

## An assessment on the efficient use of hybrid propulsion system in marine vessels

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### Abstract

Many improvements are performed in the maritime industry to ensure sustainability and energy efficiency. The use of hybrid propulsion systems (HPS) in marine vessels constitutes one of the developments in this field. In this study, both economic and environmental benefits are targeted. The study aims to reduce the high fuel consumption of the engine per unit power at low loads and minimization of emissions by sourcing them from main engine by HPS. Overcoming the limitations of Annex VI (Prevention of Air Pollution from Ships) of International Convention for the Prevention of Pollution from Ships (MARPOL) are desired and the research hopes for a beneficial result on Energy Efficiency Measures such as Energy Efficiency Operational Indicator (EEOI). A comprehensive study is accomplished on the hybrid propulsion system components and the keywords used in the literature review are revealed. Furthermore, the articles that have "efficiency", "vessel", "propulsion" and "marine" topics published in Web of Science (WOS) between 1975-2020 are examined and 44 studies are obtained. The studies that have been reached are analyzed and interests of them are collect under the 18 heading and the focal point of each study is highlighted in article. According to the results, the hybrid system provides low fuel consumption, minimizes emissions and costs, complies with the regulations of the International Maritime Organization, uses renewable energy sources, encourages the use of electric motors in addition to internal combustion engines, increases the efficiency of energy storage systems among other things. This article will be a significant resource for academicians, experts and companies on the Hybrid propulsion system in setting their focus.

Keywords: Hybrid propulsion, Energy saving, Global warming.

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## 1. Introduction

In the first stage of the study, comprehensive information about diesel engines and electric motors used in the hybrid propulsion system is described. In addition, reports on IMO's limitations, regulations and measures are highlighted and related formulas are given in the maritime sector. The main outcomes are determined with a particularized literature review based on the relevant topics that includes "efficiency", "vessel", "marine", "propulsion" and "hybrid" words in Web of Science (WOS). The results obtained from literature review are evaluated and discussed. Eventually, taking into consideration the benefits and difficulties of fundamental goals on marine vessels are explained in the conclusion part.

### 1.1. Diesel Engines and Electric Motors

Diesel engines used in the propulsion system of ships' working principle is provided with heat input at constant pressure patented by Rudolf Diesel [1]. Diesel engines are compression ignition machines [2]. Comparing diesel engines with other internal combustion engines, their usage area is quite common [3]. Diesel engines are used in almost all types of transportation [4]. Diesel engines are extensively installed in automobiles, light commercial vehicles, heavy goods vehicles, construction and agricultural machinery, railway locomotives and marine vessels [3]. Considering the decrease in petroleum resources and the increase in the unit price, noteworthy progress has been performed in the research and development of renewable and alternative fuels in order to minimize the environmentally harmful gas emissions ( $CO_2$ ,  $CO$ ,  $NO_x$ ,  $SO_x$  and  $PM$ ) from diesel engines [5] [6].

Considering the electric motors that will work in combination with the diesel engine in the hybrid propulsion system, the consequence of Michael Faraday's invention of electromagnetic induction comes to the fore. In 1831, Michael Faraday and Joseph Henry are flourishing in efforts on electric motors. In the following years, Jacobi (1834) invented the first direct current model, which forms the prototype of all electric motors from the point of torque generation [7]. Direct current motors are defined as motors that convert electrical energy into mechanical energy [8] [9]. In direct current motors, current needs to be fed to the rotor through brushes and commutators [10] [11]. Direct current motors are used for speed and torque control and in this type of motors, speed and torque is operated in direct proportion by voltage and current respectively. The alternating current motor uses the force between two rotating magnetic fields as opposed to a direct current motor. In this case, both the stator and the rotor magnetic field rotate [7]. A number of losses occur while transferring the obtained power in asynchronous motors. Losses at each stage are expressed as in Fig. 1. [8]. To begin with, the input power is described as  $P_{in}$  and then taking into account of the various losses The  $P_{out}$  is calculated.

