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EXAMINING THE EFFECT OF GENERATOR LOAD SHARING PRACTICES ON GREENHOUSE GAS EMISSIONS FOR A SHIP

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ABSTRACT: In this paper, the issue of efficient operation of generators, which is one of the energy efficiency parameters in ship electricity systems, is discussed in terms of greenhouse gas emissions. In order to meet the same power needs on a bulk carrier ship, three different load sharing situations are assessed in which the other generator is run synchronously when the active generators reach 40%, 60%, and 80% load ratios. Thus, CO_2, CH_4, and N_2O emissions from generators for each practice are analyzed depending on fuel consumption. The results show that emissions vary for certain power needs in each situation. Also, there was no change in emissions for some power needs in three situations. In addition, it was estimated that up to 22% emission reductions could be achieved, depending on the power needs of the ship, if the generators were run at an 80% load ratio instead of 40%.

Keywords: *Ship, Electrical energy, Diesel generator, Greenhouse gas emissions*

Bir Gemi İçin Jeneratör Yük Paylaşımı Uygulamalarının Sera Gazı Emisyonları Üzerindeki Etkisinin İncelenmesi

ÖZ: Bu makalede, gemi elektrik sistemlerinde enerji verimliliği parametrelerinden biri olan jeneratörlerin verimli çalıştırılması konusu sera gazı emisyonları açısından değerlendirilmiştir. Bir dökme yük gemisinde aynı güç ihtiyacını karşılamak için devredeki jeneratörün %40, %60 ve %80 yüklenme oranlarına ulaştığında diğer jeneratörün senkron olarak devreye alındığı üç farklı yük paylaşımı durumu ele alınmıştır. Böylece her bir durum için jeneratörlerden kaynaklanan CO_2, CH_4 ve N_2O emisyonları yakıt tüketimine bağlı olarak analiz edilmiştir. Sonuçlar, emisyonların her durum için belirli bir güç ihtiyacında değiştiğini göstermiştir. Ayrıca, her üç durumda da bazı güç ihtiyaçları için emisyonlarda herhangi bir değişim olmamıştır. Ek olarak, jeneratörlerin %40 yerine %80 yük oranında çalıştırılması durumunda gemideki güç ihtiyacına bağlı olarak %22'ye kadar emisyon azaltımı sağlanabileceği tahmin edilmiştir.

Anahtar Kelimeler: *Gemi, Elektrik enerjisi, Dizel jeneratör, Sera gazı emisyonları*

1. INTRODUCTION

The increase in global energy demand day by day causes a rise in greenhouse gas (GHG) emissions in the maritime sector, as in other sectors. The GHGs, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from shipping (international, domestic, fishing) increased 9.6% from the years of 2012 to 2018 (MEPC 75/7/15, 2020). In other words, equivalent CO_2 emissions have raised from 977 million tons to 1076 million tons during this time. In addition, CO_2 release, which is one of the main greenhouse gas sources, was 962 million tons in 2012 in the maritime sector and reached 1056 million tons in 2018. CO_2 increased by 9.3% in seven years (MEPC 75/7/15, 2020). The maritime sector was also responsible for around 2.9% of global anthropogenic CO_2 emissions in 2018 (Kramel *et al*., 2021). The International Maritime Organization (IMO) makes various regulations, develops measurement techniques, and encourages energy efficiency activities in order to adopt more environmentally friendly approaches on ships. Because, IMO targets include decreasing CO_2 emissions per transport work by at least 40% by 2030 and 70% by 2050 compared to 2008 (IMO, 2021). For these reasons, various techniques such as the Energy Efficiency Operational Indicator (EEOI), Ship Energy Efficiency Management Plan (SEEMP), and Energy Efficiency Design Index (EEDI) have been developed by IMO to assist the decrease CO_2 emissions and increase the energy efficiency of shipping (Fan *et al.*, 2020).

