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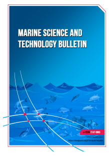

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RESEARCH ARTICLE

A techno-environmental and energy efficiency investigation of marine dual-fuel engines

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ABSTRACT

The ship-based greenhouse gas emissions along with the volumetric growth in maritime transportation have increased significantly over the years. International Maritime Organization (IMO) has tightened the emission limits by putting new regulations into effect to overcome the environmental impacts and therefore, the maritime industry has focused on energy-efficient ship design and operation, recently. Regarding the latest developments, dual-fuel engines operated with different fuels have been installed and new technological developments in emission control have been implemented onboard ships. In this context, the selection of engine systems where there are many options available has been a substantial problem in the design process of a ship, recently. The latest marine engines are capable of operating with various types of fuels at different emission control modes, therefore, energy efficiency and emission performance of the prime movers should be analyzed in detail. In this study, VLSFO, methanol, LPG, LNG and MDO-fueled engines with the same power output are investigated and the NO_X reduction device integrated engines' technical specifications are compared. Then, the selected dual-fuel engines are thermodynamically analyzed and the environmental impacts are evaluated under different engine loads, Tier II, Tier III modes and ambient conditions. Moreover, EEDI calculations are conducted under the case study of powering a medium-range tanker and engine options are evaluated in terms of energy efficiency. Finally, a sensitivity analysis of engine performance is carried and the results are validated. According to the results, the energy efficiency of the ship can be increased by up to 20% by selecting the LNG-fueled engine as the prime mover while it requires more space and equipment compared to other engines.

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Introduction

Ship design is a multidisciplinary and complicated field consisting of iterant analysis and optimization steps. A typical ship design project includes concept, preliminary, contract and detail design phases where hull form design, arrangements, maneuverability, stability, strength, resistance and power characteristics are determined (Evans, 1959; Turan & Akman, 2021). The design optimization in the process is substantial to improve energy efficiency and decrease a ship's fuel consumption and emissions. It was reported that maritime-based greenhouse gas (GHG) emissions in 2018 had a 2.89% share in global GHG along with sulphur oxides and nitrogen oxides from ships accounting for 13% and 15% of total NO_X and SO_X emissions, respectively (Han et al., 2019; IMO, 2020). International Maritime Organization (IMO) put regulations into force as Ship Energy Efficiency Management Plan (SEEMP) and Energy Efficiency Design Index (EEDI) along with the emission limits defined in MARPOL Annex VI (IMO, 2013). Currently, the Tier III NO_X emission limit per cycle is 3.4 g/kWh for the slow-speed engines (<130 rpm) which reduces the NO_X emissions approximately by 76% compared to the Tier II limit (IMO, 2013). Moreover, the sulphur rate in marine fuel oil is 0.1% in terms of mass inside the Emission Control Areas (ECAs) and 0.5% outside the ECAs determined in Reg. 13 of MARPOL Annex VI (IMO, 2019). Besides, IMO has enlarged the scope of MARPOL and enacted Energy Efficiency Existing Ship Index (EEXI), Carbon Intensity Indicator rating (CII) and enhanced Ship Energy Efficiency Management Plan regulations which have been implemented as of 1 January 2023 (IMO, 2021). In addition, to determine maritime-based fuel consumption and emission; Monitoring, Reporting and Verification (MRV) in European Union (EU) and IMO Data Collection System (DCS) have been implemented since 2017 and 2018, respectively (DNV, 2022). The current regulations aim to decrease the ship-based GHG by 40% as of 2030 and by 50% as of 2050 baselining the 2008 level of GHG (IMO, 2020). Therefore, various measures have been taken in the design and operation to increase the energy efficiency of ships and comply with the regulations. The hull and bow form, the aft body with propeller and rudder optimizations, weight reduction, low resistance hull coating, and highly efficient machinery system selection are the options in the design stage of a ship (JASNAOE, 1980; MAN, 2016a; Vidović et al., 2023). On the operation side, speed reduction, ballast and trim optimization, route optimization, on-time cleaning and maintenance, just-in-time operations and cold ironing are conducted for ships in service (JASNAOE, 1980; Johnson & Styhre, 2015; Köseoğlu et al., 2021; Vidović et al., 2023). Furthermore, there are novel systems available to increase energy efficiency and emission performance. Waste heat recovery (Akman & Ergin, 2019; Konur et al., 2022), carbon capture and storage (Güler & Ergin, 2021), air lubrication (Vidović et al., 2023), rotor sails (Wärtsilä, 2022) and performance monitoring systems (Wang et al., 2018) have been used onboard ships.

Main engines, auxiliary engines and boilers are the major fuel consumers and also the power suppliers onboard ships. According to the latest GHG report (IMO, 2020), the world fleet's main engines of containers, bulk carriers and oil tankers consume much more fuel than the engines of other types of ships. Moreover, HFO or LSFO fuel oil was reported to be the major fuel type followed by MDO and LNG in the commercial fleet (IMO, 2020). Fuel type, on the other hand, identifies the ship's energy efficiency and operational performance levels based on different chemical and combustion characteristics. Carbon fuels; HFO, LFO, LSFO, MDO, MGO, LNG, LPG, methanol (MeOH) and ethanol have been used in prime mover power generation and zero carbon fuels; ammonia and hydrogen are shown as future marine fuels (Bureau Veritas, 2022). Stiff limitations on sulphur and NO_X emissions directed shipowners and engine manufacturers to the fuel-switching option that can be conducted on dual-fuel engines. Liquid or gas fuels can be burned with pilot fuels in these engines and according to the fuel type Tier II or Tier III NO_X limitations can be complied with or without before and after treatment systems.