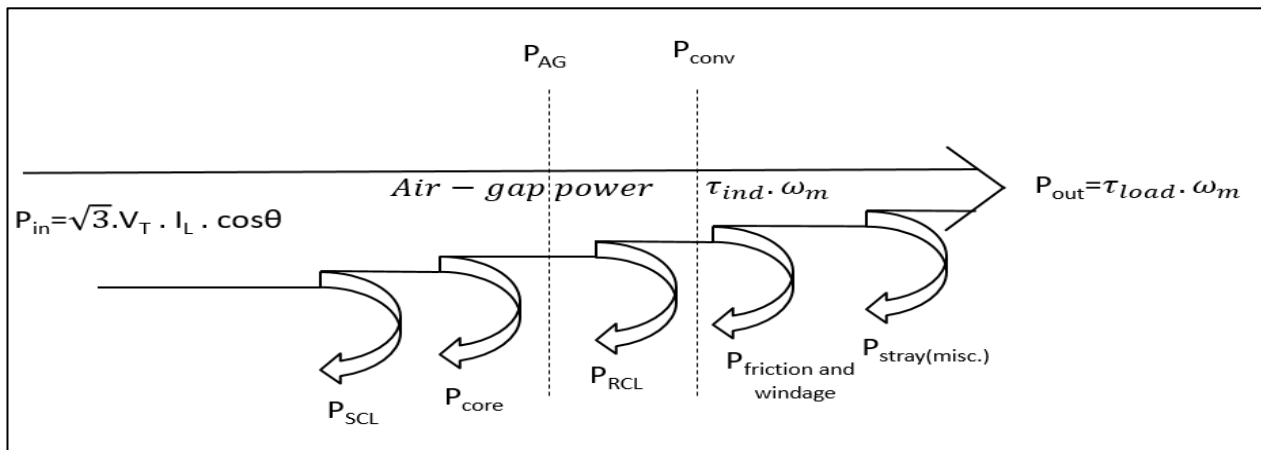


Fig. 1. Losses in asynchronous motor (J. Chapman, 2004).

Abbreviations are defined as  $P_{in}$  (input power), PSCL (stator copper and winding losses); Pore, core losses (stator lag and eddy current losses), PAG (the power transmitted to the rotor after the specified losses, PRCL (rotor copper losses),  $\omega_m$  (angular velocity of the motor),  $\tau_{load}$  (the torque value obtained on the shaft) [8]. Asynchronous motors are divided into two different groups as rotor-wound and squirrel-cage [7].

### 1.2. Emissions and IMO Regulations

Marine engineering designers make an endeavor to reduce the emission amounts from marine vessels, making allowance for the effects of atmospheric pollution on human health and climate change [1] [12]. The reason for the occurrence of air pollution is categorized under two main headings as natural and human-induced: thermal power plants, vehicles used in the transportation network, industrial processes, domestic and industrial areas are human-induced causes [13].

The exhaust gas emissions of ship diesel engines consist of nitrogen, oxygen, carbon dioxide, water vapor, carbon monoxide, sulfur, nitrous oxide, partially unreacted hydrocarbons and particulate matter [1]. Comparing to marine vessels and land vehicles,  $NO_x$  and  $SO_x$  emissions from diesel engines in marine vessels have more severe point. Nonetheless  $CO_2$ , CO and HC emissions have a relatively lower impact [14].  $NO_x$  and soots are the leading emissions from diesel machines and have a carcinogenic effect and a tendency to create acid rain [15] [1]. As a result of the collection of sulfur, which can be transported in the atmosphere for hundreds of kilometers, the level of sulphate particles increases in the soil and this causes phosphorus deficiency [1] also these particles cause emphysema, bronchitis and heart diseases [13].

Hydrocarbons formed as a result of incomplete combustion of fuel, lubricating oil and also the evaporation of fuel are at a very low level due to the efficient combustion in modern diesel engines [1] [16]. Carbon monoxide occurs as a result of insufficient air in combustion and are highly toxic in high concentrations. PM consists of incomplete combustion, partially unburned lubricating oil, thermal separation of hydrocarbons from fuel and lubricating oil, ash, sulfates and water in fuel and lubricating oil. Meanwhile,  $CO_2$  is the inevitable combustion product of all fossil fuels [1]. It constitutes 80% of the gases with global warming effect [13].

The aim of this research is to find ways of reducing the high fuel consumption of the engine per unit power at low loads and the minimization of emissions by sourcing them from main engine by HPS. The question that guides this research is:

RQ1: How efficient is the use of hybrid propulsion system in marine vessels?

## 2. Methodology

This research was a qualitative research. The researchers used a literature review method in collecting data for the research. Inferences are made at the end of the literature review. The Energy

Efficiency Design Index (EEDI), the Energy Efficiency Operational Indicator (EEOI) and the Ship Energy Efficiency Management (SEEMP) are used for the analysis.

