth Greenhouse Gas Study* published year 2020 report and the literature source *Design of Propulsion and Electric Power Generation Systems* (Woud, H.; Stapersma, D. 2002).

7.3 Calculation for the total propulsion power limit

The auxiliary engine power requirements can be estimated by three different methods using empirical formulas, electrical load analyses and simulation. Empirical auxiliary engine power calculation Equation 7 and 8 of the EEDI regulations are used in the study. According to the EEDI regulations, the auxiliary engine power can be determined as a certain fraction of the total propulsion power MCR_{ME}.

The purpose is to cover the normal auxiliary engine power requirements under maximum sea load conditions for propulsion and marine systems, excluding thrusters, cargo pumps, cargo gear, ballast pumps, maintaining cargo reefers and cargo hold fans. The calculation applies for total propulsion power limit with an auxiliary engine power 1 MW or more limitation.

The first step in the calculation is to use Equation 8 to determine whether a total propulsion power MCR_{ME} of less than 10000 kW could meet the need for 1000 kW or more of auxiliary engine power.

$$P_{AE} = (0{,}05 \times 9999\ kW\ ) = 499{,}95\ kW \qquad (12)$$

PTI mode was not taken into account in Equation 12. According to Equation 12, 9999 kW total propulsion with MCR_{ME} power gives 499,95 kW of auxiliary engine power. This result is not sufficient for auxiliary engine power limitation 1000 kW or more. Next, Equation 7 was used to determine the amount of auxiliary engine power for a total propulsion power of 10000 kW or more.

$$P_{AE} = (0{,}025 \times 30000\ kW\ ) + 250 = 1000\ kW \qquad (13)$$

PTI mode was not taken into account in Equation 13. The calculation showed that the lowest total propulsion MCR_{ME} power according to the Equation 13 is 30000 kW, this gives a P_{AE} auxiliary engine power requirement of 1000 kW. However, it should be remembered that the actual need for auxiliary power depends on the type of ship. For example, refrigerated containers on a container ship consume a lot of energy. Based on the calculation model a linear graph, see Figure 2 present the EEDI auxiliary engine power requirement, without PTI compared total propulsion power MCR_{ME} values.

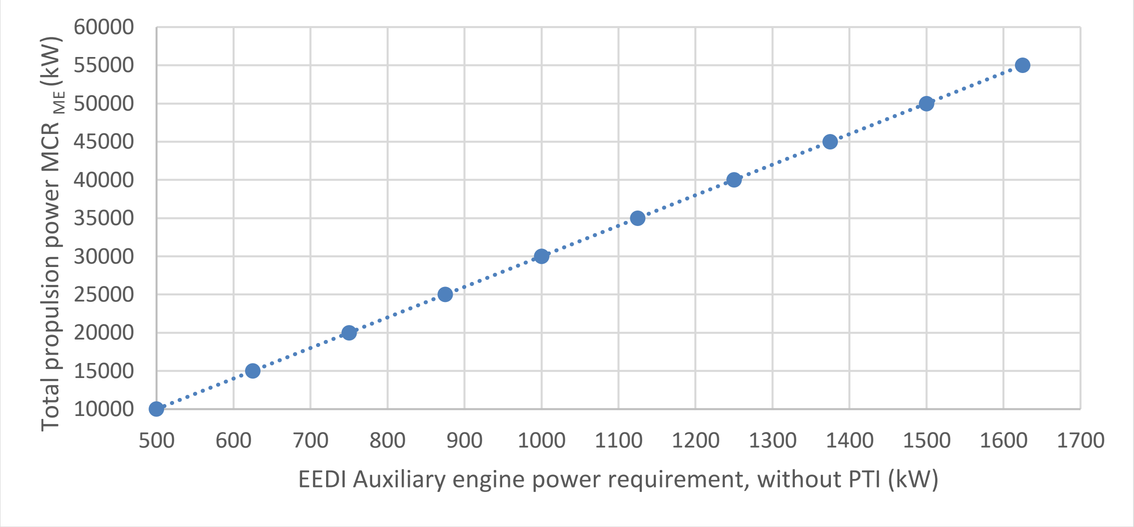


Figure 2. EEDI Auxiliary engine power in relation to total propulsion power.

7.4 Ship types and size classes

The total propulsion power MCR_{ME} limit was calculated using the EEDI regulation auxiliary engine power calculation Equation 7 and 8. The estimation of the number of ships in service for the selected ship types started by searching for ship size classes with a total propulsion power MCR_{ME} of 30000kW or more.

The determination of size classes was done by selecting individual ships with gross tonnage (GT) values close to the limits of the size class, *2022 World Merchant fleet statistics from equasis report Small GT<500, Medium 500≤GT<25000, Large 25000≤GT<60000 and Very Large GT≥60000.* The search for suitable ship size classes started with the medium size class. During the search, it was found that medium-sized ships does not fulfil the 30000kW total propulsion power MCR_{ME} requirement according to Table 7.

Next ships in the large size category to investigated. Table 7 below shows the ships used in the search. Based on the selections below, it can be concluded that in the Large 25000≤GT<60000 size class, container ships are only ship type with a total propulsion MCR_{ME} power exceeding 30000 kW.

Table 7. Selected large size merchant ships.