Regarding the importance of the topic, many studies have been conducted on the thermal, emission and economic performances of marine fuels. Spoof-Tuomi & Niemi (2020) environmentally and economically analyzed LNG, LGB (liquified biogas) and MDO-fueled Ro-Pax ferry. They found that the total operation cost of the ferry fueled with LNG is about 41% and 64% less compared to that fueled with MDO and LBG, respectively. Perčić et al. (2021) investigated the life cycle and costs of various marine fuels including diesel, LNG, methanol, hydrogen, ammonia and electricity for inland vessels. According to their assessments, electric-powered propulsion is the most cost-effective solution for inland passenger vessels while diesel is the most economical option for the selected dredger. Law et al. (2021) compared HFO, natural gas, solar and biomass-based marine fuels in terms of lifecycle energy and cost. They stated that methanol from biomass is favourable considering cost, energy and technology readiness level while hydrogen and ammonia are referred to as the worst among all fuels in terms of energy and cost. Liu et al. (2022) investigated the thermal performance of diesel, biodiesel, hydrogen, methane, methanol and ammonia fuels in a zero-dimensional model of the Millet-Sabathe cycle. They stated that the marine diesel engine's brake thermal efficiency can be enhanced by up to 53.09%. Feng et al. (2022) investigated the future SCR systems of marine engines for marine applications. They suggested that the decomposition of the catalyst with SO_2 and H_2O is challenging for the future SCR system of marine engines. Feng et al. (2022) environmentally analyzed the impacts of alternative fuels for ships and they stated that LNG is a feasible fuel for reducing SO_X and PM along with the NO_X by lean combustion. Napolitano et al. (2022) experimentally studied the SCR technology for ships and they pointed out that NO_X reduction efficiency can be increased by increasing the dosing ratio of additives. Law et al. (2022) investigated the various fuels for maritime by considering the ship type, cargo and voyage. According to their results, biodiesel has the best environmental score among HFO, ammonia, bio-methanol, LNG, hydrogen and electricity. Lu et al. (2022) conducted an optimisation study for two-stroke marine engines integrated with exhaust gas recirculation (EGR). According to their results, the proposed engine model complies with the Tier II limitations and by adjusting the EGR rate 22% and %36 Tier III limits can be fulfilled. Huang et al. (2022) performed a life cycle assessment of GHG emissions caused by fuels and a case study for a very large crude carrier. They pointed out that solar-driven methanol production from hydrogen can cause almost zero carbon and engines using pilot fuel cannot achieve zero carbon emissions. Livaniou et al. (2022) compared the emissions of LNG and MDO fuels burned in different types of ships based on the real data obtained from different databases. According to their results, using LNG reduces CO_2 and NO_X emissions about by 20.7% and 83.6% compared to MDO, respectively. Elkafas et al. (2022) analyzed the LNG, diesel and methanol fuels in terms of environmental, technical and economic perspectives. They pointed out that LNG is more environmentally friendly while methanol is a more economical fuel compared to diesel. Zou & Yang (2023) conducted life-cycle assessments of methanol, LNG, hydrogen and ammonia fuels for various-sized ships by considering shipowners and the public. They stated that HFO with scrubbers is the most economical short-term option for container ships while methanol is the most favourable solution when the social costs of the pollutants are objective.

The internal combustion engines as main prime movers directly affect the thermo-environmental and economic performance of the ship which is aimed to be operated efficiently as pointed out. Moreover, there are many options for alternative fuels complying with the regulations with emission control technologies integrated into marine engines, therefore, suitable engine selection has been a substantial question in the design stage of a ship, recently. Hence, parallel to the IMO regulations and emission targets, detailed analyses are needed on engine systems in terms of thermodynamic, technological and environmental performances. Regarding the latest studies and developments, this study reveals and compares the energy efficiency performance, technological properties of emission control systems and technical specifications of VLSFO, MeOH, LPG, LNG and MDO-fueled engines with the same power output. The selected dual-fuel engines are thermodynamically analyzed and the environmental impacts are evaluated under various engine loads, Tier II and Tier III emission control modes. After obtaining the techno-environmental data, a case study is conducted for a medium-range tanker's EEDI calculations. In addition, a sensitivity analysis is performed to point out the effect of ambient conditions on engines' performances. Apart from the literature where economic and environmental analysis of alternative fuels have been commonly studied, this study focuses on the marine dual-fuel engines operated with alternative fuels and aims to contribute literature with the technical assessments and operational condition-based thermo-environmental results that can be used for the decision-making in the powering and engine selection stages of a merchant ship design.

The workflow of the study is summarized as follows: Analyses start with the methodology to explain the mathematical model and used tools on evaluating the thermo-environmental performances of dual-fuel engines and the energy efficiency of the tanker. The next section details and compares specifications with the technological properties of emission control devices integrated into the selected engines. Then the obtained results related to thermo-environmental and EEDI are evaluated. After evaluations, sensitivity and validation studies are performed and finally, the concluding remarks are presented.

Material and Methods

Methodology

The techno-environmental investigation and evaluation consist of six steps; the determination of the engine group based on the medium-range tankers' particulars, data collection of the determined dual-fuel engines using CEAS, analysing of the collected data in terms of emission control technology integrated into the dual-fuel engines, thermal and environmental impact analyses of the engines under various engine loads and Tier II – Tier III emission control modes, a case study on engine selection for a medium-range tanker to reveal the hull to wake emissions and preliminary EEDI calculations for the tanker and finally, a sensitivity and validation study. The summary of the analysing steps is shown in Figure 1.

The data collection step is based on medium-range tankers (45000 – 55000 DWT) built after 2013 and the main particulars include length, breadth, draft, design speed, cargo capacity and power generation systems. The equations regarding tankers' particulars are obtained from previous publications (Akman & Ergin, 2019) and the latest technical reports (MAN, 2021, 2022a; MEPC.308(73), 2018) regarding the propulsion of tankers as shown in Table 1. The obtained regression-based equations show that if the main dimensions and capacity are known, engine main and auxiliary engines' power requirements can be estimated. Using a typical length of around 180 m and 49990 DWT cargo capacity engine power requirements are determined for the tanker as shown in Table 1. It is worthy of note that there may be deviations in the values of about 5-10% compared to those of the actual ship. The tanker's propulsion system consists of a single main engine with a fixed-pitch propeller, and two service generators without a shaft generator. It is assumed that there is no energy efficiency-increasing device onboard the ship.

The estimated power of the main engine is used for the selection of available dual-fuel engines. The Computerized Engine Application System (CEAS) (MAN, 2023) and technical guides (MAN, 2022b) are used for obtaining the parametric and technical data of the engines.

The CEAS database consists of two-stroke engines ranging from 35 cm to 95 cm bore with 5 to 12 cylinders and 2475 kW to 82440 kW brake power capacity. The primary fuel type, engine power capacity, number of cylinders, bore and stroke, ambient conditions including scavenge air and cooling water (coolant) temperatures and NO_X reduction technology can be changed in the CEAS. The ambient conditions are ISO, tropic and specified cold, where the air temperature ranges from 10°C – 45°C and the cooling water temperature ranges from 10°C – 36°C. Then the obtained data is used in the determination of the sensitivity of the engines.