The Rules for the Prevention of Air Pollution from Ships set limits on sulfur oxide and nitrous oxide emissions from ship engine and prohibit deliberate releases of substances that damage the ozone layer [17] The Energy Efficiency Design Index (EEDI) is defined as the ratio of the amount of carbon dioxide to multiplied by the amount of load carried and the distance also detailed formula is indicated. Moreover, this index is aimed to construct more efficient ships by using certain design limits [17].

$$EEDI = \left( \prod_{j=1}^n f_j \right) \left( \sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)} \right) + (P_{AE} \cdot C_{FAE} \cdot SFC_{AE^*}) + \left( \left( \prod_{j=1}^n f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AE_{eff(i)}} \right) C_{FAE} \cdot SFC_{AE} \right) - \left( \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME^{**}} \right) / (f_i \cdot f_c \cdot Kapasite \cdot f_w \cdot V_{ref}) \quad (1)$$

The Energy Efficiency Operational Indicator (EEOI) is a monitoring tool used to manage ship and fleet efficiency performance during the operational period. EEOI aims to measure the fuel efficiency and determine the reasons for the changes occurred on fuel consumption of the ship engine (DNV GL, 2020).

$$Ortalama EEOI = \frac{\sum_i \sum_j F C_{ij} \cdot C_{Fj}}{\sum_i m_{cargo} \cdot D} \quad (2)$$

The purpose of SEEMP is to establish a mechanism to increase the energy efficiency of the ship during operation. Ship Energy Efficiency Management stakeholders are ports, shipyards, ship owners, types of ship, cargo owners, and ship operators. An implementation system for the SEEMP should be established and continuous records should be kept [17].

### 3. Literature Review

In this section, literature review is performed on the efficiency analysis of hybrid propulsion systems in marine vessels and key information are given about the analyzed articles. In the literature review done in WOS (Web of Science), the studies using the "efficiency", "vessel", "marine", "propulsion" and "hybrid" words on their topics are examined. Thus, attention is drawn to the important issues and their abbreviations in the Table 1. The time interval between 1975-2020 is chosen as the data collection period and articles, reviews, chapters, proceedings paper are included as document types.

Table 1. Topics on Hybrid Propulsion System by the evaluation of the studies obtained in WOS

1. Reduce Costs [RC]	10. Making Improvements on Main and Auxiliary Engines [MAE]
2. Reduce Fuel Consumption [RFC]	11. Making Improvements on the Propeller and Steering System [PSS]
3. Service Vessels such as Tugboat [SV]	12. Energy Efficiency Measures (EEDI), (SEEMP), (EEOI) [EEM]
4. CO <sub>2</sub> Emission Reduction [CER]	13. Wind Energy [WE]
5. NO <sub>x</sub> Emission Reduction [NER]	14. Using of Electric Motor [EM]
6. SO <sub>x</sub> Emission Reduction [SER]	15. Energy Storage Systems [ESS]
7. Reduce Greenhouse Gas Emissions [GHG]	16. Alternative Fuels [AF]
8. Considering Marine Environmental Concerns and IMO Limitations [MEC]	17. Improvements in Ship Hull Construction [SHC]
9. Training of Staff [TS]	18. Providing Reliability [PR]

First of all, "efficiency", "vessel" and "marine" topics are written in the search section of WOS. 539 studies are obtained when the results are examined. Unrelated studies in different disciplines have been

eliminated and appropriate studies have been added to the Table 2. In the second step, "efficiency", "vessel" and "propulsion" topics are investigated, and the relevant ones out of the 243 studies are added to the Table 2. Lastly, "efficiency", "vessel" and "hybrid" topics are also assessed and related ones of 246 results are added to the Table 2