	Large, 25000≤GT<60000					
	Large, GT near 25000			**Large, GT near 60000**		
	Power MCR_{ME} (kW)	**GT**	**IMO number**	**Power MCR_{ME} (kW)**	**GT**	**IMO number**
General cargo	9960	27460	9742455	9450	46295	9574858
Container ships	21368	25294	9203526	51390	55487	9416991
Ro-Ro Cargo Ships	12000	25586	9443566	22890	51055	9547219
Bulk Carrier	8340	25065	9158159	10300	54486	9643881
Oil and Chemical tankers	9480	25723	9399363	13530	59486	9299111
Gas tankers	7800	26234	9919890	17626	49288	9193721

Next is to look for ships in the very large size category. Table 8 below shows the ships used in the search. Based on the selections below, it can conclude that the very large GT≥60000 size category is container ships and gas tankers with the potential to reach 30000 kW total propulsion MCR_{ME} power.

Table 8. Selected very large size merchant ships.

Very large, GT ≥ 60000						
	Very large, near 60000			Very large		
	Power MCR_{ME} (kW)	GT	IMO number	Power MCR_{ME} (kW)	GT	IMO number
General cargo	-	-	-	-	-	-
Container ships	42140	61870	9480198	61530	232618	9839454
Ro-Ro Cargo Ships	25560	60515	9856854	21060	74273	9789233
Bulk Carrier	13560	64877	9431173	22000	107511	9736729
Oil and Chemical tankers	13736	61303	9379612	27160	160133	9313149
Gas tankers	29052	95753	9321770	47600	115408	9870159

According to Table 7 and 8 large ship size variations only container ships exceeded the calculated 30000 kW total propulsion MCR_{ME} power limit. In the very large ships class, gas tankers and container ships exceeded the 30000kW total propulsion MCR_{ME} power limit.

7.5 The share of selected ship types

This chapter compares the proportion of suitable ship size classes of the selected medium, large and very large ship types of total numbers. The total number of medium, large, and very large container ships in relation to the selected large and very large size categories is shown in Figure 3.

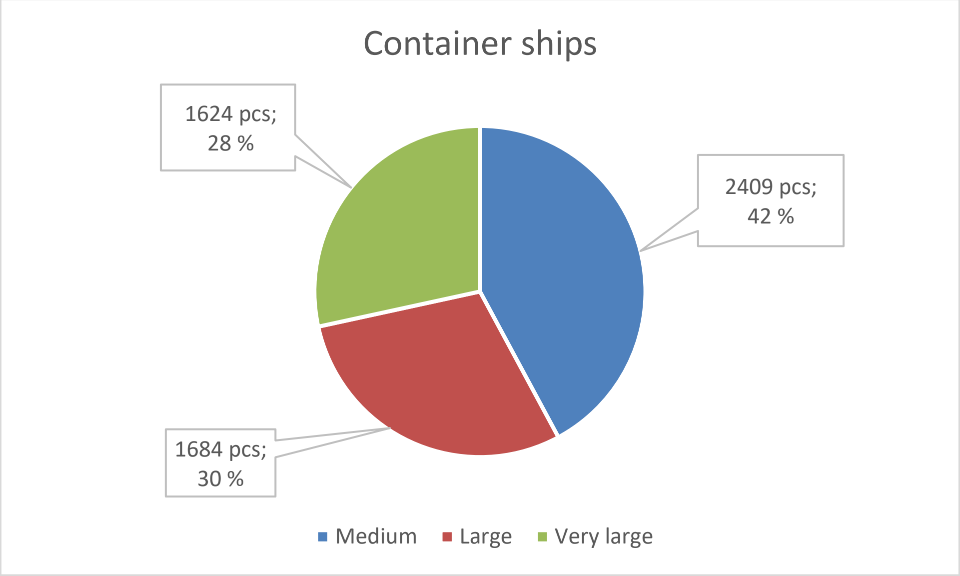


Figure 3. Number of units of medium-sized, large, and very large container ships.

Of the total number of medium, large, and very large container ships, 5717 pcs, the selected size categories large and very large cover 58% (3308 pcs). The largest single share of 42% (2409 pcs) is in the medium size class. The total number of gas tankers medium, large, and very large in relation to the selected very large size class is shown in Figure 4.