Ships have different energy efficiency potentials in many areas, such as electric, mechanic, and design. All kinds of energy efficiency activities that can be applied on board can indirectly contribute to reducing the environmental impact of ships. In this context, it is possible to use energy efficiently with various investments, such as improving efficiency in main and auxiliary machinery with waste heat recovery systems, improving efficiency in lighting systems with high-efficiency lamps, and improving efficiency in energy production with renewable energy. In addition, it is possible to provide energy efficiency in the existing system by developing operational strategies such as determining the best route and the most appropriate speed, taking into account the delivery time, economic and environmental parameters (Greenvoyage, 2021). One of the operational strategies on ships is to run generators effectively. Thus, the power needs of ships can be met with less fuel and indirectly GHG emissions can be decreased. Various studies have been carried out on marine diesel generators in the literature. Cuculić *et al.* (2016) analyzed the dynamic behavior of the generator set in the event of a failure on ships. They modeled the generator set and examined the sudden collapse of one of the running generators in the simulation environment. Nasrudin and Syafiqiuddin (2016) studied a power management design for synchronous operation of generator set on ships. They concluded that the significant parameters involved in the power management system design are frequency, terminal voltage, thrust, fast load reduction time, inertial time constant, and slew rate limit. Tarnapowicz and Matuszak (2017) investigated the effect of power factor determination on energy efficiency in a generator set on ships. They stated that the load factor of auxiliary engines should be defined by considering the efficiency of the generator and the excessive power factor of the engine relative to the generator. Başhan and Demirel (2018) identified the critical operational failures in order to contribute to the planned maintenance and repair of generator set on the ship. They stated that the most common causes of faults in generators are fuel, combustion, lubrication, and cooling systems. Başhan *et al.* (2018) carried out an economic analysis of the crane operations on a ship. They calculated the cost of using a crane at low generator loads on a ship. For this reason, they recommended the use of loaders in the port so that the generators are not operated at low capacities. Ekmekçioğlu (2019) estimated the total emissions from ships at Izmir and Mersin ports in Turkey, taking into account the movements, propulsion capacities, and power need of ships. Between September 2017 and September 2018, a total of about 45321 and 102330 tons of CO_2 emissions were calculated in Izmir and Mersin Ports, respectively. Kökkülünk (2019) performed the energy and exergy analysis of a turbocharged generator set at different loads for a ship. The highest exergy potentials were found at maximum load in exhaust gases and cooling water, respectively. Lu (2019) investigated the optimization of the load sharing and its effect on fuel consumption for a hybrid ship model with a generator set and energy storage system. It was emphasized that the storage system could reduce the connection and disconnection frequency of generator sets. Perabo and Zadeh (2020) studied a real-time simulation model to test the electric power system on a ship. They concluded that Hardware-in-the-Loop testing is a suitable methodology for testing and validating complex control systems. Yücel *et al.* (2020) performed the analytical and numerical vibration analysis on the generator set foundations with pipe profiles on ship. They determined the optimal design of the generator base, which acts as a vibration damper. Kuzu *et al*. (2021) examined the impacts of ship emissions for Bandirma Port in Turkey based on ship activities. Particulate matter (PM_{10}), nitrogen oxides (NO_x), sulphur dioxide (SO_2), and carbon monoxide (CO) emissions were calculated as about 182, 7997, 1682, and 240 tons for the year of 2018, respectively. Yiğit (2021a, 2021b) studied the effect of the operating capacity of a ship's generators on fuel consumption. It was emphasized that operating the generators at optimum loads improves fuel consumption. Yücel (2021) determined the effect of vibration on the generator set of a ship using the operational modal analysis method. It was stated that this method could provide a significant advantage in examining the effects of generator vibrations on the ship structure.

As it can be seen from previous studies, marine diesel generators have been evaluated from different perspectives. To the best of the author's knowledge, the effect of generator load sharing on GHG emissions has not been adequately studied for ships. This issue is critical both for more efficient power production and for reducing GHGs from ships. Because in the daily working routines on a ship, marine diesel generators may not always be commissioned at optimum conditions. Commissioning of generators at low capacities may indirectly affect GHGs. Therefore, in this study, the effect of load sharing of marine diesel generators on GHGs was examined. As a result of the fuel burned for electricity generation in diesel generators, GHG emissions are formed as well as other air pollutants. GHGs are defined as CO_2, CH_4, N_2O, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) under United Nations Framework Convention on Climate Change (UNFCCC, 2021). However, HFCs, PFCs, and SF_6 are not related to fuel burning but to fugitive emissions (MEPC 75/7/15, 2020). For that reason, the changes of CO_2, CH_4, and N_2O emissions from generators depending on the fuel consumption were analyzed. Thus, it is aimed to contribute to the literature on environmental efficiency of generators in the maritime field.

2. MATERIAL AND METHOD

The power need on ships is generally provided by marine diesel generators. One or more generators are run to produce electricity on ships. Therefore, the efficient operation of the generators is critical for energy efficiency. One of the important parameters for generators is the consumption rate. It depends on the generator load. Therefore, it can be estimated how much fuel the generator should use for electricity production and which load ratio the generator consumes less fuel (Rith *et al*., 2016). Consumption rates may differ depending on the characteristics of each diesel generator. At the same time, the consumption curves of generators are likely to show similarities in general terms. This situation can be expressed in Figure 1 (Wpowerproducts, 2021).