Table 2. Studies on Hybrid Propulsion System obtained in WOS

Studies/Topics	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]	[18]
Hasan and Karim (2019)				X				x				x					x	
Kumar et al. (2019)	x	x	x				x							x	x			
Van Nguyen et al. (2019)									x	x								
Andriiovych and Victorovych (2019).	x				x			x		x						x		
Lipman and Lidicker (2019)	x	x											x					
Ng et al. (2019)		x	x	X			x	x								x		
Lana et al. (2019)		x	x	X	x	x	x							x	x			
Litwin et al. (2019)	x	x		X	x	x	x	x				x			x			
Kunicka and Litwin (2019)	x	x		X	x	x	x	x						x	x			x
Ma et al. (2019)	x	x		x			x	x				x	x					
Geertsma et al. (2018)		x	x	x	x		x	x			x							x
Kamala et al. (2017)		x	x	x	x	x	x							x				x
Nielsen et al. (2018)		x			x		x	x		x		x						
Imperato et al. (2018)		x			x			x		x								
Chi et al. (2018)	x	x		x			x	x				x						
Kumar et al. (2018)	x	x	x				x			x				x	x			x
Bui et al. (2018)		x		x	x			x		x				x	x			
Zhu et al. (2018)	x	x	x				x	x		x		x		x	x			
Ma et al. (2017)	x	x		x			x	x		x		x						
Litwin et al. (2017)	x	x					x				x			x	x			x
Geertsma et al. (2017)		x					x				x							
Yuan et al. (2017)		x	x					x						x	x	x		x
Geertsma et al. (2017)	x	x	x	x	x		x	x		x	x			x	x			
Bennabi et al. (2016)	x	x	x	x	x	x	x	x						x	x			x
Soghomonian et al. (2016)	x	x		x			x	x				x		x				x
Hountalas et al. (2016)	x	x		x			x			x								
Chai et al. (2016)	x	x	x											x				x
Zhao et al. (2016)	x	x		x	x	x	x	x		x	x	x						
Dedes et al. (2016)	x	x		x	x		x	x				x		x	x			
Xiao et al. (2016)		x	x				x							x	x			x
Sciberras et al. (2015)	x	x	x	x	x	x	x	x						x		x		
Chi et al. (2015)	x	x		x			x	x				x						
Zhao et al. (2015)		x		x														
Zahedi et al. (2014)		x	x				x							x	x			x
Gali et al. (2014)	x	x					x											
Bolvashenkov et al. (2014)	x	x					x			x	x		x	x	x			
Acomi and Acomi (2014)	x	x		x	x	x	x	x				x				x		
Manea et al. (2013)	x	x		x	x	x	x	x		x		x		x			x	
Motley et al. (2012)	x	x					x				x							
Dedes et al. (2012)	x	x		x	x	x	x							x	x			x
Corbett et al. (2008)	x	x		x		x	x									x		
Krylov and Pritchard (2007)												x						
Lin (2002)		x		x	x	x	x	x		x								
Hountalas and Kouremenos (1999).	x	x										x						
Total	28	40	14	25	18	12	33	24	1	13	8	15	3	20	16	6	2	12

Between 1975-2020, 44 studies are reached and the evaluating contents of the obtained studies and the focal points of these studies are expressed in the Table 2 by using topics in Table 1. Considering the European Union and IMO emission limitations on the maritime industry, [18] stated that diesel hybrid power systems will provide fuel saving in low-speed ocean-going vessels. Hybrid power systems are made for different operations and the applicability of the batteries is investigated with the optimizations made in the light of the efficiency loss. Energy efficiency studies and carbon dioxide emission reduction

methods to be carried out on marine vessels will provide economic and environmental benefits in order to maintain sea transportation, which is one of the most common transportation methods. [19] Creates a framework that uses automatic identification system (AIS) data for real-time monitoring of the operational efficiency. The amount of transportation work, CO<sub>2</sub> emissions and fuel consumption are acquired. EEOI, one of the energy-efficiency measures, are calculated by the model created within this framework. The efficiency of the ship is calculated using a real-time monitoring system on the south west of Singapore harbor and strait in [19] study. In the software developed, the type of the ship, draft, gross tonnage, net tonnage, deadweight etc. values are used as data and thus the real time EEOI value is calculated. [20] Investigate the effect of different types of fuels on EEOI and discusses the energy efficiency improvements. The International Maritime Organization (IMO) establishes an energy efficiency design index (EEDI) to control carbon dioxide emissions. A study conducted by [21] stated that the EEDI formula will differ for ships operated in inland water and open seas thus new parameters should be used in calculating the EEDI for these ships. In the container ship with a carrying capacity of 10000 TEU, [22] show that the gains in terms of EEDI using the waste heat recovery (WHR) method in the low-speed ship diesel engine. Using WHR method, the EEDI value can reach up to 20% below the reference line. The WHR method plays an important role in reducing greenhouse gas emissions as well as energy efficiency.

[23] Aimed to minimize fuel consumption in order to achieve energy efficiency in tugboats. Optimized system provides 29.86% fuel savings compared to the diesel mechanical propulsion system and 2.9% compared to the fixed speed diesel-electricity propulsion system. Furthermore, proposed system uses a double feed induction generator in the variable speed diesel-electric propulsion. The loading situations occurred during the operation of the tugs are examined in 4 different stages; loitering, waiting, pushing / pulling the ship at low and high power. Batteries are installed to meet the load demand of the tug under 20% load during loitering and waiting processes. In addition to providing fuel saving, [23] aim to reduce costs and greenhouse gas emissions with the optimized propulsion system. In Anchor Handling Tug Supply (AHTS) vessels [24] establish an optimum balance on the Hybrid electric propulsion system by using multi-purpose optimization techniques in terms of greenhouse gas emissions, amount of fuel consumption and life cycle cost. The multipurpose optimization technique causes a 1.03% increase in fuel consumption compared to the single-purpose optimization technique. Notwithstanding, it provides 7.34% gain in greenhouse gas emissions and 21.75% in terms of life cycle costs. Compared to the traditional propulsion system, the amount of fuel consumption, greenhouse gas emissions and life cycle costs are 14.99%, 14.12% and 12.11% less, respectively.