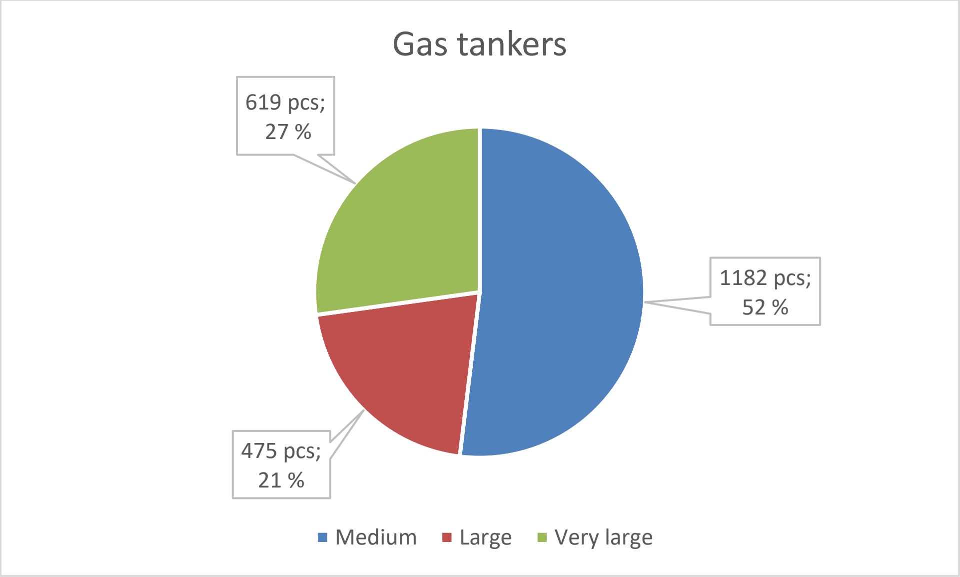


Figure 4. Number of units of medium-sized, large, and very large gas tankers.

Gas tankers medium, large, and very large out of a total of 2276 pcs, the selected size category very large covers 27% (619 pcs). The largest single share of 52% (1182 pcs) is in the medium size class.

7.6 Trends in numbers of selected ship types

This chapter shows the changes in the number of units of the selected ship types and size categories shown in Tables 7 and 8 for the period 2010-2022. Figure 5 shows the changes in the number of units of Oil and Chemical Tankers medium, large and very large size classes.

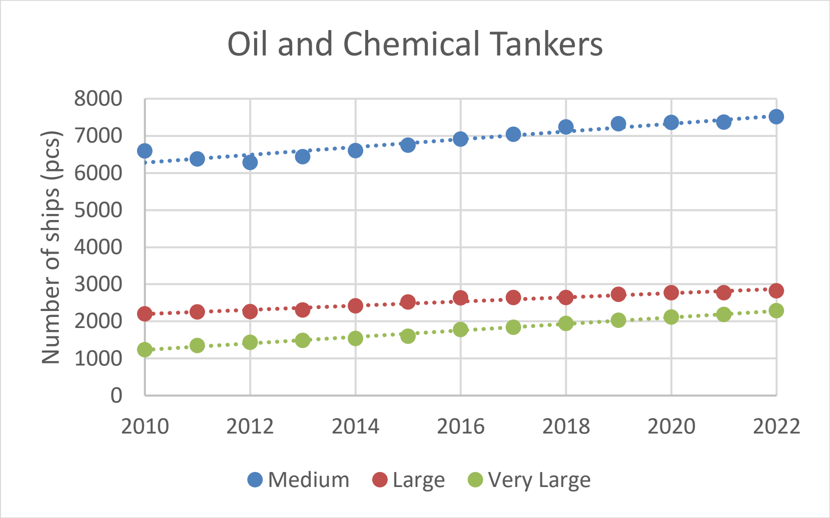


Figure 5. Changes in the number of oil and chemical tankers during the years 2010-2022.

Oil Chemical Tankers medium, large and very large volumes show a growth trend all sizes classes. The medium size category shows a growth of 13,9% (918 pcs) between 2010 and 2022, the large size category 28,2% (622 pcs) and the very large 85,1% (1053 pcs). Figure 6 below shows the changes in the number of units for the Bulk Carriers medium, large, and very large ship size classes between 2010 and 2022.

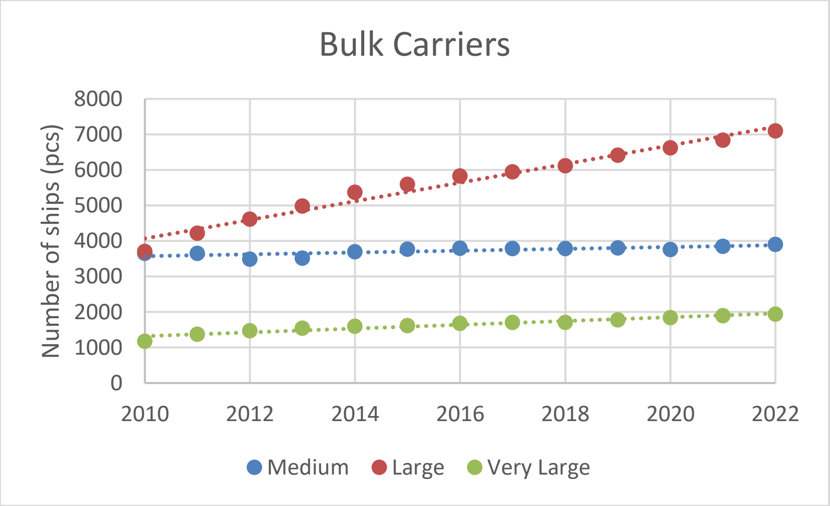


Figure 6. Changes in the number of bulk carriers during the years 2010-2022.

The most positive trend in the number of units for Bulk Carriers is in the large size category. The medium size class will see a 6,9% (251 pcs) increase between 2010 and 2022, the large size class 91,9% (3401 pcs) increase and the very large 65,0% (763 pcs) increase. Figure 7 below shows the changes in the number of pieces for the general cargo medium and large ship size classes between 2010 and 2022. Based on statistics, there are no very large ships in the general cargo ship type.

