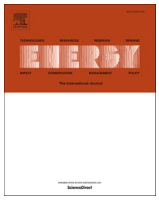
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Entropy-based environmental analyses of marine fuel preferences for onboard ships

M. Ziya Sogut

Matitime Faculty, Piri Reis University, Istanbul, Turkiye

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ABSTRACT

The maritime industry is currently discussing various aspects of alternative fuels, and finding viable and adaptable options for alternative fuels remains a sectoral issue. This study examines the impact of eight alternative fuels on energy and environmental sustainability, based on operating data of a two-stroke diesel engine. Entropy-based thermodynamic analyses were conducted for five different operations using two indices developed to consider the environmental impact, aimed at serving the decarbonization of this sector. Liquid hydrogen led to an 18 % reduction in fuel load, while ethanol resulted in a 5.55 % increase in engine efficiency. In contrast, using hydrogen resulted in a cumulative 27.01 % reduction in CO_2 emissions. When evaluating the reduction rate alongside the improvement rate, it indicates a potential of 34.96 %. Additionally, recommendations for alternative fuels during the sector's decarbonization transition were proposed at the end of the study.

Nomenclature

Symbols		Indices	
$\dot{E}$	Energy (kW)	*ch*	Chemical
$\dot{E}x$	Exergy (kW)	*dest*	Destruction
h	Entalpy (kJ/kg)	*h*	Heat
$\dot{I}$	Exergy destruction (kW)	*ι*	Dead state
$\dot{m}$	Mass (kg/s)	*In*	Input
$\dot{Q}$	Total energy (kW)	*i*	System
s	Entropy (kJ/kgK)	*kin*	Kinetic
$\dot{S}_{gen}$	Entropy generation (kJ/K)	*Out*	Output
$S_{gen,c}$	Entropy generation based on reversible (kJ/K)	*ph*	Physical
T	Temperature (K)	*pot*	Potential
$\dot{W}$	Net power (kW)	*00*	Partial
Greek Symbols			
ω	Fuel's standard specific chemical exergy		
ψ	Flow Exergy		
η_{ι}	Energy efficiency		
$\eta_{\iota\iota}$	Exergy efficiency		
η_{Carnot}	Carnot efficiency		
θ	Improvement rate		
Abbreviations			
DWT	Deadweight tonnage		
EPI	Environmental Performance Index		
EER	Energy efficiency ratio		
IMO	International Maritime Organization		
IP	Improvement potential		
IPPC	Intergovernmental Panel on Climate Change		

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(*continued*)

SI	Sustainable index
LNG	Liquid Natural Gas
CO_2	Carbon dioxide
DNV	Det Norske Veritas
ICE	Internal Combustion Engine
LPG	Liquefied Petroleum Gas

1. Introduction

The maritime industry's use of fossil fuels creates the main source of emissions and sectorial emission control and management regulations continuously improve with the help of International Maritime Organization (IMO). In addition to adhering to IMO regulations, the sector promotes the use of alternative fuels for emission management and raises awareness among stakeholders to achieve the set IMOs targets. Operational processes in shipping have directly or indirectly affected global fossil fuel-related CO_2 emissions. For this purpose, industrial stakeholders take effective measures to reduce CO_2 emissions caused by operational processes, in line with IMO regulations. Sectoral stakeholders have supported many regulations or studies for reducing fossil fuel emissions, by IMO's international responsibility. One of IMO's most significant initiatives is the regulation to reduce greenhouse gas emissions from maritime transportation by at least 50 % compared to 2008 levels by 2050 [1,2]. To achieve this goal, industry stakeholders have conducted intensive research and development studies on various issues.

E-mail address: mzsogut@gmail.com.

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These studies include advanced navigation and control systems, advanced power technologies, and sustainable and environmentally friendly alternative fuel options, including effective rerouting [3–6]. However, to ensure the energy efficiency and environmental sustainability of ships, they should be designed with the concept of green transition in mind and expected to use alternative fuels that are appropriate for their intended purpose [7]. Maritime transport is responsible for conducting critical potential greenhouse gas emissions due to its reliance on fossil fuels and has for roughly 80 % of global trade [8]. Effective changes are necessary to achieve the energy and environmental sustainability goals for ships, especially concerning main engine technologies. In this context, the use of alternative fuels is accepted as an important option. However, the limited advancements in energy efficiency of internal combustion engine technologies are hindering emission reduction efforts [6]. Despite all improvements, the energy efficiency potential of reciprocating engine technologies used in ships is known to be between 50 % and 60 % [9]. However, the institutional framework for energy and environmental sustainability in maritime transport is multifaceted and complex. As ships function as living organisms, their systems and operations consume energy intensively. Various studies in the relevant literature show differences in examples. Upon analysis of these studies, it becomes even more apparent that research on enhancing fuel efficiency and efficient energy management is of paramount importance. For example, Zaccone et al. [10] aimed to increase fuel efficiency by making a dynamic management program for functional processes. Yana et al. [11] worked on an energy efficiency model that takes into account environmental factors and is directly linked to big data. Çetin and Sogut [12] developed an energy efficiency model and presented a framework that considers environmental sustainability in ships. Yasser and Olçer [13] tried to improve fuel consumption efficiency and energy sustainability by developing a forecasting model with an artificial intelligence approach.

