World Journal of
Environmental Research

Volume 10, Issue 2, (2020) 50-60

www.wjer.eu

Increasing ship energy efficiency and emission reduction with diesel-electric propulsion system

Murat PAMIK [a*], Dokuz Eylül University Maritime Faculty, Adatepe Neighborhood Dogus Street No: 207/0, İzmir 35390, Turkey

Mustafa NURAN [b], Dokuz Eylül University Maritime Faculty, Adatepe Neighborhood Dogus Street No: 207/0, İzmir 35390, Turkey

Suggested Citation:

Pamik, M & Nuran M (2020). Increasing ship energy efficiency and emission reduction with diesel-electric propulsion system. *World Journal of Environmental Research*.10(2), 50-60. https://doi.org/10.18844/wjer.v10i2.5345

Received from August 20, 2020; revised from October 11, 2020; accepted from December 15, 2020;

Selection and peer review under responsibility of Assoc. Prof. Dr. Murat Sonmez, Middle East Technical University, Northern Cyprus Campus, Cyprus.

Abstract

Today, the goal of reducing fossil fuel consumption and increasing the use of renewable energy is one of the most important issues in the maritime field. Regulations created by IMO in order to prevent environmental and air pollution in the maritime field have increased its effect day by day and made it necessary to move away from conventional systems and turn to alternative systems. Although studies in the area of using fully electric marine vehicles or using fully renewable energy systems are also ongoing, they are not preferred due to the high costs and lack of sustainability. While the use of Diesel Electric (DE) Propulsion System in marine vehicles is one of the alternatives in this field, it may be the most efficient choice with the improvements made on this system. The aim of this study is to examine the increase in ship energy efficiency using diesel-electric propulsion systems rather than the original ferry system.In the study, the historical development of the DE Propulsion System was investigated and other studies on the subject were examined. Detailed navigation data of a ferry using fossil fuels in the Gulf of Izmir were recorded, and a case study was carried out to examine the status of this ship's DE Propulsion System by using data such as engine load and fuel consumption. According to the results obtained, it has been revealed that using the DE Propulsion System can be much more efficient in terms of fuel consumption and emissions. It has been observed that the system provides benefits in terms of reliability and reduction of noise pollution. For future studies, it may be aimed to provide the ferry to be charged from the port and to increase the benefits of the system by using renewable energy.

Keywords: Diesel-Electric, Energy Efficiency, Emission,ship

* ADDRESS FOR CORRESPONDENCE: Murat PAMIK, Dokuz Eylül University Maritime Faculty, Adatepe Neighborhood Dogus Street No: 207/0, İzmir 35390, Turkey.

1. Introduction

The world population continues to increase day by day, and more than 80% of the growing trade volume due to globalization is sea transportation [1]. The heavy reliance on maritime transport has also led to an increase in pollution from ships. In this context, [2] predict that exhaust emissions from marine activities will triple by 2050 .

The dilemma of the size of fossil fuel reserves and how long we can continue to use them effectively is a fundamental question to be answered. [3] established an econometrics model to calculate when fossil fuel reserves will be depleted and to explain the relationship between fossil fuel reserves and some basic variables. According to this model, the only fossil fuel remaining after 2042 will be coal, and oil and gas will be depleted by 2042.

In recent years, electric propulsion systems have been preferred for many types of ships. Such systems, which are powered by electric motors and driven at variable speeds, where power stations are established with diesel generators or gas turbines, have been found to be useful in various aspects. Reduced fuel consumption and exhaust emissions, low maintenance costs, improved maneuverability, high reliability, reduced noise and vibration are some of these benefits [4].
After many experimental applications of battalions, in the late 19th century in Russia and Germany, electric power steering systems were used, and the first generation of electric propulsion systems were used in the 1920s as a result of the empowerment of shortening the passenger transit passenger capacity. In those years, high propulsion power could only be met by turbo electric motors. 'SS Normandie' is one of the best known in this area [5].