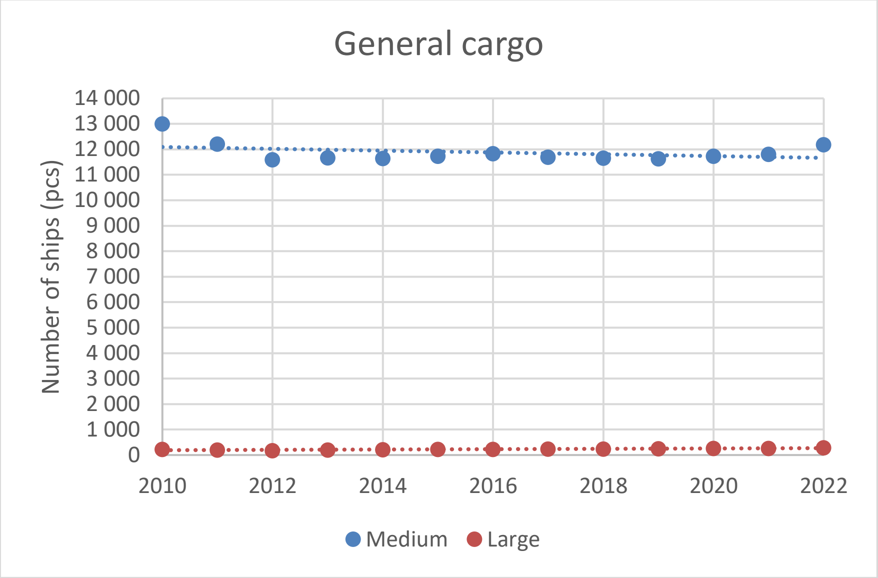


Figure 7. Changes in the number of general cargo ships during the years 2010-2022.

There are considerably more general cargo ships in the medium size category than other cargo ships. In the medium size category, the change in the number of units between 2010 and 2022 was negative – 0,3% (-8 pcs), while in the large size category it was positive 26,3% (60 pcs). Figure 8 below shows the changes in the number of pieces for the container ships medium, large and very large ship size classes between years 2010 and 2022.

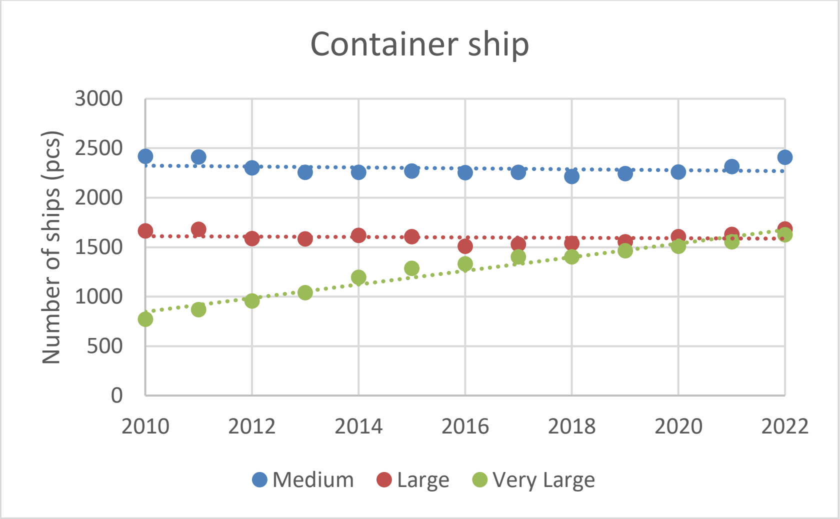


Figure 8. Changes in the number of container ships during the years 2010-2022.

The largest growth trend is in the very large size category of container ships. The medium size class will see – 0,3% (-8 pcs) decrease between 2010 and 2022, the large size class increase is 1,3% (21 pcs) and the very large 110,4% (852 pcs). Figure 9 below shows the changes in the number of ships for the Ro-Ro cargo ships medium, large and very large ship size classes between years 2010 and 2022.

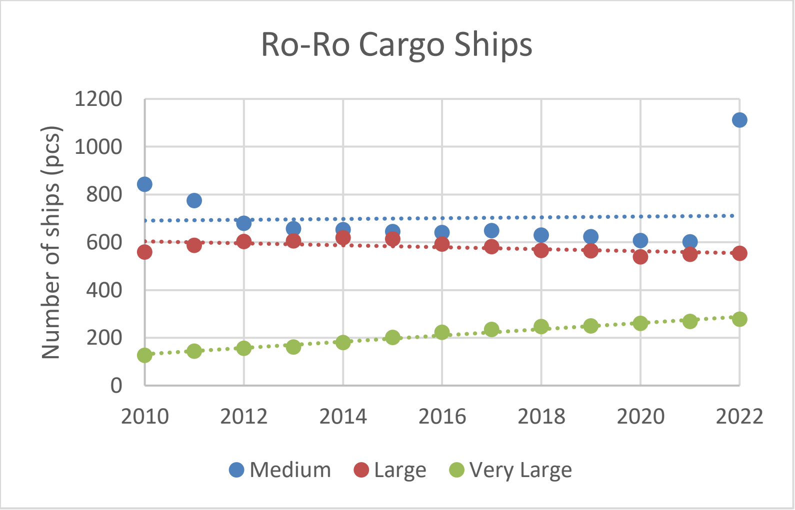


Figure 9. Changes in the number of Ro-Ro cargo ships during the years 2010-2022.