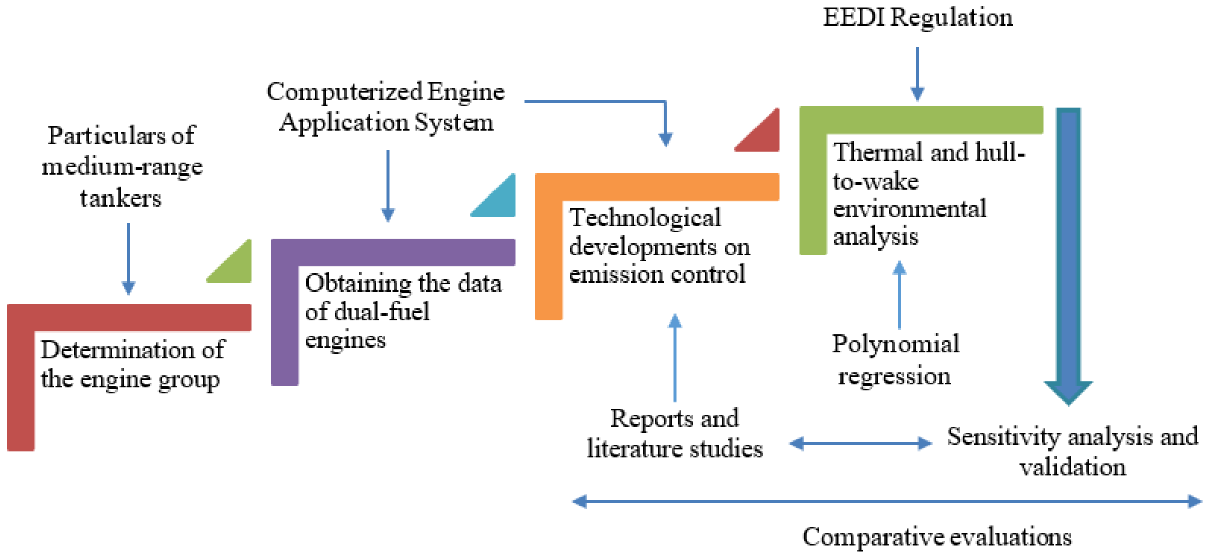

Figure 1. Techno-environmental analysis steps and tools used in the analyses

Table 1. Main particulars of the medium-range tanker (Akman & Ergin, 2019; MAN, 2021, 2022a; MEPC.308(73), 2018)

Properties	Value	Unit	Regression-Based Estimations
Length between perpendicular (L_{PP})	183	m	$L_{PP} = F_{\mathrm{des}} \cdot DWT_{\mathrm{scant}}/(B \cdot T_{scant})$
Moulded breadth (B)	32.2	m	$B = F_{\mathrm{des}} \cdot DWT_{\mathrm{scant}}/(L_{PP} \cdot T_{scant})$
Scantling draught (T_{scant})	13.0	m	$T_{scant} = F_{\mathrm{des}} \cdot DWT_{\mathrm{scant}}/(L_{PP} \cdot B)$
Design speed (V)	14.5	knot	14.5
Capacity (DWT)	49990	ton	$DWT = L_{PP} \cdot B \cdot T_{scant}/F_{\mathrm{des}}$
M/E power (full load)	8600	kW	$0.0652 \cdot DWT + 5960.2$
A/E power (full load)	840 (x2)	kW	$0.05 \cdot MCR_{ME}$

The polynomial regression is applied to the parametric data and thermodynamic performances with environmental impacts of the engines are calculated using the equations as follows:

The brake thermal efficiency of dual-fuel engines can be calculated by,

$$\eta_{th}{}^{i,j} = \frac{P_b}{Q_{LCV}{}^{i,j}\cdot \dot{m}_{fuel}{}^{i,j}} \tag{1}$$

where P_b is the main engine's (ME) brake power. The superscripts i and j indicate the engine load and fuel type specific to the engine, respectively. The parameter $\dot{m}_{fuel}$ shows the fuel consumption in terms of kg/s. The low calorific values (LCV) of VLSFO, MeOH, LPG, LNG and MDO are 41700 kJ/kg, 19900 kJ/kg, 46000 kJ/kg, 48000 kJ/kg and 42700 kJ/kg, respectively (EPA, 2014; MEPC.308(73), 2018). The CO_2 emitted by the dual-fuel engines, $R^{i,j}$ in t/h can be estimated by

$$R^{i,j} = \frac{SFC^{i,j}\cdot P_b}{10^6}\cdot C_{F_j} \tag{2}$$

where SFC is specific fuel consumption and $C_{F,j}$ is the factor used to convert of fuel consumption to CO_2. The C_F of VLSFO, MeOH, LPG, LNG and MDO are 3.15, 1.375, 3.015, 2.75 and 3.206, respectively (EPA, 2014; MEPC.308(73), 2018).

$$EEDI_k = \frac{P_{ME}\cdot C_{F_{ME,j}}\cdot SFC_{ME,j} + P_{ME}\cdot C_{F_{ME,j}}\cdot SPOC_{ME,j} + P_{AE}\cdot C_{F_{AE}}\cdot SFC_{AE}}{f_i\cdot f_c\cdot DWT\cdot f_w\cdot V_{ref}} \tag{3}$$

where SFC of main and auxiliary engines is taken at 75% MCR. The specific pilot oil consumption ($SPOC$) is taken at the same engine load of 75% MCR and MDO is used as pilot oil for gas fueled engines. The auxiliary engines are assumed to be fueled with MDO and SFC_{AE} is taken as 215 g/kWh (MEPC.308(73), 2018). The f_i, f_c and f_w are the capacity factor, cubic capacity correction factor and factor for speed reduction at sea, respectively. The factors are taken as 1 and the average reference speed is 14 knots (MEPC.308(73), 2018). The VLSFO, MeOH, LPG and LNG fuels are assumed to be the primary fuels for the ship for each EEDI calculation.