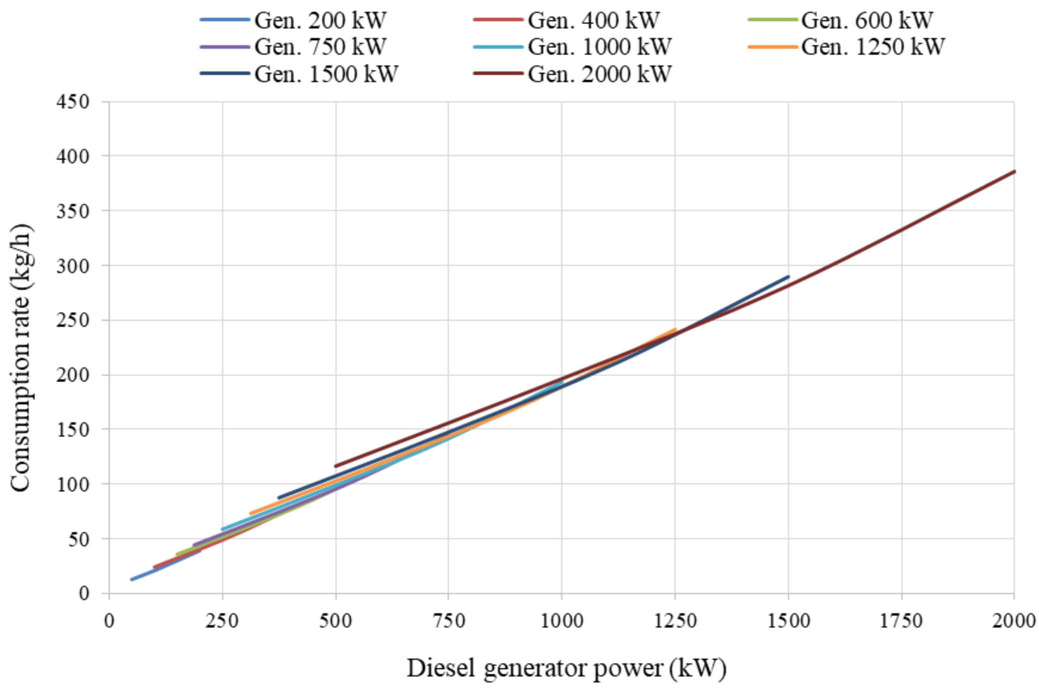

Figure 1. Consumption rate curves for different diesel generators

Figure 1 indicates the approximate fuel consumption of generators based on capacity and load ratio. It can be said that running generators at low loads increases fuel consumption, while running generators at optimum loads decreases fuel consumption. In general, the consumption rate is specified in the test catalog for certain load ratio of generators. The consumption rate corresponding to the uncertain load can be estimated by regression analysis, taking into account the polynomial functions. The polynomial function of the relationship between the consumption rate and the generator power can be represented as follows (Gan *et al*. 2015).

$$\mathrm{CR}\,(\mathrm{P_i}) = \mathrm{a_n}(\mathrm{P_i})^{\mathrm{n}} + \mathrm{a_{n-1}}(\mathrm{P_i})^{\mathrm{n-1}} + \cdots + \mathrm{a_1}(\mathrm{P_i}) + \mathrm{a_1} \quad (1)$$

Here, CR is the consumption rate (kg/h), Pi is the output power of the ith diesel generator (kW), a is the polynomial coefficients, and n is the degree of polynomial. Thus, the total fuel consumption of the generators can be expressed as follow:

$$\mathrm{FC} = \sum_{\mathrm{i}=1}^{\mathrm{N}} \mathrm{CR}\,(\mathrm{P_i}) \times \mathrm{t} \quad (2)$$

Here, FC is total fuel consumption needed for electricity production (kg), t is the operating hour of the ith diesel generator (h), N is the number of active generator.

Total GHG emissions from generators can also be estimated as follow (EEA, 2019).

$$\mathrm{E_j} = \mathrm{FC} \times \mathrm{EF_j} \quad (3)$$

Here, E_j is the total emission from generators (g), EF_j is the fuel-based emission factor (kg/ton), and j is the emission type. For the calculations, it was assumed that the ship uses marine diesel oil (MDO) as a fuel for power production. Therefore, emission factors were taken as 3206 kg/ton for CO_2, 0.05 kg/ton for CH_4, and 0.18 kg/ton for N_2O (MEPC 75/7/15, 2020).