The most positive trend in unit growth for Ro-Ro Cargo ships is in the very large size category. The medium size class will see 31,8% (268 pcs) increase between 2010 and 2022, the large size class decrease -1,1% (-6 pcs) and the very large increase 119,8% (151 pcs). Figure 10 below shows the changes in the number of ships for the gas tankers medium, large, and very large ship size classes between years 2010 and 2022.

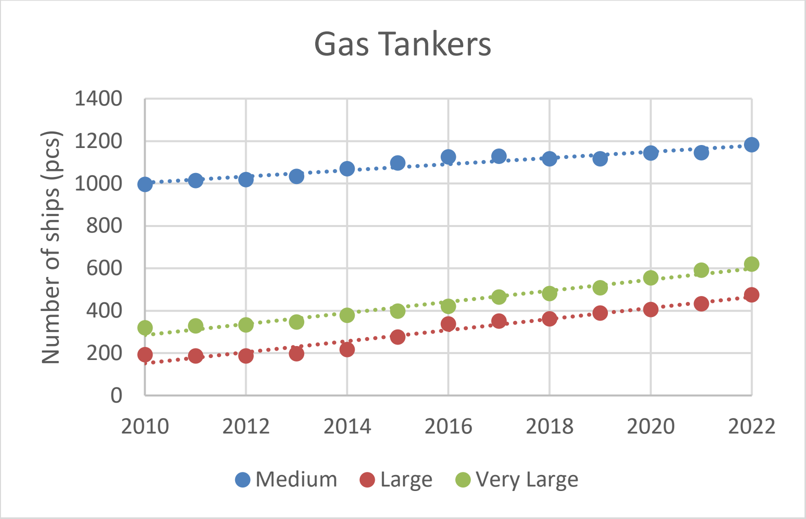


Figure 10. Changes in the number of gas tankers during the years 2010-2022.

The growth trends in the number of gas tankers are found in all size classes. The medium size class will see 18,8% (187 pcs) increase between 2010 and 2022, the large size class increase 147,4% (283 pcs) and the very large increase 94,0% (300 pcs).

8 Results

The first step was to investigate possible marine industry ship types with the possibility of using 1MW auxiliary engine power and the commissioner shaft generators. The study found that the propulsion system for the potential applications should include a mechanical power plant with direct drive 2-stroke diesel main engine propulsion system. The 1MW auxiliary engine power limitation imposed a ship size limitation for medium, large, and very large ships.

The impact of an auxiliary engine power limitation of 1000kW or more on the total propulsion power was investigated using the auxiliary engine power equations of the marine legislation governing engine emission EEDI rules. First, an Equation 8 was tested to calculate the auxiliary engine power for total propulsion power below 10000 kW. The calculation did not take into account the additional power provided by the PTI mode. The result of the first calculation, 499,95 kW was less than 1000kW. Next, it was tested Equation 7 to calculate the auxiliary engine power of a total propulsion power equal to or higher than 10000kW. By iterating the test, 1000kW auxiliary engine power, the total propulsion power MCR_{ME} result was 30000 kW.

With a total propulsion power MCR_{ME} of 30000kW, suitable merchant ship types and sizes were investigated. The search resulted in container ships and gas tankers, with container ships size category large and very large. Gas tankers in the size category very large. Suitable container ships represent 57,7% (3308 pcs) of the total number of container ships in 2022, according to Figure 11.

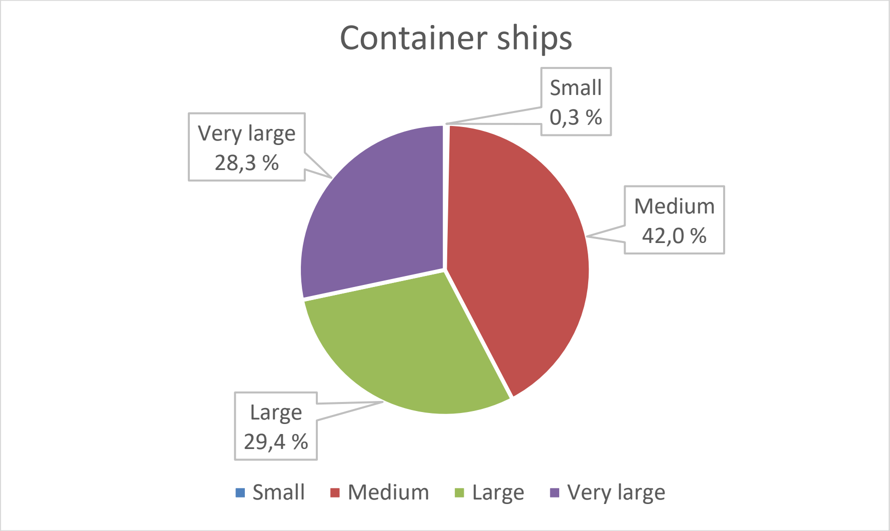


Figure 11. Number of container ships by size category.

Suitable gas tankers very large size category represents 26,8% (619 pcs) of the total number of gas tankers in 2022, according to Figure 12.