Dual-Fuel Engines and Emission Control Technologies

Analyzed main power generation systems are capable of burning liquid and gas fuels, low-speed and two-stroke dual-fuel engines generating 8.6 MW brake power (P_b) at full load as can be seen in Figure 2. The engines have a single turbocharger (T/C), 5 cylinders, 500 m bore and 2500 mm stroke, classified as ultra-long stroke. The engines are also electronically controlled and named "G-type" which have a low bore-to-stroke ratio (0.2) and lower rpm requiring a large diameter of the propeller which decreases fuel consumption by up to 7% (MAN, 2016b). The engines' dimensions are the same and length x width x height are about 5.8 m x 3.6 m x 9.8 m, respectively. The dry mass of the gas-fueled engines is 215 tons and it is 211 tons for the VLSFO-fueled engine. The mass of the NO_X reduction device varies; high-pressure SCR and EGR systems weigh 4 tons and 12 tons, respectively. The total mass of oil and water in the engines is 1.6 tons.

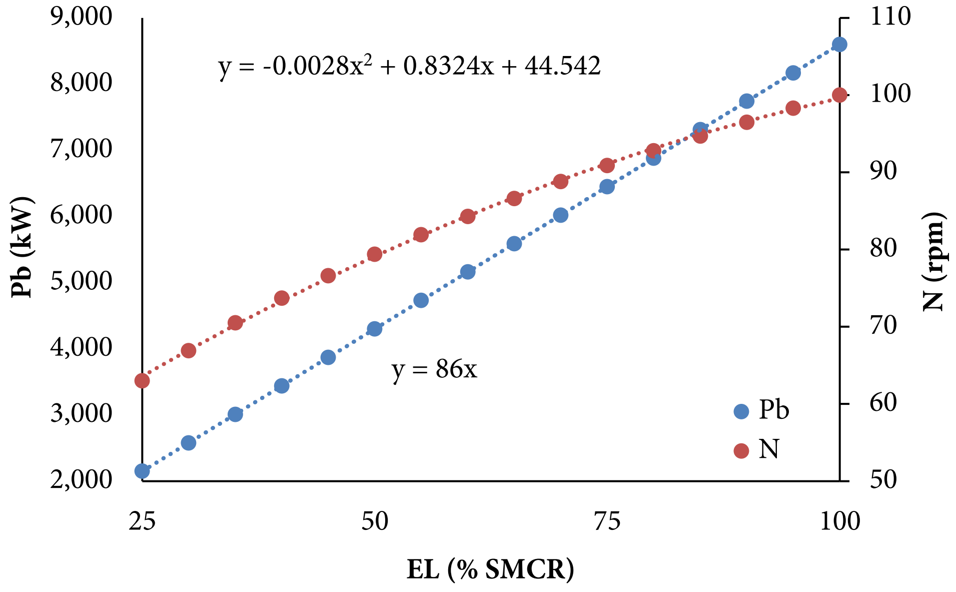

Figure 2. Brake power output change of the engines concerning RPM and engine load (EL)

Table 2. The properties of the engines' fuel systems

Engine Model	Main Fuel	Pilot Fuel	Fuel System Design Pressure (bar)	Fuel Supply Pressure (bar)	Sealing oil consumption (l/24h)	Tier III Technology
5G50ME-C9.6	VLSFO	-	6	4	-	SCR
5G50ME-C9.6-LGIM	MeOH	MDO	16	13	24	EGR
5G50ME-C9.6-LGIP	LPG	MDO	65	53	24	SCR
5G50ME-C9.6-GI	LNG	MDO	350	300	6	SCR

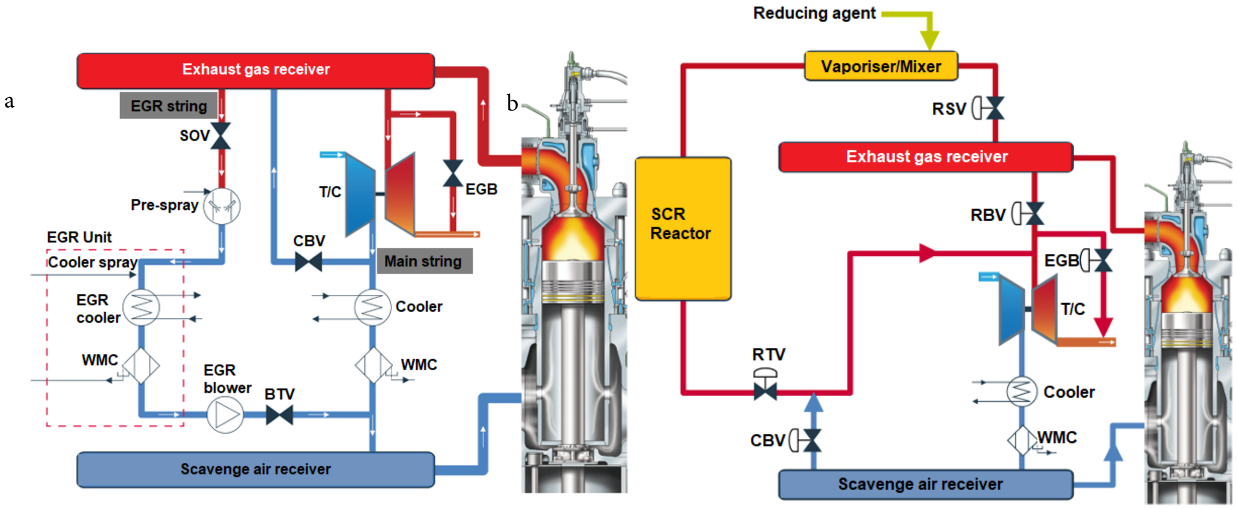

Figure 3. The diagrams of the EGR (a) and high-pressure SCR (b) systems (MAN, 2022a)

The fuel system properties of the engines are shown in Table 2. According to tabulated data, engines are operated under main and pilot fuel which prevents knocking and misfiring during the combustion of MeOH, LNG or LPG (Woodyard, 2004). On the other hand, the design and supply pressures of fuel systems are remarkably different. LNG-fueled engines require more complex and costly infrastructure and it is reported that LNG engines occupy about 3-4 times while methanol-fueled engines occupy about 2 times as much space as marine gas oil-fueled engines (Harris et al., 2022b). According to the obtained data, LNG, LPG and MeOH engines' fuel tanks are 1.7, 1.3 and 2.4 times higher relative to marine gas oil fuel tank size (MAN, 2014). Moreover, it is stated that the new-building cost of a ship increases about by 22% and 10% when LNG and MeOH-fueled engines are used as prime movers (Harris et al., 2022a). However, the LNG-fueled engine's sealing oil consumption which prevents the gas oil to penetrate the hydraulic oil of the valves is quite less compared to that of other engines.