In this study, the power system of a bulk carrier ship was taken into account. The ship's power needs are met by three identical 400 kW diesel generators. The specified consumption rates for generators were taken from literature (Başhan and Kökkülünk, 2020). As a result of the regression analysis, the consumption rate corresponding to the different powers of the generators was also obtained with a quadratic polynomial function:

$$\mathrm{CR}\,(\mathrm{P_i}) = (2 \times 10^{-5})(\mathrm{P_i})^2 + (1651 \times 10^{-4})(\mathrm{P_i}) + 12.35 \quad (4)$$

In addition, the total fuel consumption of the generators for the load sharing situations was analyzed with (2). GHG emissions corresponding to fuel consumption were also estimated with (3). Thus, the situation of commissioning generators at three different load capacities for the same power needs on the ship was discussed, and its effect on GHGs was evaluated. The method used to determine the load sharing situations in the study can be summarized as follows: in the first, second, and third situations, the primary allowable load ratio on generators was set at 40% (160 kW), 60% (240 kW), and 80% (320 kW) of their rated output (400 kW), respectively. If the first generator is insufficient to supply the necessary power, the second generator is run and the power is provided equally by the two generators. When the two generators reach the maximum allowable load ratio of their nominal capacities, the third generator is also run to meet the higher power needs. Thus, the total power is provided equally by the three generators. The load sharing situations of generators based on the maximum allowable load ratio and the typical power distribution of the electrical system of a ship can also be illustrated in Figure 2.

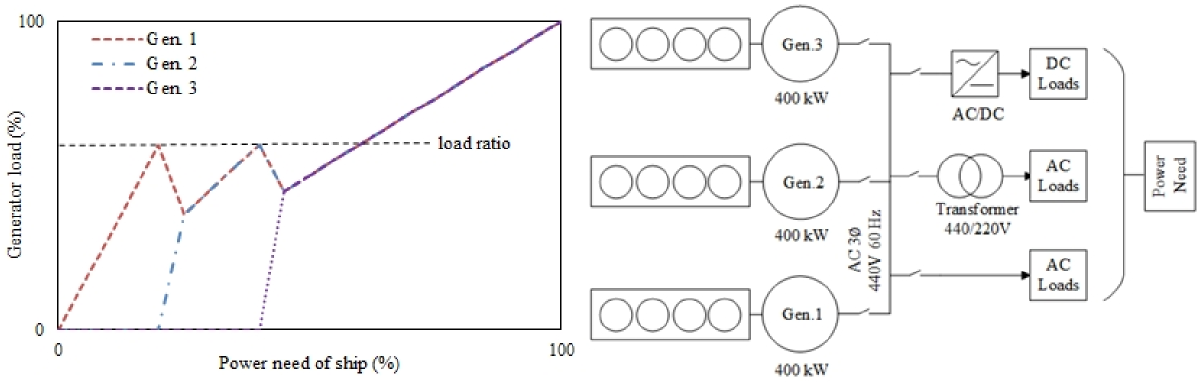

Figure 2. Load sharing of diesel generators and power system architecture of a ship

As a result, GHG emissions from the generators were analyzed for the same power need in each load sharing situation depending on the fuel consumption.

3. RESULTS AND DISCUSSIONS

The maximum allowable load ratio affects the load sharing of the generators according to the power needs of the ship. Therefore, the consumption rate varies depending on the load ratio and the power need. The changes in the consumption rate per generator for the three situations are given in Figure 3.