A historical cruise ship has 25 m length equipped with 73 kW diesel main engine is examined in the sense of the energy efficiency of the hybrid propulsion system by experimental studies realized from [25]. 4 kW and 15.1 kW thrust power will be sufficient respectively considering the speed limit of 6 km /h cannot exceed along the ship historical channels and the sailing speed of 12 km /h in open seas is sufficient by the ship-owner. Parallel and serial propulsion systems are used in calculating energy efficiency. Investment costs reach extremely high levels while the serial system is the most environmentally friendly propulsion system. Consequentially, diesel electric type parallel propulsion system is the most efficient option. Aims to gain from fuel consumption with this optimization technique, [26] performed the genetic algorithm (GA) method on the generators used in the diesel electric propulsion system of the diving support vessel (DSV). The operations of the DSV ship are examined in 4 different stages as transit pass, dynamic position, maneuvering and diving process. Fuel gains from operations are calculated as 2.98, 2.96, 0, 31.18 kg / hour, respectively. At the end of a year, 126.81998 t fuel saving is acquired from the total fuel consumption. In addition to this gain, improvements in system reliability are also achieved with this optimization technique, by the way system reliability is improved. An energy efficiency experimental study on the parallel hybrid drive

system conducted by [25] explained that four times energy efficiency saving is acquired, CO<sub>2</sub> emissions are diminished, and noise emissions are decreased 100 times. Container ship operated in inland waters are shipped by the electric motor at low speed and power (below 7 kW and 7 km / h). Energy efficiency level is around 85% in electric mode nonetheless the internal combustion engine is 22% in case of operation at low speed and power. According to the data obtained, significant gains are achieved in fuel consumption, operating costs and extent of emissions. The technical efficiency levels of trawler boats in Vietnam and the analysis of these level markers are made through face-to-face interviews and surveys by [27]. Year of construction of the ship, experience of the captain and crew, distance to the fishing zone, type of engine and regional differences affect technical efficiency level.

With the improvements sustained on the Ro-Ro vessel, the gains in fuel consumption, fuel costs, CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub> emissions are approximately 46%, 24%, 46%, 43% and 94% respectively. On the other hand, [28] stated that the gains obtained from the tugboat analyzed in transit and standby mode remain at low levels. Ship speed, draft, shaft power, exhaust gas temperatures, oil and fuel tank levels can be saved instantly by specialized monitoring program. [29] focus on the energy efficiency effect of trim to reduce fuel consumption and increase energy saving by analyzing and monitoring the operation data obtained from ROPAX vessel. Gains of the hybrid propulsion system on the passenger ferry operated small inland waters are highlighted by [30] and a towing test is performed on a model created by scaling the passenger ferry. The resistances on the ferry are calculated and the power is estimated at the specified speeds by towing test. Electric motors used in the hybrid system are equipped with lithium batteries and charged via solar panels. In order to ensure environmental awareness, amounts of emission are acquired from the existing passenger ferry and a data set is created. In view of the use of electrical systems becomes a noteworthy potential, considering compliance with global emission limits and environmental concerns. In the optimization study conducted to meet the energy demand on the tugboat by [31] . 21.4% gain by installing a 50 kWh battery storage system also 25.5% gain by wireless inductive power transfer (WIPT) is acquired from fuel consumption compared to conventional tugboats. Besides, 2.6% fuel consumption is saved by using a double-fed induction generator in power generation. Eventually, the operation costs and greenhouse gas emissions in diesel electric tugboats are minimized by optimized energy management.

Hybrid systems come to the fore conducted by [32] mentioned that IMO's emission limitations and energy efficiency regulations can be met by using energy storage systems and alternative energy sources together. In all hybrid electric ships under dynamic loading conditions maximum fuel consumption efficiency and system reliability are aimed with Model Predictive Control (MPC) method. The hybrid propulsion system becomes economically beneficial, if the engine operated 40% load below for a significant period of time. Hybrid systems with advanced control strategies can reduce fuel consumption and emissions by up to 10-35%, provide ease of maintenance, maneuverability and comfort also reduce noise. [33] focuses on smart ships and different types of propulsion systems, respectively, the efficiency of mechanical, electrical, hybrid propulsion systems are examined. 25% total commercial energy is consumed from transportation sector so that the new ship constructions should have a high energy efficiency and reliability and cause the least damage to the environment. Hybrid propulsion system applications are proposed in order to meet the limitations of IMO on greenhouse gases and pollutant emissions by [34]. In order to increase the efficiency level, improvements are being made for the electrical energy systems on board considering air quality, global warming concerns, and emission regulations in the maritime sector. For this purpose, [35] stated that maximum efficiency will be achieved by an improved interface in electrical systems, energy saving lamps and capacitors using for electric motors. [36] evaluated the applicability, advantages and disadvantages of the electric propulsion system in different types of vessels also compared mechanical and hybrid propulsion system. Disadvantages of electric propulsion systems can be eliminated with the advancing technologies so that

can be compare with traditional propulsion systems in sense of economically. Electric propulsion system is very suitable for ice-breaking vessels, ferries, tankers and bulk carriers.