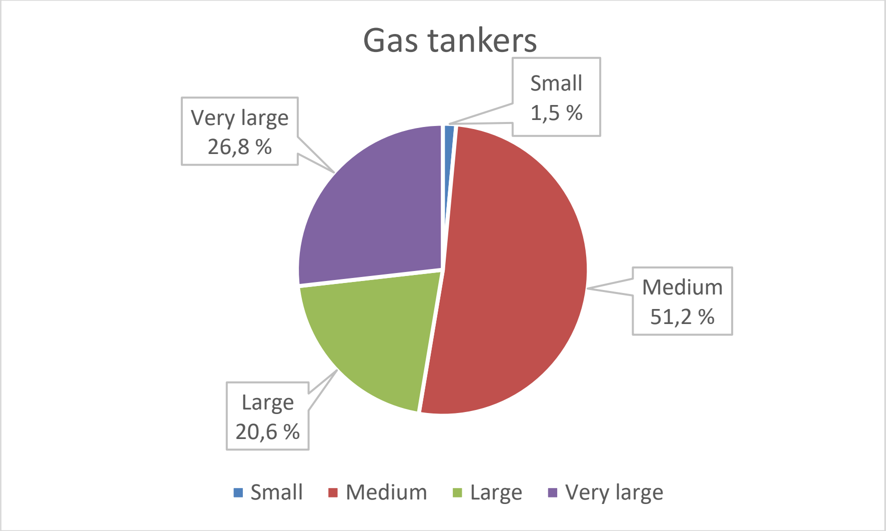


Figure 12. Number of gas tankers by size category.

The number of suitable merchant ships (3927 pcs) as a percentage of the total number of merchant ships in 2022 (126947 pcs) is 3,1%. The increase in the number of container ships between years 2010 and 2022 is 1,3% (21 pcs) in the large size category and 110,4% (852 pcs) in the very large size category. The increase in the number of gas tankers between years 2010 and 2022 in the very large category is 94% (300 pcs).

The second research question was to determine the differences in the applications of diesel-electric propulsion compared to diesel-mechanical propulsion. Diesel-electric propulsion systems are used in passenger ships, icebreakers, ferries, research ships. Diesel-electric propulsion systems are also found in smaller chemical and tanker ships. Reasons for this can be lower noise and reduced vibration levels, lower emissions, more flexibility to generate auxiliary energy and highly redundant design possibilities. The study also examined the IMO's plan for reducing greenhouse gas emissions through technological measures, do not contain direct measures for diesel-electric propulsion or diesel-mechanical propulsion selection.

8.1 Trustworthiness of the results

This chapter discusses the reliability of the results of the study. The analysis of reliability is divided into four parts. The first part examines the suitability of the EEDI auxiliary engine power equations. In the second part, the deviations of the total propulsion power of the selected ships from the results of previous studies are examined. The third part examines the reliability of the 2022 statistics on the number of merchant ships in the present day. The fourth part examines the relationship between the reference ship types of the commissioner and the ship types identified in the study.

The EEDI auxiliary propulsion power limit used in the total propulsion power limit definition, Equation 7 and 8 take into account the normal maximum sea load conditions for auxiliary propulsion machinery/ systems and accommodation such as main propulsion pumps, navigation systems and equipment and on-board accommodation. Auxiliary power is not considered for propulsion machinery/systems such as thrusters, cargo pumps, cargo gear, ballast pumps, maintaining cargo such as reefers and cargo hold fans. The EEDI Equations 7 and 8 also do not take into account the redundancy requirement for auxiliary engine power.

However, taking into account the operation of the shaft generator under the condition at sea, when the ship is sailing at normal speed. The shaft generator is also not intended to achieve redundancy in the operation of the ship, but to improve overall efficiency and achieve lower carbon dioxide emissions and operating costs. The shaft generator and the EEDI calculation equation match in terms of condition and operating characteristics.

Tables 9 and 10 below show a comparison of total propulsion power using the DWT and average engine power ratio equations derived from the regression analysis of the study presented in Chapter 2. The ship numbers of the average engine power equations derived from the regression analysis are presented in Table 2.

Table 9. Comparison between regression analyses average engine power and installed ship propulsion power for large ships.

Ship type	Actual ship DWT (t)	Regression average engine power (kW)	Installed ship propulsion power MCR_{ME} (kW)	Deviation between installed and average engine power	IMO number
Tanker	37959	7622	9480	20 %	9399363
Bulk carriers	41327	7401	8340	11 %	9158159
General cargo ships	45224	10318	9960	3 %	9742455
Container ships	32391	19163	21368	10 %	9535187
Ro-Ro ships	13375	14749	12000	19 %	9443566
LNG carriers	17233	9757	7800	20 %	9919890

The average of the deviation between installed total propulsion power of the large ships shown in Table 9 and the calculated average engine power is 14%. For very large ships shown in Table 10, the average of the deviation between the actual total propulsion power and the calculated average engine power is 10%.

Table 10. Comparison between regression analyses average engine power and installed ship propulsion power for very large ships.