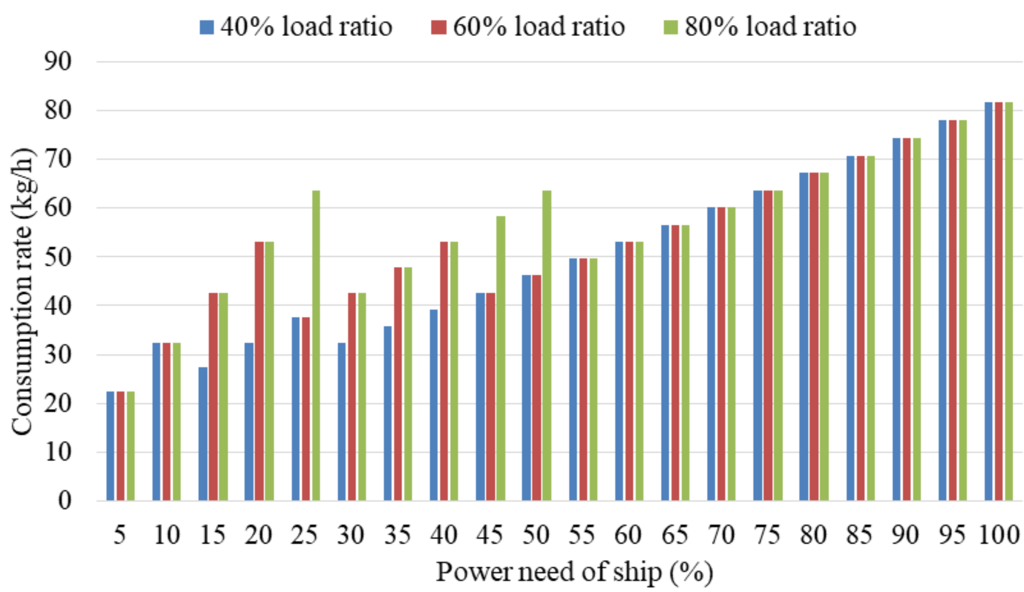

Figure 3. Consumption rate per generator

According to Figure 3, when the power need was 5% (60 kW) or 10% (120 kW) of the total capacity (1200 kW), the consumption rates were similar in all three situations. It was 22 kg/h and 32 kg/h, respectively. Because only one generator was run to meet power need. When the power need was 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 95%, or 100% (between 660 kW and 1200 kW), the consumption rates were also similar in all three situations. It was 50 kg/h, 53 kg/h, 57 kg/h, 60 kg/h, 64 kg/h, 67 kg/h, 71 kg/h, 74 kg/h, 78 kg/h, and 82 kg/h, respectively. Because all the generators were active. On the other hand, when the power need was between 15% (180 kW) and 50% (600 kW), the consumption rate per generator was different in the three situations. In this range, it showed an increasing trend, then a decreasing trend, finally a rising trend. Because different number of generators were run depending on the load sharing situation and power need. When the power need was 15% of total capacity, the consumption rate was

27 kg/h for a load ratio of 40% and 43 kg/h for load ratios of 60% and 80%. While the power necessity was 20% (240 kW), it was 32 kg/h for a load ratio of 40% and 53 kg/h for load ratios of 60% and 80%. When the need of power was 25% (300 kW), it was 38 kg/h for load ratios of 40% and 60%, and 64 kg/h for a load ratio of 80%. While the necessity of power was 30% (360 kW), it was 32 kg/h for a load ratio of 40% and 43 kg/h for load ratios of 60% and 80%. When the power need was 35% (420 kW), it was 36 kg/h for a load ratio of 40% and 48 kg/h for load ratios of 60% and 80%. While the power necessity was 40% (480 kW), it was 39 kg/h for a load ratio of 40% and 53 kg/h for load ratios of 60% and 80%. When the need of power was 45% (540 kW), it was 43 kg/h for load ratios of 40% and 60%, and 58 kg/h for a load ratio of 80%. While the necessity of power was 50% (600 kW), the consumption rate was 46 kg/h for load ratios of 40% and 60%, and 64 kg/h for a load ratio of 80%.

The total fuel consumption of the generators, depending on the load sharing situations and the power need of the ship, is also illustrated in Figure 4.