[37] describe the hybrid propulsion system and specifying system's components. Firstly, the Power Take off (PTO) mode is specified in that process the main engine rotates the propeller with a gearbox, at the same time, the generator is connected to this system to meet ship's electricity needs. The Boost Power Take in (PTI) mode, high power demands are met by working in combination with the electric motor and the main engine. In Power Take Home (PTH) mode, the main engine of the ship does not work and the propulsion system is operated by the electric motor. Fuzzy comprehensive evaluation method is used on PSV that has 79-meter full length, 17.6-meter breadth, 7.7-meter depth, and 6000 HP main engine also designed, built and tested in accordance with the American Bureau of Shipping (ABS). Consequently, the hybrid propulsion system is more scientific and accurate in terms of applicability, reliability, sustainability, economy and mobility. The aim is to reduce fuel consumption and emissions with it, with a redesigned propulsion system. Model is created using real engine data 31 separate voyages of five bulk carriers at various loads and ballast conditions. PTO, PTI and PTH mode are used in the model.

[18] stated that saving up to 4.1 million tons in CO<sub>2</sub>, 0.07 million tons in SO<sub>x</sub> and 0.32 million tons in NO<sub>x</sub> can be achieved depending on the storage system, ship type and operation mode. This indicates that emissions can be reduced 14% and 1.8% in the bulk carrier sector and the world fleet, respectively. [38] designed a power distribution system in order to increase the efficiency of passenger ships and offshore supply vessels operated in short sea transportation. The main goal is reducing fuel consumption, providing high energy efficiency and benefit from battery energy storage systems, whose costs decrease over time. Operation modes for the supply vessel are described in seven different stages high speed transition, economic speed transition, high speed economic speed transition, dynamic position waiting, waiting for suitable weather conditions, waiting in the dock. In the hybrid system created on the offshore support vessel has a gain 16.3% to 22% from fuel consumption and additionally this gain is between 0.32% and 5.76% on the cruise ship.

In order to estimate the fuel consumption value, the amount of power transferred to the propeller and the speed of the ship in different operating situations, [39] perform a study on the container ship that has 14280 kW main engine power. Simulations are performed with the model created in Matlab / Simulink software. Simulation values, application results and data in the literature are compared and the calibration process of the model is carried out taking into account the margins of error. [40] aims to provide gains in fuel consumption and emissions compared to conventional vessels by using the efficient energy management system (EMS) on direct current hybrid electric vessels. The load demand in the ship's operations is examined in 5 different modes and the appropriate model is created in the Matlab / Simulink section. Significant reductions in fuel consumption and harmful gas emissions are achieved by realized scenarios in which engine operates at optimum power. In order to minimize fuel consumption in different loading situations, the optimization algorithm created in Matlab / Simulink software for diesel engines, generators and batteries is performed on an offshore support vessel (OSV). In the OSV ship, the operation modes are examined as harbor, low / high dynamic position, anchor handling, bollard pull and transit supply / towing modes. According to the simulation results obtained by [41], the DC power system without a battery storage system creates a remarkable fuel gain compared to the traditional AC power system. Additionally, by using optimized energy storage in DC power systems, this gain can be doubled. Based on the hydrodynamic movements of a 23000 DWT container ship during operation, a model created in Matlab / Simulink to evaluate fuel consumption and greenhouse gas emissions carried out by [42] in the ship hydromechanics laboratory of Delft University. The power management system strategy is used in order to minimize the thrust loss caused by the



waves occurred in heavy sea conditions. The ship speed reduction module saves fuel and reduces the emission of harmful gases, also provide gains up to 40% on propulsion.