Ship type	Actual ship DWT (t)	Regression average engine power (kW)	Installed ship propulsion MCR_{ME} (kW)	Deviation between actual and average engine power	IMO number
Tanker	115878	14506	13736	5 %	9379612
Bulk carriers	119376	13555	13560	0 %	9431173
General cargo ships	-	-	-	-	-
Container ships	74375	40047	42140	5 %	9480198
Ro-Ro ships	17309	15968	25560	38 %	9856854
LNG carriers	79006	29292	29052	1 %	9321770

The reliability of the statistics on the number of merchant ships in year 2022 was examined in terms of the time taken to build very large a merchant ship. For example, very large container ships take approximately 2,5 years to build. Based on this information, the year 2022 merchant ship statistics can be used in year 2024 (Nektarios, A.; Konstantinos, D.2023).

The results of the study obtained for the merchant ship types have a 50% correspondence with the reference ship types of the commissioner, according to Table 11. It should be noted here, however, that the results obtained for container ships and gas tankers presents for the largest proportion of the ship quantity commissioner references. The study also does not know whether all the reference ships of the commissioner have an auxiliary engine power requirement of 1MW or more.

Table 11. Comparison between commissioner reference merchant ship types and ship types obtained in the study.

	Commissioner references	**Selected ship types**
General cargo	No	No
Container ships	Yes	Yes
Ro-Ro Cargo Ships	Yes	No
Bulk Carrier	Yes	No
Oil and Chemical tankers	Yes	No
Gas tankers	Yes	Yes

8.2 Implications

Based on the research, the commissioner’s technology is suitable for a merchant ship type using a mechanical power plant concept direct drive propulsion system. The auxiliary power limitation of 1MW or more limits the applications to container ships and gas tankers. In the container ship size categories, large and very large ships are suitable. For gas tankers, very large ships are suitable.

Between years 2010 and 2022, the growth in the number of large container ships was 1,3% and 110,4% for very large ships. The increase in the number of very large gas tankers was 94,0% between 2010 and 2022. IMO's plan for reducing greenhouse gas emissions through technological measures, do not contain direct measures for diesel-electric propulsion or diesel-mechanical propulsion selection. No potential applications for a diesel-electric propulsion system were found among the first research question suitable ship types.

9 Discussion

The first research question of the thesis was to determine the variations of merchant ships suitable for auxiliary engine power of 1 MW or more today and in the future. The study is challenging due to the number of variations in type and size of merchant ships and the wide range of propulsion system technologies in use. However, it is necessary to identify more precisely the current and potential new applications of the commissioner’s shaft generators.

The first research question was addressed by starting with a literature review based on previous studies and the commissioner’s reference cases. The narrowing down of the use cases was also refined using the most compatible power plant concepts. Next, the 1MW or more auxiliary power limitation was considered. For this study, the EEDI determination of auxiliary engine power equations were used to determine the total propulsion power required for the 1MW auxiliary engine power requirement. The total propulsion power was used to identify the ship types and size classes of the selected merchant ship types that had a total propulsion power of the limit value obtained in the calculation.

The total propulsion power limit value was used to determine applicable large and very large size classes for container ships and large size class for gas tankers. Based on previous results, it was possible to retrieve year 2022 numbers for the large and very large container ship sizes from the Merchant Shipping Register database. Similarly, it was possible to retrieve the year 2022 numbers for the very large size ships for gas tankers. Based on the register database, the work identified the 12-year trends change in numbers for the selected merchant ship types. Finally, a comparison was made between the commissioner’s reference ship types and the suitable ship types identified in the study.

The second research question was to find out the differences between the applications of the diesel electric propulsion system and the diesel mechanical. The second research question used diesel-electric propulsion system component suppliers' pages as a source. From the component supplier's website, it was possible to get ship types for which the component suppliers had previous references. The survey also included a literature review of the applications of diesel electric propulsion systems. The applications of the diesel mechanical propulsion system were clarified in the explanation of the first research question. The work also investigated the effects of IMO's plan for reducing greenhouse gas emissions on propulsion systems.

9.1 Practical applications

As a result of the work, a requirement for the IMO number of the merchant ships is added to the commissioner’s documentation. In the future, this will enable more detailed information applications of shaft generators. With this information, it is also possible to specify the requirements of the applications for the commissioner’s shaft generator products.

As a result of the work, the commissioner’s also gets a more detailed picture of the current applications of shaft generators on merchant ships in the maritime industry and their share in the number of units of the entire merchant ship fleet in the maritime industry. With this information, the commissioner’s sales can better target potential sales targets. The work result also provides information on merchant ship types and size classes have the largest numbers. This information can be used when planning the strategy of the product family.

9.2 Recommendations

Based on the results of the work, it is recommended to reduce the 1MW auxiliary engine power limit to 0,75 MW. With this change, the number of suitable applications can be increased from 3,1% (3927 pcs) to 7,1% (8985 pcs). With this change, the ship types and size classes shown in Table 12 can be achieved.

Table 12. Merchant ship type and capacity classes with proposed 0,75 MW auxiliary engine power.

	Large	**Very Large**
Container ships	Yes	Yes
Ro-Ro Cargo Ships	Yes	Yes
Bulk Carrier	No	Yes
Oil and Chemical tankers	No	Yes
Gas tankers	No	Yes

The second recommendation is for the commissioner to acquire a licence for the world's largest application for the maritime industry, the IHS database Sea-web™. The database contains 180000 ships, over 200000 maritime industry company documents including shipowners, managers, operators, and shipbuilders. Through this it is possible to obtain information on propulsion systems of existing ships, total propulsion power, main operating points, amount of installed auxiliary power. This can be used to retrieve statistical information on existing ships for the above parameters. The price of the licence in 2023 was around 4700€/year.