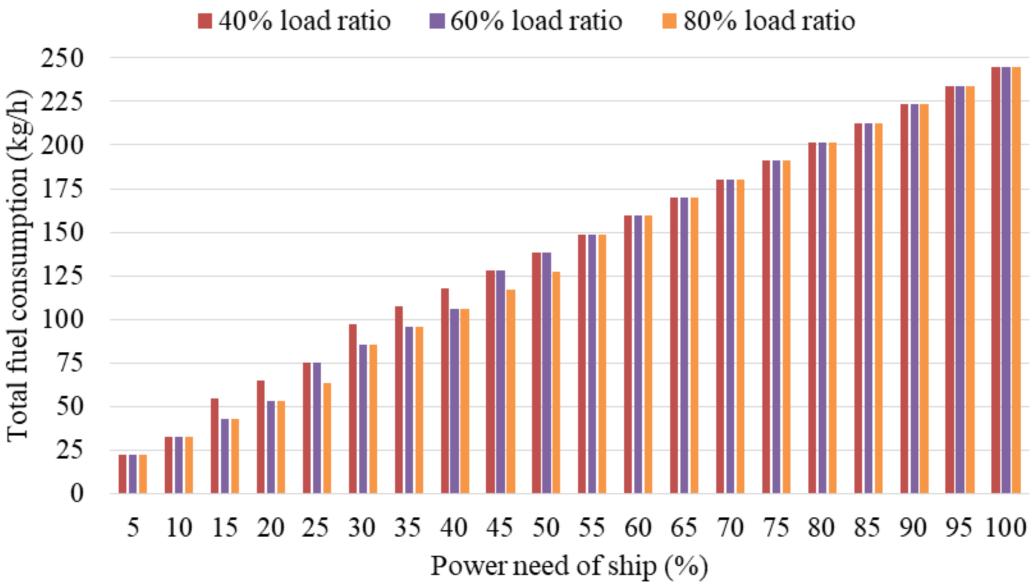

Figure 4. Total fuel consumption of the generators

According to Figure 4, when the power need was between 5 – 10% and 55 – 100% of total capacity, the total fuel consumption of the generators was similar in all three situations. It was between 22 – 32 kg/h and 149 – 245 kg/h, respectively. On the other hand, when the power need was between 15% and 50% of total capacity, total fuel consumption varied between 43 kg/h and 139 kg/h depending on the load sharing situations.

The change in the fuel consumption of generators also indirectly affects the amount of GHGs. Total GHGs from the generators, depending on the load sharing situations and the power need of the ship, are also demonstrated in Figure 5 and Figure 6.

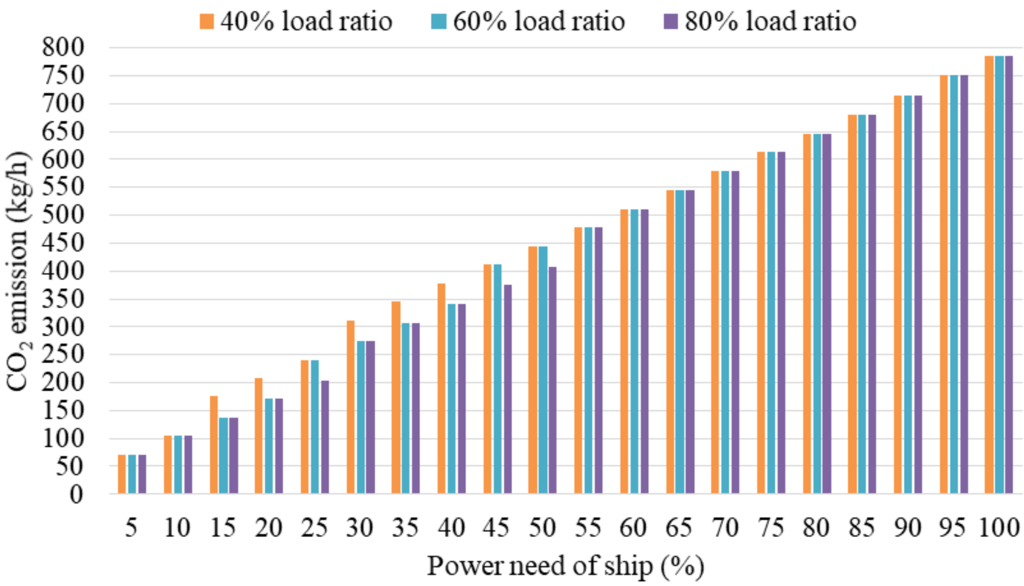

Figure 5. Total CO_2 emission from the generators

According to Figure 5, when the power need was between 5 – 10% and 55 – 100% of total capacity, the total CO_2 emissions from the generators were similar in all three situations. The hourly total CO_2 emissions were 72 kg at 5% and 104 kg at 10% of the total capacity. CO_2 was also 477 kg at 55%, 511 kg at 60%, 545 kg at 65%, 578 kg at 70%, 612 kg at 75%, 647 kg at 80%, 681 kg at 85%, 715 kg at 90%, 750 kg at 95%, and 785 kg at 100% of total capacity. On the other hand, when the power need was 15% of total capacity, the hourly total CO_2 emission was 176 kg for a load ratio of 40% and 137 kg for load ratios of 60% and 80%. While the power necessity was 20%, it was 208 kg for a load ratio of 40% and 170 kg for load ratios of 60% and 80%. When the need of power was 25%, CO_2 was 241 kg for load ratios of 40% and 60%, and 204 kg for a load ratio of 80%. While the necessity of power was 30%, it was 312 kg for a load ratio of 40% and 274 kg for load ratios of 60% and 80%. When the power need was 35%, CO_2 was 345 kg for a load ratio of 40% and 307 kg for load ratios of 60% and 80%. While the power necessity was 40%, it was 378 kg for a load ratio of 40% and 341 kg for load ratios of 60% and 80%. When the need of power was 45%, CO_2 release was 411 kg for load ratios of 40% and 60%, and 374 kg/h for a load ratio of 80%. While the necessity of power was 50%, the hourly total CO_2 emission was 444 kg for load ratios of 40% and 60%, and 408 kg for a load ratio of 80%.