In an effort to highlight the exhaust gas recirculation (EGR) system, [43] conducted a research on the methods of its use in the reduction of the NO<sub>x</sub> emission in low-speed ship diesel engines and its very low cost compared to other emission reduction methods. According to the results, NO<sub>x</sub> emissions can be reduced by 37.9% to 53.5%, depending on the operating mode of the main engine and the degree of the exhaust gas recirculation system and additively EGR system meets IMO restrictions on NO<sub>x</sub> emissions. [44] state that international transportation accounts for 2.1% and 13% of global greenhouse gases and NO<sub>x</sub> emissions, respectively. Applications on fuel index in engines equipped with EGR system are indicated. A significant reduction in the amount of smoke is obtained in sea trail also provides maximum fuel efficiency and minimizes NO<sub>x</sub> emissions without damaging the engine via these applications [45] demonstrated the emission reduction methods in four-stroke ship engines and the achievements of using these methods in combination with the separated fuel injection system. Although the EGR system reduces 90% NO<sub>x</sub> emissions, 10% increase is observed in fuel consumption. Moreover, NO<sub>x</sub> emissions 50% can be reduced without a serious increase in fuel consumption by combining EGR system and the Miller Cycle. Using the early pilot injection model causes an increase in the carbon monoxide, total hydrocarbon and soot in the exhaust gases, nevertheless there is any advantage in view of NO<sub>x</sub> emissions. Tier III regulations of the IMO on NO<sub>x</sub> emissions are met with the combined Miller cycle and EGR. In order to maximize energy efficiency, the timing of the Miller cycle should be optimized and the EGR system should be operated at adjusted low rates. [46] aims to regulate the exhaust emissions and increase the total energy efficiency in the 4-stroke diesel auxiliary engine on board by WHR system created on the basis of the Rankine cycle. In the thermodynamic model, two different fluids namely steam and R245ca are performed. Ultimately, significant amount of fuel saves in commercial ship auxiliary engines. Engine load is 5.3% and 6.1% to save maximum fuel when using R245ca fluid in the system. Furthermore, load value is between 4.9% and 7.2% when the steam is used. With the installment of the Organic Rankine Cycle (ORC), [47] aims to reduce fuel consumption on the platform supply vessel (PSV), that use liquefied natural gas (LNG) as a fuel. ORC system. IMO limits are met and carbon emissions are reduced by ORC. Specified as the main goal is 7% fuel consumption saving. The ORC system pays for itself in 2.7 years and this situation is very attractive for ship owners. According to the study conducted by [48] , fuel consumption savings and greenhouse gas emissions decreasing are acquired by using the electric propulsion system on the PSV. [49] indicate that the catalyzed particle filter provides reduction in PM and harmful gas emissions. According to the results, carbon monoxide concentration decreases with the use of this system. At low torque values of the engine, the amount of nitrogen oxide increases, but its concentration decreases as the engine speed increases. Smoke opacity is reduced to very low levels and even reaches zero in some engine speed. There is an increase in fuel consumption and CO<sub>2</sub> concentration, because the air-fuel ratio and oxygen concentration decrease by the system. Based on the pressures of the cylinder and fuel injection systems in two-stroke ship diesel engines, the causes of the failures are determined, and they are repaired so that engine performance increases [50] . [51] targets the new markets that will arise from the applications carried out to prevent marine pollution from ships and to emphasize the use of green energy. The amounts of NO<sub>x</sub>, SO<sub>x</sub> are specified according to the ship types and the methods of reducing them are described. In addition to emissions, new technologies used in ballast water treatment are expressed. Optimized sail using on ships provides energy efficiency, [22] developed the test model by using computational fluid dynamics. In terms of EEDI the model provides 4% gain for the ships that has sailing system also provides 18.2% gain for ships that hasn't any sails. The sailboat operated in the 3 specified routes fuel consumption gains are 20%, 18.75% and 16.1%, respectively together with optimized sail, this level of gain reaches 21.16%, 20.13% and 17.6%, respectively. Focusing on the fuel consumption saving with the use of wind

energy in passenger ferries, [52] anticipates 25% to 40% fuel savings at seven knots operation speed by using wing sail. In order to demonstrate the gains achieved by the improvements made in the ship hull, [53] catamaran model constructed to use towing test. The equipment used to reduce resistance in ship hull, increases the efficiency of the propulsion system. In order to demonstrate the gains of the adaptive pitch control (APC) system for ships that has mechanical and hybrid propulsion systems operated by diesel fuel, [54] performed a study. 5% to 15% fuel consumption saving and CO<sub>2</sub> emission decreasing provided also increases maneuverability by APC. In the Patrol vessel the pitch control system provides up to 30% fuel gain, depending on the operating conditions. Amount of harmful gases and noise generated from the propulsion system are reduced, in addition to reinforce maneuverability [54]. [55] Performed an approach on propellers to minimize fuel consumption. At the same time different propeller designs are compared strength limits and cavitation rates. [56] used the energy and environmental analysis model for marine systems to calculate the amount of emissions resulting from the use of alternative fuels. Although distilled fuels cause extra CO<sub>2</sub> emissions during production stages, greenhouse gas emissions are partially reduced by their use in ship operations. In addition, the use of distilled fuels provides 70% to 85% reduction in SO<sub>x</sub>.