Maritime stakeholders have pursued alternative options depending on their responsibilities, with a growing significance on engine technology efficiency. Alternative fuels, including low-sulfur fuel, LNG, and methanol, have proven advantageous in promoting energy and environmental sustainability initiatives [14–16]. This study aims to enhance the energy efficiency of ship technologies, develop solutions to enhance performance in ship design and applications and explore alternative fuel options to foster sectoral change. This study assessed the efficacy of the seven alternative fuels, and diesel fuel by utilizing dual-fuel diesel engine technology and operating data. Sector-specific processes were considered during the development of the study. The fuel demands of eight reference fuels were analyzed, along with their energy and exergy efficiencies. These analyses were based on the power-generated data obtained under defined speed conditions. The study examined the effect of entropy production due to exergy destruction and the environmental impact potential of reference fuels based on two specific indicators on a reference dual-fuel engine. For this purpose, five distinct shipboard operational processes were employed as a framework. The thermodynamic and environmental effects of the specified fuels were investigated for each operational process. The study sought to accomplish three primary goals given below;

- Finding the energy and exergy efficiency of engine efficiency for specific operational processes,
- To define the exergy destruction and entropy production that occurs due to the irreversibility of the engine for operational processes,
- To define the entropy-based environmental pollution caused by operational consumption and the energy efficiency potential due to environmental effects on engine irreversibility.

In the study's conclusion, the sectoral contributions and gains of the parametric values toward decarbonizing the sector were evaluated.

2. Fuel preference and transition of decarbonization

Industrial forecasts show that shipping has currently been gaining influence in global trade and competition daily, and future projections indicate a 4 % yearly increase. Nevertheless, the escalation in commodity usage is expected to result in a threefold rise in environmental repercussions by 2050 [13,17]. However, the existing challenges in the sector-specific plans created by the IMO require a significant overhaul. At the 72_{nd} IMO Marine Environment Protection Committee (MEPC) convened in 2018, both the short-, medium-, and long-term objectives and their associated actions were presented in conjunction with industry stakeholders. Effective targets are being planned to reduce the annual total greenhouse gas emissions, predominantly from maritime transport, while also formulating action strategies for decarbonization by the sectoral framework [2]. Action processes for decarbonization represent a course of action that is widely supported by all stakeholders of the sector [18]. IMO also plays a role in this and has developed critical regulations [19]. However, guidelines concerning decarbonization in sector policies like DNV's scenario-based studies have been recognized as a roadmap for change [20]. Almost all scenarios necessitate sectors to enable transition away from fossil fuels considering decarbonization or green transition. Regrettably, if the proposed changes in sectoral policies are not enforced, the expected emission potential will double. As a result, IMO has stressed two essential objectives that industries are meant to fulfill in the medium and long term [21]. The foremost goal is to attain zero emissions during the decarbonization process with a goal of 2100. The IMO has set a second target of reducing its absolute emissions by 50 percent and carbon intensity by 70 percent by 2050 [22]. All decarbonization scenarios and roadmaps predict that the main focus for change is the use of fossil fuels like heavy fuel oil, marine gas oil, and diesel.

Today, the primary driver for decarbonization is the difficulty of transitioning to new and alternative zero-carbon/carbon-neutral fuels and non-traditional technologies. Nevertheless, promoting energy efficiency and technologies for energy recovery in the maritime sector remains a significant gain in the decarbonization process. Although advantageous for the industry, the challenges presented require a systems-level approach and a stronger focus on optimizing and integrating existing technologies. However, promising options or scenarios for decarbonization lie with alternative fuels like LNG, biofuels, hydrogen, and electric power. An evaluation of the energy and environmental sustainability of these fuels indicates that at present, LNG and biofuels are the most feasible options. Hydrogen and electric power, on the other hand, necessitate significant investments in infrastructure. In the developed scenarios, it is evident that fuel change is a crucial concern for achieving decarbonization, as depicted in Fig. 1.