In addition, total CH_4 and N_2O emissions depending on the load sharing situations are given in Figure 6.

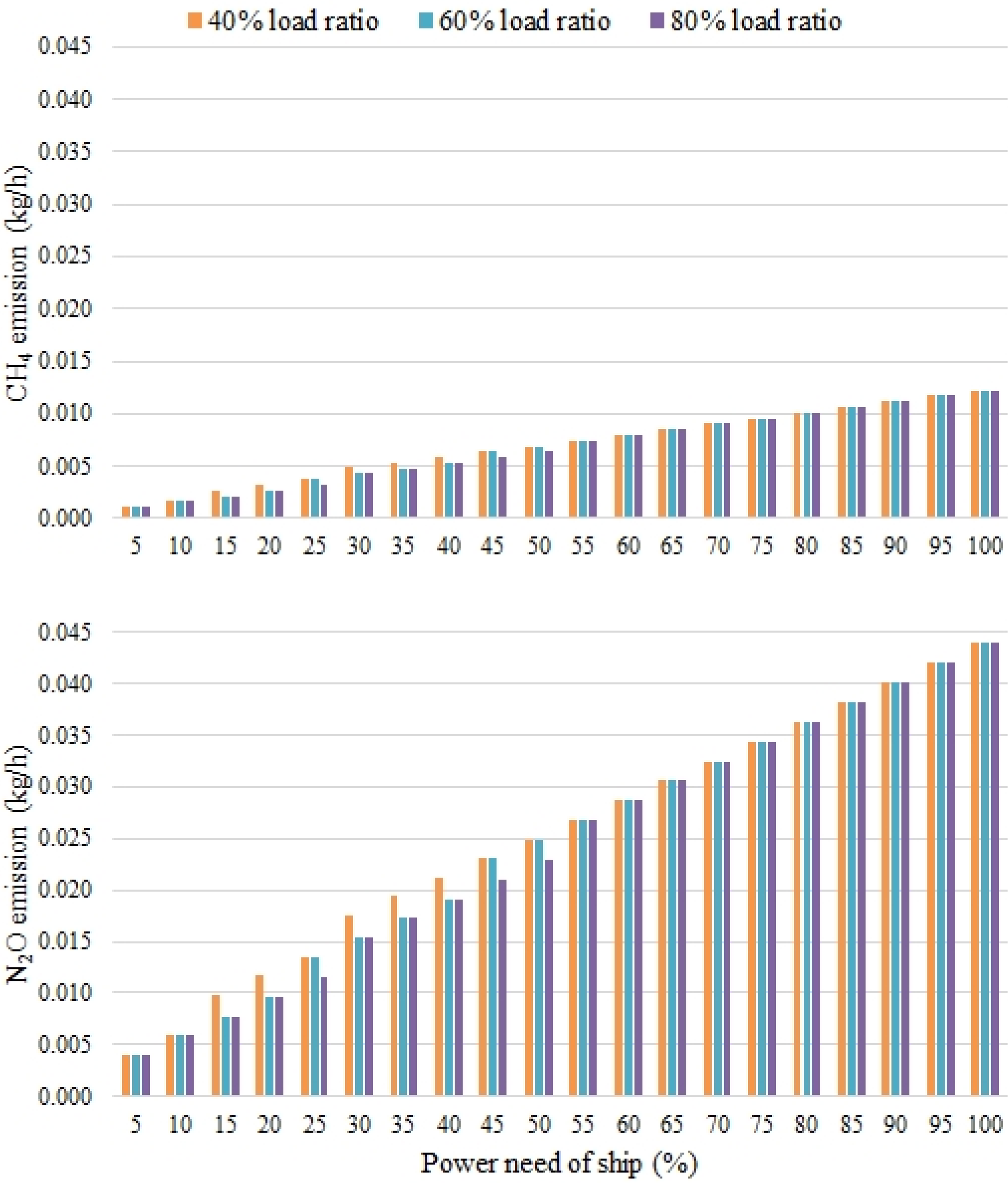

Figure 6. Total CH_4 and N_2O emissions from the generators

Figure 6 shows that CH_4 and N_2O emissions were also similar between 5 – 10% and 55 – 100% of total capacity at three load ratio situations. On the other hand, when the power need was between 15% and 50%, the emissions of CH_4 and N_2O were also different in the three situations. Estimated emissions are very low compared to CO_2. CH_4 varied between 5 – 10% of the total capacity from 0.001 to 0.002 kg/h. When the power was between 15 – 50% of its total capacity, it carried out between 0.003 – 0.007 kg/h. Hourly emissions in this range were slightly different for each load ratio situation. While the power requirement was also between 55 – 100% of the total capacity, the amount of CH_4 was between 0.007 – 0.012 kg/h. In addition, N_2O changed between 5 – 10% of the total capacity from 0.04 to 0.06 kg/h. It realized as between 0.010 – 0.025 kg/h when the power capacity was between 15 – 50%. Hourly emissions in this range were slightly various for the three load ratio situations. For the power capacity of 55 – 100%, the amount of N_2O was also between 0.025 – 0.044 kg/h.

The results show that the load sharing ratio affects GHG emissions from generators when the power needs of a selected ship are between 15% and 50% of the total capacity. While maximum GHGs from generators were realized at a 40% load ratio, minimum GHGs occurred at an 80% load ratio. Changes in

GHGs are also given in Table 1 when the primarily maximum allowable load ratio on generators is set to 60% and 80% instead of 40%.

Table 1. The decrease of GHGs compared to 40% load ratio

Power need of ship		60% load ratio				80% load ratio			
%	kW	%	CO_2 (kg/h)	CH_4 (kg/h)	N_2O (kg/h)	%	CO_2 (kg/h)	CH_4 (kg/h)	N_2O (kg/h)
15	180	22	39	0.001	0.002	22	39	0.001	0.002
20	240	18	38	0.001	0.002	18	38	0.001	0.002
25	300	0	0	0.000	0.000	15	37	0.001	0.002
30	360	12	38	0.001	0.002	12	38	0.001	0.002
35	420	11	38	0.001	0.002	11	38	0.001	0.002
40	480	10	37	0.001	0.002	10	37	0.001	0.002
45	540	0	0	0.000	0.000	9	36	0.001	0.002
50	600	0	0	0.000	0.000	8	36	0.001	0.002