### 3.1 repetitions of topics on studies

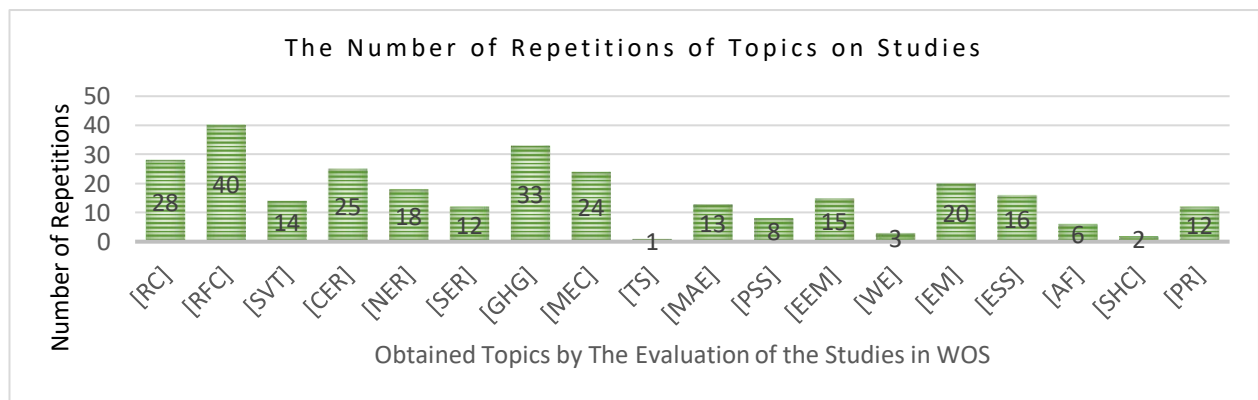


Fig. 2. The number of repetitions of topics on studies.

## 4. Discussions

The most interesting topics and their number of repetitions are expressed in Fig. 2. when the studies obtained in WOS are assessed according to different 18 topics. 40 of the 44 studies aim to provide gains in fuel consumption when the contents of the studies are evaluated. Also, fuel consumption reduction is the most prominent one among the analyzed studies [27] [4] [26]. In 33 studies that is aimed to minimize the greenhouse gas emissions. 28 of the 44 studies want to draw attention to cost reduction applications. Additionally, CO<sub>2</sub> Emission Reduction, Considering Marine Environmental Concerns and IMO Limitations, Using of Electric Motor, NO<sub>x</sub> Emission Reduction, Energy Storage Systems Energy Efficiency Measures (EEDI), (SEEMP), (EEOI), Service Vessels such as Tugboat, Making Improvements on Main and Auxiliary Engines, SO<sub>x</sub> Emission Reduction, Providing Reliability, Making Improvements on Propeller and Steering System, Alternative Fuels Using, Wind Energy, Improvements in Ship Hull Construction and Training of Staff are the others issues respectively in 44 studies on energy efficiency.

Evaluating all the outputs obtained from the analysis, in order to provide energy efficient fuel consumption, the most eminent research are those that address reduced fuel consumption by using

alternative fuels, renewable energy sources as well as optimization techniques, aiming to minimize the formation of greenhouse gases such as CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub> and PM as a result of combustion in main and auxiliary engines, taking into account of International Maritime Organization regulations, the global warming and environmental pollution. Minimizing the expenses in operations, considering the initial investment costs of the new technologies should be considered (37). Using of energy obtained from generators or renewable energy sources in the propulsion of the electric motor, is aimed at gaining fuel savings and reducing emissions (Bui, 2018).

## 5. Conclusion

With the developing technologies, the cost of producing batteries that will be frequently applied in the future in all areas decreases. The amounts of power obtained per unit volume increases, and the operating temperature ranges are expanded. EEDI, SEEMP and EEOI are established by the International Maritime Organization in order to minimize the energy loss in the construction of ships and the operations performed and efforts are being made to comply with these regulations. Energy efficiency studies are also carried out on ships that provide services for various purposes such as offshore platforms, maneuvering in the port, and diving operations. Provide energy efficiency on main and auxiliary engine with systems such as reuse of the exhaust gas generated as a result of combustion in the engine called as Exhaust Gas Recirculation (EGR), the washing system of the exhaust gas, the use of Organic Rankine Cycle (ORC). In addition to energy saving is provided by new propeller types used or improvements made on existing ones.

Consequently, in sense of maritime industry the main objectives of the studies obtained are reducing fuel consumption, to meet IMO emission limitations and regulations, costs saving, renewable energy using, and providing efficiency in marine propulsion systems by making improvements in main engines and auxiliaries with different applications such as EGR and ORC. This study will be a substantial resource for academicians and industry employees who will work on the energy efficiency and hybrid propulsion system in marine vessels. The experiences and results will be defined by established a hybrid propulsion system model as a future study.

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