Developments in variable-speed electric drive systems have created electric-propulsion systems based on the energy station and typical second-generation electric propulsion systems, first with AC / DC rectifiers in the 1970's and then with AC / AC converters in the early 1980's [6] [7]. The stationary voltage and frequency energy station consists of a generator group which, together with the propulsion, feeds the same mains that meets the energy needs of hotel power and auxiliary machinery. Propulsion system; variable speed control with fixed blade angled propellers. This solution has been used exclusively on specific vessels such as research vessels and icebreakers, as well as on passenger ships. The 'SS Queen Elizabeth II' was transformed into an electric propulsion system in the mid-1980s, followed by the Fantasy and Princess class passenger ships, several Dynamic Positioning (DP) ships and a shuttle tanker.

This system, which started with the use of diesel machinery in ships in 1903 and then transferred the power produced from the diesel machine to electric motors, has been further developed over the years. By 1995, the fleet of electric propulsion systems in the world has found 269 pieces that was built in. In 2013, this fleet increased rapidly to 1750 and 199 of them were built on this date [8].
Electric propulsion system is preferred in various ship types due to its different advantages. It is often preferred for cruise ships because it provides a safer and comfortable voyage with low noise and vibration [5][9]. Platform supply vessels, oil and gas exploration vessels, pipe laying vessels and icebreaking vessels prefer electric propulsion systems because of the compatibility of dynamic positioning systems which keep the sheep’s position constant [10]

Several researches have considered better or more efficient ways of increasing energy consumption [11] especially the ship’s fuel energy. [12] for instance studied how to use electric propulsion to increase efficiency. [13] also studied how using electric propulsion system is sustainable and could reduce pollution. [14] also studied diesel-electric in comparison with hybrid-electric propulsion system. Evidently, there have been several researches around this area, but most of these researches were conducted in different locations with different ferries and under different conditions. This research therefore aims to extend the current literature in this area, by examining the increase in ship energy efficiency using diesel-electric propulsion systems rather than the original ferry system in the Izmir area of Turkey.

From the previous studies, this research came up with the following hypothesis:

H1: Diesel-electric propulsions will increase ship energy efficiency

To guide this study, the following research questions were asked:

RQ1: Are diesel-electric ferries more energy efficient than ferry originals?

RQ2: Do diesel-electric propulsion system ferries reduce emissions?

2. Method

This research was an experimental research. For secondary data, the research made use of previous research findings. For primary data, the researchers made use of a case study in arriving at the findings for the research. Three ferry ships were the subject of the study. Their movements were observed over a period. However, the number of trips they went on was considered rather than the period. The three ferries movements served as the data for this research. In total, the number of trips that was considered for the research was the ferry's daily trip which was twenty-six in total. The average load per trip was also considered as well as Propulsion Power, Fuel Consumption and Main Engines Specific Fuel Consumptions of 26 trips of Ferry. At the end, consumption differences between Ferry original and Ferry Diesel Electric were considered.

In this study, the load characteristics of a ferry operating in the Gulf of Izmir were examined, and it was aimed to show how the fuel consumption would be affected by using a Diesel-Electricity propulsion system and how the generated gas emissions would change accordingly.

The electrical efficiency of the system is:

$$\eta = \frac{Po}{Pi} = \frac{Po}{Po - Pl} \qquad (1)$$

Where Po is power outlet, Pi is power inlet and Pl is power loss. For each of the components, the electrical efficiency can be calculated, and typical values at full (rated) power are for; generator: η = 0.95-0.97, switchboard: η = 0.999, converters: η = 0.98-0.99 and electric motor: η = 0.95-0.97 [5]. Also, batteries have (Li-Ion): η = 0.8-0.9 efficiency value, but in this study, it is not considered [15]. Therefore, the efficiency of a diesel electric system from the diesel engine shaft to the electric drive motor shaft is normally between 0.88 and 0.92 at full load. Efficiency depends on system loading.