Table 1 indicates that GHG reductions are achieved for some power needs on the ship at 60% and 80% load ratio practices of generators compared to 40%. It can be said that maximum GHG reduction is achieved when the power need is 15% of the total capacity. The decrease in GHGs was 22% for both situations. In addition, an 80% load ratio application in generators provided more GHG savings than 60%.

As a result, it is possible to state that operating marine diesel generators as close to their nominal capacities as possible will contribute to the decrease of emissions. Thus, this awareness can contribute to the IMO's efforts to decrease GHG emissions and the effects of climate change from shipping.

4. CONCLUSIONS

In this paper, the effect of efficient operation of marine diesel generators on greenhouse gas emissions is emphasized. The changes in CO_2, CH_4, and N_2O resulting from three different generator load sharing practices under the same power need are estimated for a bulk carrier ship. The load ratio of the generators is set at 40%, 60%, and 80%, respectively. Thus, when the active generators reach the defined load ratio, the next generator starts to run synchronously. In this way, it aims to estimate greenhouse gas emissions that may occur as a result of possible load sharing situations among the generators on a ship. The results show that there are no emission changes for each load sharing situation when the power need is between 0 – 15% and 50 – 100% of the ship's total capacity. Because in order to meet these power needs on the ship, either a single generator or all generators must be activated. On the other hand, when the power need is between 15% and 50% of the total capacity, the load sharing ratio of generators affects emission releases. Because the same power need can be met with different generator numbers in these intervals. The maximum greenhouse gas emission saving was 22% for 60% and 80% load ratio practices compared to 40% while the power need was 15% of the total capacity. When the power need was 20% of the total capacity, the saving rates were also 18% in both situations. It can also be stated that an 80% load ratio application in generators will save more greenhouse gases in some power needs compared to a 60% load ratio. For this reason, providing the power need by operating the generators at optimum capacity as much as possible will contribute to the reduction of greenhouse gas emissions on the ship. Thus, a certain rate of improvement can be achieved in the ship's electrical system.

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