The environmental sustainability of alternative fuels for ships is determined by their impact on air and water quality, as well as their contribution to climate change. The emissions from traditional marine fuels contribute significantly to air pollution, particularly in coastal areas and ports. The emissions of sulfur and nitrogen oxides from these fuels also contribute to acidification and eutrophication of marine ecosystems. LNG has lower emissions of carbon dioxide, sulfur, and nitrogen oxides than traditional marine fuels, making it a cleaner option. LNG is produced by cooling natural gas to −162 °C, which reduces its volume by 600 times, enabling it to be stored and transported in liquid form. However, the production and transport of LNG can result in methane emissions, which are a potent greenhouse gas. Biofuels are considered carbon-neutral, as they do not add to the net carbon dioxide emissions in the atmosphere. However, the production of biofuels can have negative impacts on land use, biodiversity, and food security. Hydrogen and electric power are both zero-emission options for ships, making them the most environmentally sustainable options. However, the production and transport of hydrogen require significant infrastructure investments, while electric power requires the development of batteries and fuel cells that are both cost-effective and efficient.

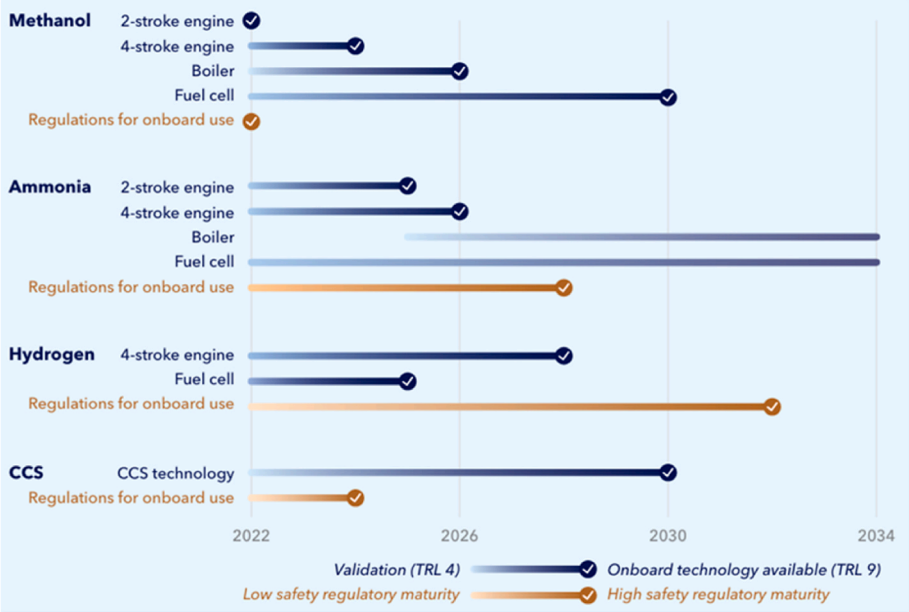


Fig. 1. Distributions and predictions of alternative fuels [18].

2.1. Marine engines

Towards the end of the 19th century, the first application of internal combustion engines (ICEs), which replaced steam engine technologies in maritime transport, was the low-speed engine developed by Wärtsilä (Sulzer) and later the medium-speed engine of MAN [23,24]. Technically, what started with a 9-cylinder medium-speed four-stroke engine has developed into an indispensable choice for almost all types of ships. It then provided changes in engines, starting with IHI (Ishikawajima--Harima Heavy Industries Co., Ltd., Japan) and MARINTEK (Norwegian Marine Technology Research Institute) developing high-pressure dual-fuel engines. Developing processes related to global climate change has enabled the compatibility with IMO NOx Tier II in engine technologies and the development of low-pressure dual fuel (LPDF) engines and lean combustion spark ignition engines. ICEs used in maritime transport are considered in two main structures. These are pure gas engines and dual fuel (DF) engines. In these engines, which work on a cycle basis, although pure engines are expressed with an Otto cycle, DF engines can operate on both diesel and Otto cycles [25].

Today, in terms of engine technologies, marine engines have been experiencing significant problems with the NOx Tier III regulations stipulated by IMO [26,27]. These problems are respectively can be listed such as [26,27]. These problems are respectively; Unburned hydrocarbons (UHC) and Methane have a high GWP(Global Warming Potential) factor and operating stability of engines. And low-load operation of lean combustion gas engines [28]. Although it is seen as a threat to decarbonization today, the fact that ICE technologies will continue to dominate the sector in the next 30 years has led the solution to fuel preferences in the decarbonization processes that develop with the foresight of IMO [29]. In this context, the study has been developed considering the thermophysical and operational characteristics of a dual-fuel engine referenced in the study.