3. Results

3.1 Findings from previous research

Figure 1 shows us the numerical development of electrical propulsion systems over the years and the types of ships they are used in. In 1995, the electric propulsion fleet was built from 269 units, and 11 units were delivered that year. In 2013, the fleet consisted of 1750 units, with 199 units delivered that year alone [16].

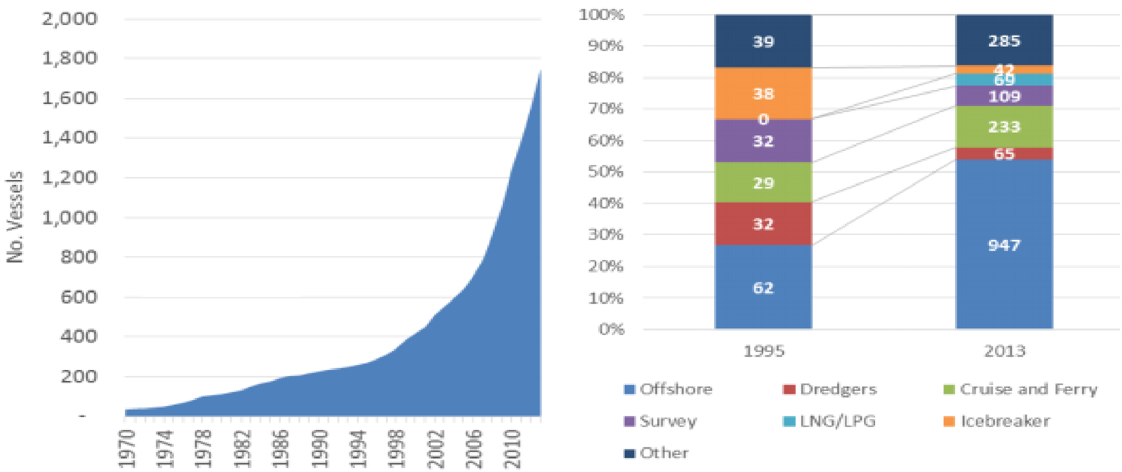

Fig.1 - Development and distribution of electrical propulsion fleet [16].

According to a study by Adroit Market Research in 2019, the hybrid electric marine propulsion engine market is estimated to reach USD 708.6 million by 2025, growing at a CAGR (Compound annual growth rate) of 7.3% during the forecast period. Increase in commercial shipping is majorly driving growth of this market.

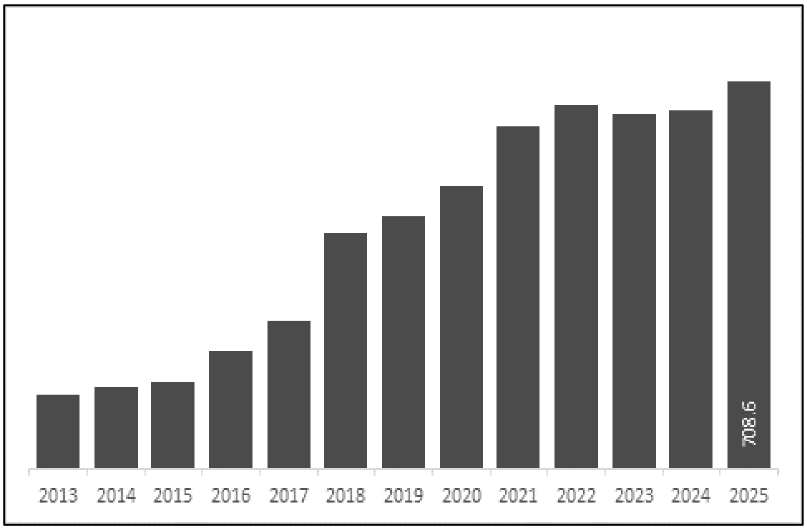

Fig. 2 electrical propulsion systems forecasting 2013 to 2025 [17].

The implementation of hybrid electric propulsion engines on offshore vessels are gaining momentum. The hybrid electric propulsion engines have resulted in reduced fuel consumption and CO_2 emission levels thereby improving efficiency and decreasing cost of operations [17].