The gas and methanol-fueled engines meet the Tier II NO_X limits and Tier III NO_X limitations are fulfilled by EGR or SCR systems (MAN, 2022b). The schematic diagrams of EGR and SCR systems are shown in Figure 1 (MAN, 2022a). The exhaust gas bypass (EGB) valve in EGR and the reactor bypass valve (RBV) in the SCR units control the switching of Tier II or Tier III modes. The NO_X reduction units are integrated into the exhaust gas line and operated when NO_X control is needed. It is reported that EGR and SCR systems can decrease NO_X emissions by 80% to 90% (MAN, 2016c). On the other hand, compared to EGR the capital cost of SCR is less for engines under 15 MW; however, the operating cost of SCR is higher than the EGR system (MAN, 2015).

Part of the exhaust gas in the EGR system of the MeOH-fueled engine is cleaned, cooled and mixed with the scavenge air to decrease the O_2 content by using CO_2 before the combustion. The heat capacity of the scavenge air is increased to reduce the combustion peak temperature which is the main factor in the formation of NO_X (MAN, 2022a). In Tier II mode, the EGR valve and blower throttle valve (BTV) are closed and the recirculation starts with the opening of these valves in Tier III mode. After pre-spraying, the EGR blower forces the flow to enter the scavenge air cooler and the water mist catcher (WMC) which avoids reaching the liquid water into the cylinders.

The SCR system consists of an SCR reactor, vaporiser/mixer and dosing units. As can be seen in Figure 1 (b), the SCR unit is deactivated by the reactor throttle valve (RTV) and reactor sealing valve (RSV). When the RBV is opened the exhaust gas is forwarded to T/C. The SCR unit of the selected engines is working on the high-pressure which means that the process is maintained with exhaust gas before T/C. When the exhaust gas is bypassed to the SCR line, the reducing medium is injected into the vaporiser/mixer by the dosing system and the medium is vaporised and mixed with the exhaust gas. Then the mixture is sent to the reactor for reducing NO_X. The SCR system is operated at high exhaust temperatures; therefore, the temperature of exhaust gas should be kept 50-175°C (MAN, 2022a) higher compared to that on the low-pressure side. Moreover, during the engine is in Tier III mode the SCR system is adjusted to operate above the sulphuric acid condensation temperature limit of 200°C (MAN, 2022a). An automatic heating system is positioned on the SCR system to keep the temperature above the specified limit. In addition, the soot-blowing system is operated against the clogging of the reactor by soot particles.

Results and Discussion

The results and discussions are presented in subsections; thermal and environmental performance evaluations and, sensitivity analysis with the validation of the obtained results. The load and emission control mode-depended performance parameters including fuel consumption, brake thermal efficiency, CO_2 emission and EEDI are evaluated and discussed. Then, the incremental effects of ambient conditions and engine load on performance parameters are analyzed. Finally, the results are validated using the literature studies.

Thermal Performance

The dual-fuel engines with the same power output and dimensions have remarkable differences in terms of fuel consumption. Figure 4 shows the specific fuel (a) and pilot oil (b) consumption of the engines under various engine loads at Tier II mode. The point data is also given in polynomial functions where engine load is variable. According to the plots, methanol-fueled engines consume approximately 50% more fuel compared to other engines. The main difference is based on the specific energy content (kJ/kg) and density (kJ/m^3) of methanol which is about 53% and 58% less compared to MDO (MAN, 2014). The fuel consumption of LNG-fueled engines is less in comparison with that of the other engines based on the same reasons that the energy content of LNG is about 12% higher than MDO. Besides, the fuel consumptions at the light and heavy engine loads are higher compared to the normal continuous rating of 85% MCR for each engine. On the other hand, the MDO as pilot oil consumption decreases by the engine load. The methanol-fueled engine's SPOC is about 60% and 220% higher than that of LPG and LNG-powered engines, respectively. On the other hand, the fuel consumption increases at Tier III mode approximately by 0.73%, 0.72%, 0.76% and 3.58% for LNG, VLSFO, LPG and MeOH-fueled engines, respectively. In addition, the fuel consumption at light loads rises from 1% to %5 based on the fuel type. The MeOH-fueled engine has the highest fuel consumption at Tier III mode based on the EGR activation. The reason for the fuel increase is related to the combustion characteristics at Tier III mode where the combustion temperature is higher and firing pressure is lower compared to those at Tier II mode (ABS, 2020).

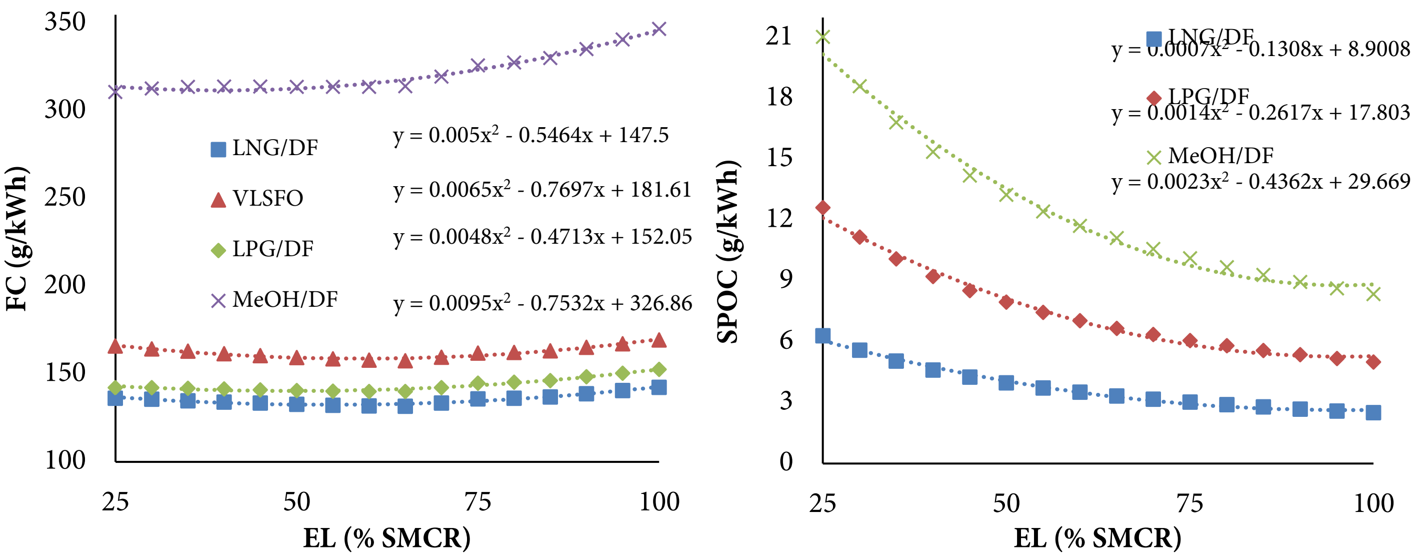

Figure 4. The change of specific fuel (a) and specific pilot oil consumptions (b)