9.3 Further work

A further study would be useful to determine the need for auxiliary power for the installed shaft generator. This information could be obtained from the ships machinery automation control system. Market study for a 0,75MW shaft generator can be carried out in the future. In new technology side a further study would be useful to rim drive propulsion system, here it would be interesting to investigate the applicability of the commissioner's technological know-how to this propulsor system. This would also enable the product portfolio to grow into diesel-electric propulsion system products.

10 Conclusions

The first research question investigated the applications of the commissioner's shaft generators in the marine industry. The study took into account technological feasibility, maritime legislation on emissions from the marine industry and the major databases in the marine industry. The technological study focused on the suitability of the power plant concept. The study identified a direct drive mechanical power plant concept, including a low-speed 2-stroke diesel main drive, as the most suitable power plant concept. Suitable technological applications are set in the merchant ship cargo variations, this result was also confirmed by previous comparative studies and previous reference cases of the commissioner.

The work was limited to applications where the auxiliary engine power requirement is 1 MW or more. The impact of the auxiliary engine power limitation on the total propulsion power was clarified by the EEDI provisions of the maritime legislation on emissions from the marine industry. The auxiliary engine power calculation equation presented in the EEDI regulations enabled the 30MW total propulsion power requirement for the 1MW auxiliary engine power limitation for merchant ship cargo variants to be determined. Based on the total propulsion power requirement, the study narrowed down the suitable merchant ship types to container ships and gas tankers. The suitable capacity categories for container ship are large (overall capacity $25000 \leq GT < 60000$) and very large (overall capacity $GT \geq 60000$). The appropriate size category for gas tankers is very large.

Based on the 2022 statistics, there are 3927 pcs suitable merchant ships. 3,1% of the total number of merchant ships. For all the selected types and sizes of suitable ships, the increase in numbers of units between years 2010 and 2022 was positive, with the largest increase in the very large capacity category. Reducing the power limit to 0,75 MW increases the number of potential applications to 8985 pcs, 7,1% of the total number of merchant ships.

The second research question was to determine the differences in applications between diesel-mechanical and diesel-electric propulsion systems. No single dominant propulsion system emerged from the study, but diesel-electric and diesel-mechanical propulsion systems may be used in different applications in the future. Based on the literature survey, it was found that cruise ships, icebreakers, ferries, shuttle tankers, chemical carriers, and research ships there are references to the use of the diesel-electric propulsion system.

IMO's plan for reducing greenhouse gas emissions through technological measures, do not contain direct measures for diesel-electric propulsion or diesel-mechanical propulsion selection. The study found that it is likely that in the future trend will be to continue for large cargo ships to use diesel-mechanical propulsion in combination with other energy efficiency enhancing accessories and to reduce greenhouse gas reductions through alternative energy sources, technical hybrid solutions, low-density hull coatings, propeller control, use of renewable energy, navigation routes and sailing speed control.

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Short-, medium-, and long-term plans in the IMO Strategy

Type	Years	Measure	Target	Current status
Short-term	2018-2023	Improve energy efficiency framework, focusing on EEDI and SEEMP	New vessels	EEDI requirements set through 2025
		Develop new operational and technical efficiency measures	In-service vessels	SEEMP planning required
		Establish an Existing Fleet Improvement Program	In-service vessels	EEXI and CII adopted at MEPC 76 in 2021
		Consider speed reduction and optimization	In-service vessels	Indirectly encouraged through EEXI and CII
		Consider measures to address methane and VOC emissions	Engines and fugitive emissions	Under consideration at MEPC
		Encourage National Action Plans to address GHG emissions	In-service vessels, port emissions, and fuels	Member states have begun submitting their NAPs to IMO
		Continue cooperation under Integrated Technical Cooperation Programme	Developing countries	Ongoing
		Encourage port developments and global activities to facilitate GHG reductions	Port emissions and fuels	Ongoing
		Establish International Maritime Research Board to oversee R&D to improve ship energy efficiency	R&D funds	Under consideration at MEPC
		Develop incentives for first movers to develop and adopt new technologies	Incentives	Under consideration at MEPC
		Develop lifecycle GHG/carbon intensity guidelines for all types of fuels	Fuels	Under development at MEPC
		Promote the work of IMO to the international community on reaching the Sustainable Development Goals	Public relations	Ongoing
		Undertake additional GHG studies and other studies to inform policy decisions	Research	Fourth IMO GHG Study published in 2020
Mid-term	2023-2030	Establish an alternative low-carbon and zero-carbon fuels implementation program	Fuels/new and in-service vessels	Not started
		Further operational efficiency measures (e.g. SEEMP, operational efficiency standard)	In-service vessels	SEEMP planning required
		Introduce market-based Measures (MBMs) to incentivize GHG reduction	In-service vessels/fuels	Under consideration at MEPC
		Continue and further cooperation under ITCP	Developing countries	Ongoing
		Develop feedback mechanism to collect information to enable sharing of best practices	Information sharing	Ongoing
Long-term	2030+	Development and provision of zero-carbon or fossil-free fuels	Fuels/new and in-service vessels	Ongoing
		Facilitate uptake of other emissions reductions technologies	New and in-service vessels	Ongoing