In the new emission legislation, there has been a greater shift towards hybrid marine propulsion and power systems. The most important developments in DE system have been with the inclusion of batteries in the system and the emergence of technologies that allow DC grid. New diesel-electric power generation technology is emerging with energy storage devices such as batteries, supercapacitors, and fuel cells. In addition, thanks to DC grid, the increase in efficiency reaches levels to meet high costs. Previously, the efficiency of the system was limited by the efficiency the generators had to supply AC voltage at a certain frequency (usually 50 or 60 Hz) to the main switch board [18].

3.1.1 Increasing efficiency in Diesel Electric Propulsion System

The least fuel consumption in fixed speed diesel engines is generally obtained in the maximum continuous rate of 80-85% (Figure 3). At low engine loads, fuel efficiency decreases significantly. Thanks to the DC grid technology developed by ABB, variable speed diesel engines were used, and loss of efficiency was prevented. The main difference of DC grid technology from a conventional AC system is that electrical power is fed from the generator through a rectifier to a common DC bus. Thus, all elements that will use energy are fed from their own inverter units. In order to make the system more efficient, energy storage devices and further converters can be easily added [19].

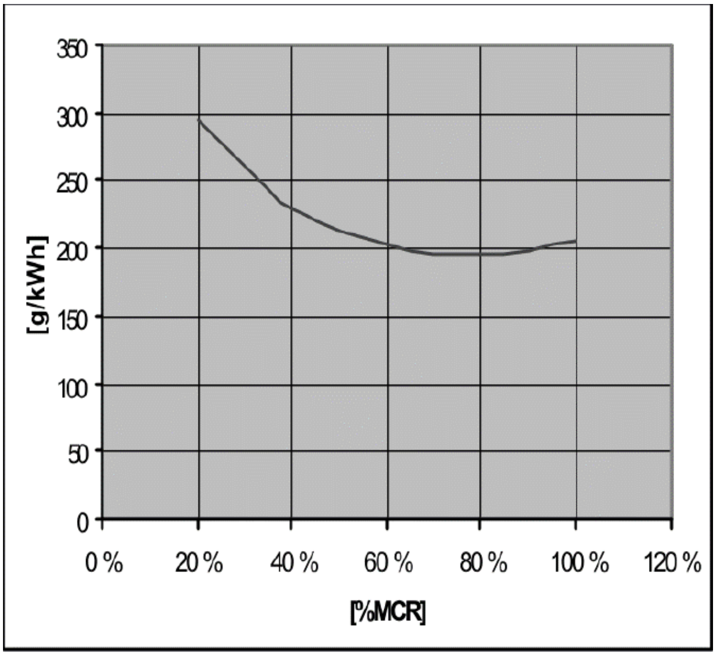

Fig. 3: Fuel efficiency curve depending on the load for constant speed diesel engines [5].

Figure 4 shows a single line diagram of a diesel-electric power system using on-board DC grid. Diesel engines can now be controlled independently of each other. Although the ship's energy needs are variable, an efficient, stable load balance can be created. All energy consumers are fed by their own inverter units. In this way, propeller transformers and AC panels are no longer needed. Thanks to the reduced equipment, the total weight and volume of the new system is decreased.