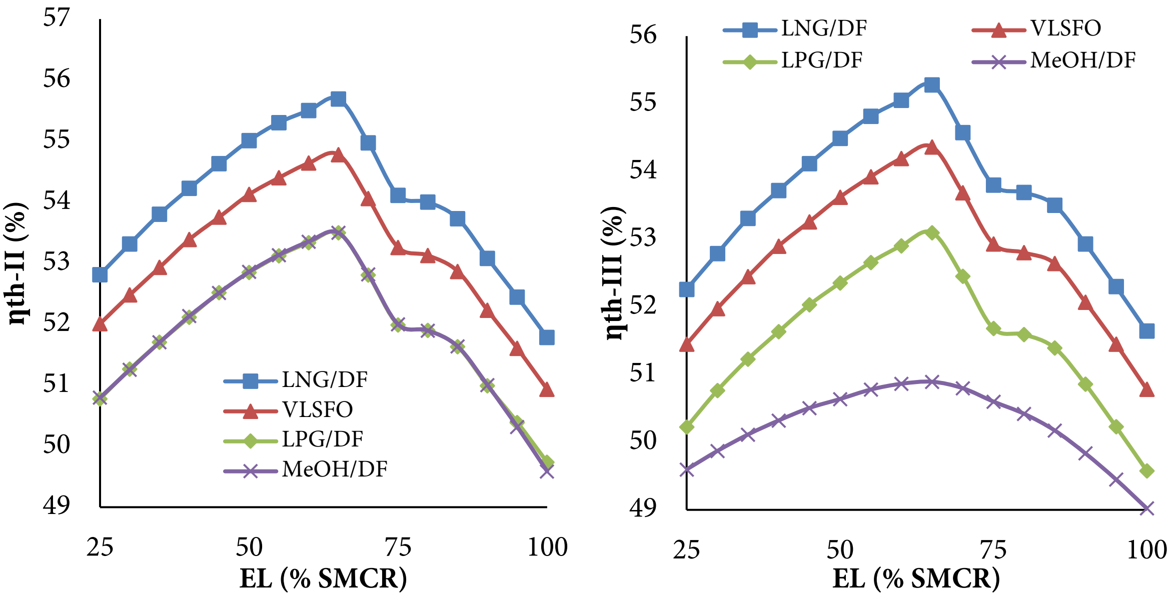

Figure 5. The change of thermal efficiencies under Tier II (a) and Tier III (b) modes

The thermal efficiency of the engines under different engine loads and Tier II (a) and Tier III (b) modes are indicated in Figure 5. According to the ISO ambient conditions, LNG-fueled engines are more efficient in terms of thermal performance. In Tier II mode, the calculated maximum thermal efficiencies are 55.7%, 54.8%, 53.4% and 53.5% for LNG, VLSFO, LPG and MeOH-powered engines, respectively. Switching the engine from Tier II to Tier III mode, the thermal efficiency of the engines decreases by 0.5% to 4.9%. NO_X reduction devices are operated in Tier III mode which requires more fuel for producing the same power output as Tier II mode. Furthermore, according to the plots, the thermal efficiency of the engines is remarkably low at the light and heavy loads; therefore, the dual-fuel engines should be operated at medium loads (between 60% - 70% MCR) for energy efficiency. The reason behind this phenomenon is related to the combustion characteristics depending on the load. The analyzed engines are turbocharged and at light loads scavenge air pressure drops which cause low combustion efficiency and increase fuel consumption and carbonization (Garcia et al., 2014). Moreover, the formation of carbon deposits due to the lack of sealing can increase and the steam production capacity from economizer can decrease at light loads for two-stroke engines (Dere et al., 2022). Fuel consumption also substantially increases at higher loads based on more power demand.

On the other hand, the brake thermal efficiency plots show that approximately 50% of fuel energy is lost by the cooling and exhaust gas of the engines. Such two-stroke dual-fuel engines have jacket cooling, scavenge air cooling and lubrication oil cooling loads which correspond to about 20% - 25% of the total fuel energy and the exhaust gas has a share of about 25% in total (Akman & Ergin, 2021, 2022; Singh & Pedersen, 2016). Moreover, switching the engine mode from Tier II to Tier III increases the cooling load and exhaust gas heat potential. Therefore, the remaining part of the heat energy after the combustion process can be harvested for increasing the energy efficiency of power generation systems onboard ships.

Environmental Performance and EEDI

The estimated CO_2 emissions released by the engines at ISO ambient conditions are shown in Figure 6. Raising the engine load substantially increases fuel consumption and CO_2 emissions. According to the results, VLSFO-fueled engine emits more CO_2 which is calculated as 3.82 ton/h CO_2 at 85% MCR and Tier II mode, and at the same operating conditions LNG, LPG and MeOH-fueled engines emit 2.82 ton/h, 3.35 ton/h and 3.53 ton/h, respectively. The CO_2 emissions increase in Tier III mode that VLSFO, LNG, LPG and MeOH engines at 85% MCR release 3.84 ton/h, 2.83 ton/h, 3.37 ton/h and 3.64 ton/h, respectively. Activation of SCR or EGR at the Tier III mode significantly lowers the NOx emissions which comply with the regulations where Tier III NOx is at least 76% less than that at Tier II. However, the Tier III mode has higher fuel consumption resulting in more CO_2. Therefore, load optimization is significant in both NO_X and CO_2 reduction. As discussed in the previous sections, medium loads ranging from 50% to 75% MCR seem more efficient in CO_2 and NO_X reduction.