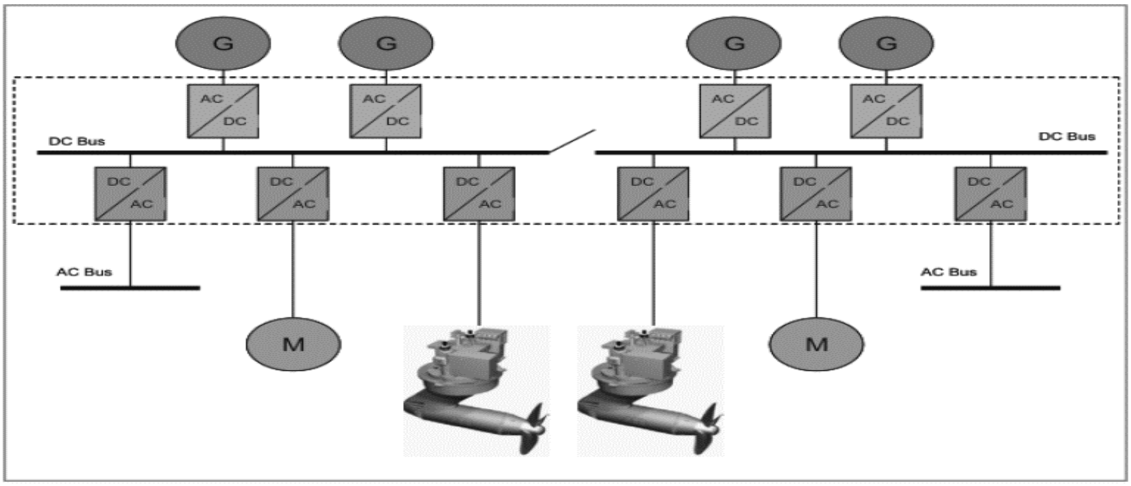

Fig 4: Single line diagram for a diesel-electric propulsion system with the on-board DC grid installed [18]

In addition to reducing fuel consumption and emissions, Diesel-Electric Propulsion System has quieter and less vibration feature, allowing a much more comfortable journey. Also, the system with increased manoeuvrability provides a much safer navigation opportunity [20]

3.2. Findings from current research

Lenght Over All	39 M	Lenght Between Perp.	38,12 M
Breadht	11,6 M	Depth	3,5 M
Gross Tonnage	488 GT	Net Tonnage	146 T
Propellers	2*CPP	Bunker Capacity	9,38 M3
Full Speed	20 Knot	Maneuvering Speed	8 Knot
Pax Capasity (Summer)	426	Pax Capasity (Winter)	426
Main Engines	2*736kw	Aux, Engines	2*106kw

Fig. 5: Particulars of the ferry

Figure 5 shows the essential characteristics of the ferry under study. Two 12-cylinder, high-speed diesel engines are used as the main engine in the propulsion system. While each machine generates 736 kWh of power, the total maximum propulsion power of the ship is (P_M) 1472 kWh, approximately 2000 hp.

Two diesel engines are also used to meet the electricity needs of navigational equipment, auxiliary machinery, air conditioners and lighting on board. These machines are also capable of generating 212 kWh (P_J) of total electrical energy.

Cruising distance of approximately 2.38 nautical miles with a speed of approximately 9.5 knots and the cruising time of the ferry, including the arrival and departure maneuvers, is 15 minutes. After staying at the port for 5 minutes, it returns the same route at the same time. The ferry makes 26 trips a day. There are 78 trips on the same route with two similar ferries. The number of trips only reduces on Sundays, where the trips are 72 instead of 78.

The fuel consumption (F_C) of the ferry was measured and it was found to be 38.81 liter for a cruise. Total fuel consumption was calculated as 3,027.3 liters for a total of 78 voyages per day (all voyages were considered to be equal). The density of the fuel used (at 15C°) was taken as ρ = 880g / dm^3 from the Safety Data Sheet (SDS) found on board. Since Specific Fuel Consumptions (SFC) will be used frequently to better express the transactions, the fuel consumption value is converted to grams.

The generators are assumed to operate at constant load and are excluded from the total fuel consumption by considering the engine manufacturer's catalog data. Thus, only the fuel consumption of the propulsion system is evaluated. In addition to the fuel consumption, the instantaneous load characteristic of the ferry was also recorded, and the results are given in table 1 below.

Table 1: Propulsion Power, Average Load, Fuel Consumption
and Main Engines Specific Fuel Consumptions of 26 trips of Ferry.

Trip Number	Propulsion Power (P_M) (kWs)	Average Load λavg (%)	Fuel Consumption F_C (liter)	Main Engines Specific Fuel Consumptions SFC (g/kWs)
1	604,4	41,06	40,5	220,43
2	490,61	33,33	37	246,94
3	557,45	37,87	39,5	232,69
4	549,49	37,33	39	232,85
5	582,9	39,6	40	225,55
6	495,47	33,66	37	244,52
7	577,9	39,26	39,8	226,28
8	545,52	37,06	39	234,55
9	565,24	38,4	39,6	230,1
10	496,5	33,73	37	243,52
11	594,68	40,4	40	221,08
12	535,8	36,4	38,5	235,52
13	611,32	41,53	40,8	219,66
14	501,36	34,06	37	241,16
15	558,32	37,93	39,5	232,32
16	496,5	33,73	37	243,52
17	584,82	39,73	40	224,8
18	521,97	35,46	38	238,38
19	578,93	39,33	39,8	225,87
20	546,55	37,13	39	234,1
21	566,13	38,46	39,4	228,49
22	497,53	33,8	37	243,02
23	550,28	37,4	39,2	233,8

24	523	35,53	38	237,91
25	583,79	39,66	40	225,2
26	512,25	34,8	37,5	239,63

Using the power values of the ferry, the propulsion system will be simulated as diesel electric. Thus, the prime movers' loads will be kept in the more efficient 70% -80% range, not at inefficient low loads, and the results will be shown in the table again.

The maximum power the new system should have be capable of supplying the power of the main engines and the generator of the ferry.

$$P_{DE} = P_M + P_j \tag{2}$$

Where: P_{DE} is Diesel Electric Propulsion System Power

When the values in Fig. 5 are transferred to the formula, we find the total power of the system PDE 1578 kW. Thus, the system can be set up with 4 generators, each with a capacity of 405 kW (P_{DEJ}). In this way, by adjusting the number of generators according to the ship's power needs, it is aimed to operate the engines in the most efficient way. The specific fuel consumption (SFC) value is determined for the new average load λDE_{avg} taken by using the characteristic fuel consumption graph of the diesel engine. How the values change with the Diesel Electric Propulsion System is shown in the table 2.

Table 2: Propulsion Power, Average Load, Fuel Consumption, Diesel Motor Specific Fuel Consumptions and Consumption differences between Ferry original and Ferry Diesel Electric.

Trip Number	Propulsion Power kWh(P_{DE})	Average Load % (λDE_{avg})	Specific Fuel Consumption g/kWh (SFC)	Total Fuel Consumption liter F_C	Fuel Consumption Differences (ΔF_C)
1	646,8	79,85	196	36,015	4,485
2	533,01	65,8	199	30,133	6,867
3	599,85	74,05	197	33,57	5,93
4	591,89	73,07	197	33,125	5,875
5	625,3	77,19	196	34,817	5,183
6	537,87	66,4	199	30,107	6,593
7	620,3	76,58	196	34,539	5,261
8	587,92	72,58	197	32,903	6,097
9	607,64	75,01	196	33,834	5,766
10	538,9	66,53	199	30,466	6,534
11	637,08	78,65	196	35,473	4,527
12	578,2	71,38	197	32,359	6,141
13	653,72	80,7	196	36,4	4,4
14	543,76	67,13	198	30,586	6,414
15	600,72	74,16	197	33,619	5,881
16	538,9	66,53	199	30,466	6,534
17	627,22	77,434	196	34,924	5,076
18	564,37	69,67	198	31,745	6,255
19	621,33	76,7	196	34,596	5,204
20	588,95	72,7	197	32,961	6,039
21	608,53	75,12	196	33,884	5,516
22	539,93	66,65	199	30,524	6,476
23	592,68	73,17	197	33,169	6,031
24	565,4	69,8	198	31,803	6,197

25	626,19	77,3	196	34,867	5,133
26	554,65	68,47	198	31,199	6,301

The fuel consumption differences shown in Table 2 are used in equation 3 to calculate the total fuel savings ($\mu 1$) in 1 day for 3 sister ships. By accepting this data as an average value for each day in the year, the fuel savings (μy) to be made on this line in a year is also found.

$$\mu 1 = 3\sum_{x=1}^{26} \Delta F_C \tag{3}$$

Although we do not have any data on the exhaust emissions of the ferry, it is possible to calculate the emission reductions resulting from the fuel savings. To make this calculation, fuel-based emission table was used from the study prepared by Buhaug J. et al and presented in the second greenhouse gas study of IMO in 2009. These factors are shown in Fig. 6 one except for NO_x emissions to take MARPOL Annex VI into consideration.