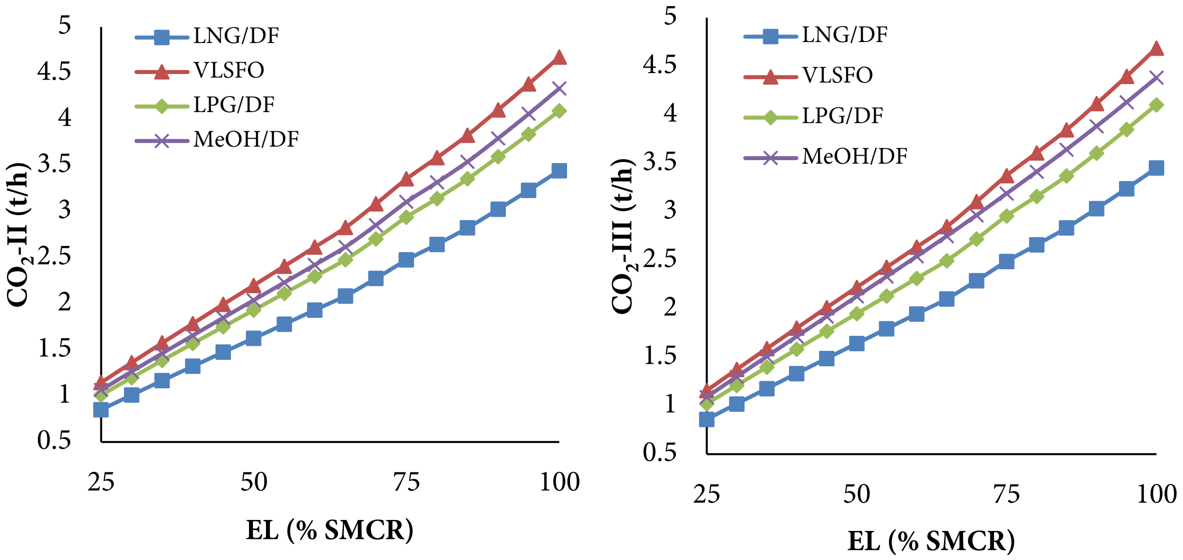

Figure 6. The estimated hull-to-wake CO_2 emissions under Tier II (a) and Tier III (b) modes

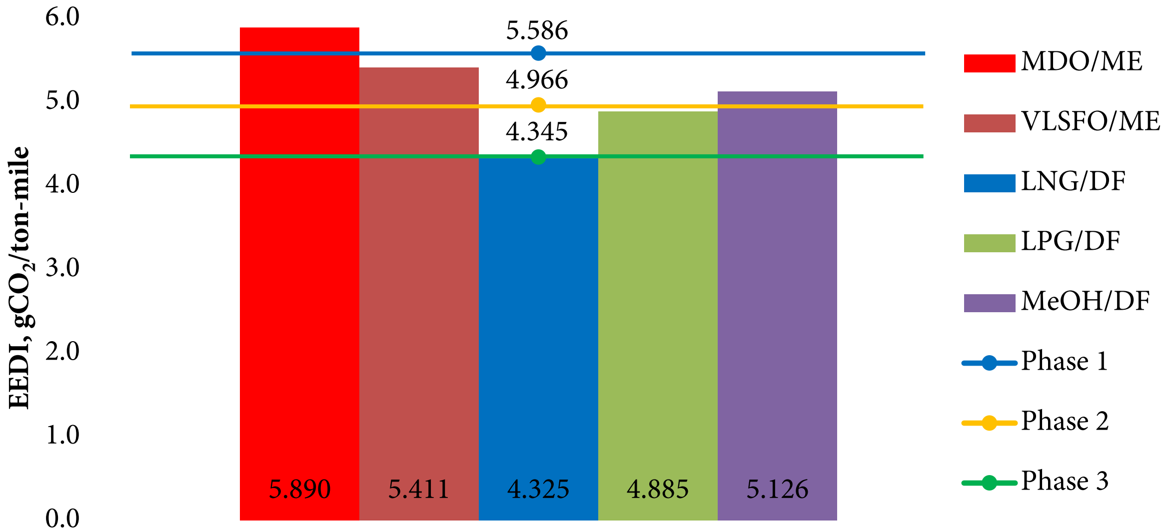

Figure 7. The estimated EEDI values of tanker installed with different main engines

The Energy Efficiency Design Index for ships is defined as the mass of CO_2 emission per unit of transport work and depends on the fuel consumption of main and auxiliary engines with boilers. Main engines are the major fuel consumers; therefore, the primary fuel has a significant role in EEDI. During calculations, only main and auxiliary engines are considered and the reference engine load is taken as 75% MCR. Figure 7 shows the reference and attained EEDI of a medium-range tanker installed with different dual-fuel engines. The reference EEDI value varies regarding ship type and for a tanker, it is 6.206 g-CO_2/ton-mile (IMO, 2012). According to the regulation (IMO, 2012), EEDI reduction factors by baselining reference EEDI are given as 10%, 20%, and 30% for Phase 1, Phase 2 and Phase 3, respectively.

According to the preliminary calculations, the ship with an MDO-fueled engine complies with none of the EEDI phases. Even though the ship with VLSFO and LPG-fueled engines complies with sulphur regulations, the attained EEDI of this engine-integrated ship is above Phase 3. LNG and LPG-fueled engines comply with the current regulation and methanol-fueled engines can be an option considering the optimized design. However, it should be noted that methane slip is a problem in LNG-fueled engines which increases the ship-based GHG emissions and for the analyzed engine slip is about 0.2 g/kWh (MAN, 2021a). Besides, as discussed in the previous section, medium loads are energy efficient both in Tier II and Tier III modes and enable to obtain of low EEDI. Moreover, the thermal performances show that the majority of the fuel energy is lost by exhaust gas, engine scavenge air, jacket water and lubrication oil cooling; therefore, integrating the energy efficiency-increasing devices such as waste heat recovery systems onboard ships can reduce the attained EEDI.