	(kg/tonne of fuel)	
CO	7.4	
CO_2	3130	*Residual fuel oil*
	3190	*Marine diesel oil*
NO_X	85	*Slow-speed diesel engine*
	56	*Medium-speed diesel engine*
N_2O	0.08	
PM	6.7	*Residual fuel oil*
	1.1	*Marine diesel oil*
SO_2	54	*Residual fuel oil (2.7 % S)*
	10	*Marine diesel oil (0.5 % S)*

Fig. 6: Fuel-based emission factors [21]

Although the specified emission factors vary depending on the engine load and combustion quality, they are important in terms of easy calculation and have been used in many scientific studies. The Table 3 is created by using the fuel savings value calculated with Equation 3 and the emission factors specified in Figure 6, and this table shows the change in emissions related to fuel consumption.

Table 3. Fuel Saving and Emission Reduction with Diesel Electric Propulsion System

	Fuel Saving (kg) or Emission Reduction (kg)
Marine Diesel Oil	125733,316
CO	930,426
CO_2	401089,278
PM	138,306
SO_2	251,466

Table 3 shows the gains obtained with the Diesel Electric Propulsion System. While composing this table, the factors in Figure 6 for Marine Diesel Oil were taken into consideration, and for SO_2 emission, correction was made according to the sulfur value of 0.1% taken from the SDS form.

4. Discussion

The aim of this study was to examine the increase in ship energy efficiency using diesel-electric propulsion systems rather than the original ferry system. Three sister-ferry-ships located in Izmir were the subject of the study. The study experimented the diesel-electric systems on the ships in the treatment group alongside the ships in the control group. The results from twenty-six different trips from each of the groups were collected and they were analyzed with the differences observed as well.
From the results of the study, it was evident that the diesel-electric propulsion system was more efficient than the ferry original. The hypothesis was therefore accepted. This finding confirms. The fuel consumption for ferry diesel-electric was lower than the fuel consumption for ferry original. This finding conforms with the findings of [22] and [14].
The research also calculated the emission of diesel-electric propulsion system ferries and based on the reduced fuel consumption; the calculated fuel reduction was deduced. The second research question 'Do diesel-electric propulsion system ferries reduce emissions?' was therefore answered. This showed that diesel-electric propulsion system reduces emission of toxic gases into the air. It therefore addresses sustainability issues, while providing efficient energy for ships. Diesel-electric ferries therefore addresses two needs at the same time. This finding is in collaboration with the findings of [13], [23] [2].

5. Conclusion

Based on the work discussed in the foregoing, it has been shown that the Diesel Electric Propulsion system can be more advantageous than the conventional system on ferries in the Gulf of Izmir. Installation of several sets of generators, more attractive than two sets of large diesel engine. It has been observed that fuel consumption can be reduced significantly.

In this study, batteries were not included in the system, but it is predicted that much better results can be obtained by integrating the batteries in future studies. By reducing fuel consumption-related emissions, it is easier to comply with new regulations and an environmentally friendly system can be introduced. For future studies, it may be aimed to provide the ferry to be charged from the port and to increase the benefits of the system by using renewable energy.

References:

[1] T. İnan, and A. F. BABA, "Prediction of geostrophic currents using big weather data archive and neural networks for the Aegean Sea", *Global Journal of Computer Sciences: Theory and Research*, 9(1), 10–20, 2019.