Sensitivity Analysis and Validation

The analyzed two-stroke dual-fuel engines show different performances at various ambient and loading conditions. Table 3 shows the fuel consumption of the engines at specified cold, ISO and tropical air and coolant temperatures at Tier II mode. The ambient conditions are defined in CEAS (MAN, 2023) and fuel consumptions are tabulated at varying engine loads. The obtained data show that fuel consumption depends on not only the engine load but also the intake air and freshwater temperatures. Hence, for the evaluation of the engines' performance sensitivity, loads and temperatures are increased by one unit. According to the results, increment of ambient temperatures by 1°C, the fuel consumption increases approximately by 0.05%. Mean deviations are calculated by baselining ISO condition at 75% MCR and results show that the MeOH-fueled engine has higher tolerance on ambient conditions compared to other engines as can be seen in Table 3. On the other hand, when the engine load is increased by 1% MCR, fuel consumptions increase about by 1.5%. The light loads (<50% MCR) have higher tolerances rising to 3.5% as stated in the engine manufacturer's performance reports (MAN, 2023).

Table 3. Engines' fuel consumption at various ambient and loading conditions

Ambient Conditions	Engine Load (%)	Fuel Consumption by Engine Type (g/kWh-Tier II)			
		VLSFO-DF	MeOH-DF	LPG-DF	LNG-DF
Specified	25	162.1	311.0	134.5	136.4
Air temperature: 10°C	50	155.5	313.5	135.6	132.8
Coolant temperature: 10°C	75	157.4	324.5	140.4	135.2
	100	164.5	344.5	148.6	141.7
ISO	25	164.1	315.3	136.4	138.1
Air temperature: 25°C	50	157.4	317.7	137.4	134.4
Coolant temperature: 25°C	75	159.4	328.7	142.2	136.9
	100	166.4	348.9	150.5	143.5
Tropic	25	165.8	319.1	138.0	139.7
Air temperature: 45°C	50	159.1	321.4	139.0	135.9
Coolant temperature: 36°C	75	161.0	332.4	143.8	138.4
	100	168.3	352.8	152.1	145.0
Mean deviation by baselining ISO Condition (%)	75	1.129	1.202	1.195	1.169

Validation of the results is conducted by comparing the available literature studies where the same calculation methodology is used. Grljušic et al. (2015) calculated the efficiencies of a ship power plant including a marine two-stroke diesel engine with 18660 kW and integrated waste heat recovery system under different engine loads. The calculated brake thermal efficiencies at 50%, 75%, 85% and 100% MCR are about 51.3%, 51.4%, 51% and 49.7% in the reference study. Compared to the results obtained in this study where the thermal efficiency of VLSFO fueled engine is shown in Figure 5 (a), there is a maximum 5% deviation between the results. The difference can be related to using of different ambient conditions and engine models during calculations.

Conclusion

Main engines available for a medium-range tanker and capable of burning VLSFO, methanol, LPG, LNG and MDO are investigated to compare the technical and emission-control-based technological features of the engines. The dual-fuel engines are thermodynamically analyzed and the CO_2-based environmental impacts are presented under different engine operating conditions. Then, EEDI calculations are conducted for a medium-range tanker using the analyzed dual-fuel engines. The following conclusions are drawn that can be used in the decision-making processes of a ship design where there are research gaps in suitable engine selection based on techno-environmental and energy efficiency assessments:

- The engines have the same size and brake power output but burn different types of fuels which chemical and physical properties are different. LNG is stored and supplied at about 5- and 20-times higher pressures compared to LPG and MeOH, therefore LNG fueled engines with tanks and equipment occupy about 50% more volume onboard compared to MeOH-fueled engines.
- The available NO_X reduction systems for the analyzed engines are EGR or SCR for complying with the Tier III limits. The systems are operated as before or after treatment emission control. The system selection depends on the engine size and cost but the EGR system seems feasible for engines with high power output (>15MW).
- The main and pilot fuel consumption of LNG-fueled engines in terms of ton/h is approximately 16.6%, 8.6% and 140% less compared to that of VLSFO, LPG and MeOH-fueled engines. Therefore, LNG-powered engines have higher brake thermal efficiency under various engine operating conditions.
- Regarding the carbon content and fuel consumption, the VLSFO-powered engine has the highest hull-to-wake CO_2 emissions while the LNG-powered one has the least at the same engine operating conditions.
- EEDI calculations show that LNG-powered engines seem more favourable compared to other engines. The attained EEDI can fulfil the Phase 3 level when LNG is used as the primary fuel.
- Sensitivity analysis indicates that engine load is the dominant parameter of the engine performance compared to intake air and cooling water temperatures. Medium loads are feasible in terms of efficient operation.
- Detailed well-to-wake assessments can vary the optimal fuel order; however, LNG and methanol-powered dual-fuel engines seem the midterm option for IMO GHG targets.
- The brake thermal efficiency of the engines at different loads and Tier modes shows that there is a significant amount of waste heat to recover. In future studies, analysis can be expanded by integrating the waste heat recovery devices into the engines to increase the thermal efficiency of the power generation systems and EEDI performance of the ships powered with alternative fuels.
- In future studies regarding the selection of optimal marine engines operated with alternative fuels, a comprehensive well-to-wake thermo-economic analysis can be conducted. During analysis, ship types which have different operational profiles can be included and evaluated in terms of economic sustainability.

Compliance With Ethical Standards

Conflict of Interest

The author declares that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

Data Availability Statements

All data generated or analyzed during this study are included in this published article.

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Nomenclature

Abbreviations

A/E	Auxiliary engine
CEAS	Computerized Engine Application System
CO_2	Carbon dioxide
DF	Dual-fuel
DWT	Deadweight tonnage
EEDI	Energy Efficiency Design Index
EGR	Exhaust gas recirculation
EL	Engine load
F	Factor
FC	Fuel consumption
GHG	Greenhouse gas
IMO	International Maritime Organization
LCV	Lower calorific value
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
MEPC	Marine Environment Protection Committee
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
M/E	Main engine
MeOH	Methanol
NO_X	Nitrogen oxide
PGS	Power generation system
SCR	Selective catalytic reduction
SPOC	Specific pilot oil consumption
SFC	Specific fuel consumption
T/C	Turbocharger
VLSFO	Very low sulphur fuel oil

Symbols

C	Coefficient
f	Factor (for EEDI)
η	Efficiency
$\dot{m}$	Mass flow rate (kg/s)
N	Speed (rpm)
$\dot{Q}$	Heat flow (kW)
P	Power (kW)
R	Emission (ton/h)

Subscripts

b	Break
des	Design
pgs	Power generation system
ref	Reference
scant	Scantling
th	Thermal