[2] H. Wang, and G. Hon,"Reducing Greenhouse Gas Emissions from Ships: Cost Effectiveness of Available Options", *International Council for Clean Transportation* ,ICCT 2011.

[3] S. Shafiee and E. Topal, " When will fossil fuel reserves be diminished?" *Energy policy*, *37*(1), 181-189,2009.

[4] J.F. Hansen, "Modeling and Control of Marine Power Systems. Doktora Tezi, Norwegian University of Science and Technology, Department of Engineering cybernetics," Trondheim, Norway, 2000.

[5] A.K. Ådnanes, "Maritime electrical installations and diesel electric propulsion", ABB AS Marine and Turbocharging Tutorial, September 2015.

[6] V. Mrzljak and T. Mrakovčić, " Comparison of COGES and diesel-electric ship propulsion systems", *Pomorski zbornik*, (1), 131-148, 2016.

[7] V.R Aravind and M.K. McConnell, " A computer-based tutor for learning energy and power," *World Journal on Educational Technology: Current Issues*, 10(3), 174–185, 2016.

[8] J. W.Arrington, "The Analysis of Components, Designs, and Operation for Electric Propulsion and Integrated Electrical System. Naval postgraduate school monterey ca, Sep. 1998.

[9] K. Harangus, Z.I Horváth and E. Szentes, "Existing and to be developed teacher competences in engineer teacher training", *Contemporary Educational Researches Journal*, 10(4), 123–130, 2020.

[10] A.T Anıker, "Gemi manevrası ve dinamik konumlandırma sistemi." 2015.

[11] E. Gurer, O. Taylan and T. Yuksel, "Driving cycle and temperature effects on the energy performance of a solar-powered electric vehicle in Istanbul", *World Journal of Environmental Research*, 8(1), 8–16, 2018.

[12] C. Nuchturee, T. Li and H. Xia, "Energy efficiency of integrated electric propulsion for ships – A review", Renewable and Sustainable Energy Reviews, vol. 134, p. 110145, 2020.

[13] N.P Nguyen , A.T. Hoang, S. Nizetic , X.P. Nguyen , A.T Le , C.N Luong, V.D Chu, V.V Pham, "The electric propulsion system as a green solution for management strategy of CO2 emission in ocean shipping: A comprehensive review", *International Transactions on Electrical Energy Systems*. 7:e12580, Sep 2020.

[14] V.G. Bolbot, E. Theotokatos, Boulougouris, and D. Vassalos. "Comparison of diesel-electric with hybrid-electric propulsion system safety using System-Theoretic Process Analysis," 2019.

[15] T.B Reddy, "Linden's handbook of batteries (Vol. 4)", New York: Mcgraw-hill, 2011.

[16] H. Pestana, "Future trends of electric propulsion and implications to ship design", 2014.

[17] Adroit Market Research , "Global Hybrid Electric Marine Propulsion Engine Market Size by Capacity ", 2019.

[18] Siemens, "Solutions and products for electric propulsion/drives", 2020.

[19] O. D. ABB, "The step forward in power generation and propulsion", 2015.

[20] E. Sofras, and J. Prousalidis, "Developing a new methodology for evaluating diesel—electric propulsion," *Journal of Marine Engineering & Technology*, *13*(3), 63-92, 2014.

[21] J. Buhaug, Corbett, V.Endresen, J. Eyring, S. Faber, D. Hanayama, D. Lee, H. Lee, A. Lindstad, Markowska, et al., "Second IMO GHG study 2009," *International Maritime Organization (IMO*) London, UK, vol. 20, 2009.

[22] B. Jeong, E. Oguz , H. Wang , P. Zhou , "Multi-criteria decision-making for marine propulsion: Hybrid, diesel electric and diesel mechanical systems from cost-environment-risk perspectives. Applied Energy," 15;230: pp.1065-81, Nov 2018.

[23] M. Dibra and S. Baraku, "Regeneration of the protected area of Lake Shkodra for sustainable tourism development. Global Journal of Business, Economics and Management: Current Issues, 9(3), 95–104, 2019.