3. Thermodynamics background

The environmental analyses, which are based on entropy and its principles are essentially assessed according to the second law of thermodynamics. As it has clearly been shown in so many different academic works, the analyses, which are based on exergy have contributed to evaluation based on the approach for the environmental impact of the engine performance [30–32]. However, especially concerning the fuels and their quantitive aspect, the very first law of thermodynamics is valid concerning the performance of the engines. Under normal circumstances, in order to obtain holistic approaches and analyses, the analyses of the steady state are considered. In this regard, the first, essential and foremost parameter is mass flux. The mass flow Under these circumstances, the first item and parameter to be considered is mass flow and this envisaged mass balance should be considered independently from the concept of time. The envisaged mass balance pertains to this context [33]:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

where, $\dot{m}$ states to the mass flow rates through each component of the cycle. In this context, the energy balance due to the general mass flow of the engine is handled in the same structure. General energy balance for steady-state conditions;

$$\dot{Q} - \dot{W} + \sum \dot{E}_{in} - \sum \dot{E}_{out} = 0 \tag{2}$$

where $\dot{Q}$ and $\dot{W}$ are the two criteria for a net transfer of the heat and the work. $\sum \dot{E}$ is the sum of energy entering and leaving system boundaries. Exergy balance due to irreversibility and dead state temperature in thermal processes is given in Eq. (3).

$$\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k - \dot{W} + \sum \dot{E}x_{in} - \sum \dot{E}x_{out} - \dot{E}x_{dest} = 0 \tag{3}$$

where $\dot{Q}_k$ and $\dot{W}$ state to the net exergetic potential of heat and the work. Other hand, $\dot{E}x_{dest}$ is related to exergy destruction of the process considering control volume. The total exergy for the control volume related two thermal system is the sum of *kinetic*($\dot{E}x_{kin}$), *potential* ($\dot{E}x_{pot}$), *physical* ($\dot{E}x_{ph}$), *and chemical exergy*($\dot{E}x_{ch}$). The total exergy is shown in Eq. (4):

$$\dot{E}x = \dot{E}x_{kin} + \dot{E}x_{pot} + \dot{E}x_{ph} + \dot{E}x_{ch} \tag{4}$$

in this system boundary, the exergy of the flow (ψ) is derived by enthalpy and the entropy form considering the real and the dead state condition of the system [34].

$$\psi = (h - h_0) - T_0(s - s_0) \tag{5}$$

when h points to enthalpy, s is refers to entropy, the zero subscript is defined as a dead state based on termo-physical parameters of the surroundings. Similarly, entropy generation is a balanced condition for a steady-state, steady-flow system as given following Eq [29,35]:

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = 0 \tag{6}$$

The total entropy generation of a system is a quantitative measure of the potential for irreversibility in the environment of the control volume. Total entropy generation for all thermodynamic processes is a variable that depends on the environment and serves as a direct measure of exergy destruction. This value is determined by the extent of irreversibility for all systems, as stated in The Gouy–Stodola theorem like below [36]:

$$\dot{E}x_{dest} = T_0 \dot{S}_{gen} \tag{7}$$

The second law efficiency for the processes can be expressed as a form of both exergy flows and exerge destruction. Exergy efficiency for all thermodynamic systems;

$$\eta_{Ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \tag{8}$$

Exergy destruction requires an engineering approach associated with the irreversibility of a system as a potential for improvement. Improvement potential (IP) is expressed in a form that directly creates a boundary condition in systems and is related to the efficiency of exergetic flows. Accordingly, IP [37];

$$\dot{IP} = (1 - \eta_{Ex})\left(\sum \dot{E}x_{in} - \sum \dot{E}x_{out}\right) \tag{9}$$

4. Exergetic irreversibility and environmental indicators

Fuels are measured in thermal efficiency resulting from combustion processes in engine technology, with the engine's operational structure based on a thermodynamic cycle. Thus, a new perspective based on energy and exergy analysis has been developed to evaluate the energy and environmental sustainability of fuels. Environmental sustainability protection involves the production of entropy by relying on irreversibility in thermal processes. Exergetic approaches are utilized to analyze the irreversibility in this context. Gas engines are part of a thermodynamic system that has a mass balance. To assess the fuel-induced combustion process, boundary conditions and assumptions must be carefully evaluated. Thus, the cycle was designed for continuous flows without considering the chemical and kinetic effects of the engine, and the viscous effects in connection, pipe, and process flows. In this regard, the anticipated thermodynamic equations are included in the appendix.

4.1. Entropy management and environmental indicators

Extensive research has been conducted on the environmental consequences of consuming fossil fuels. The irreversibility caused by these systems can have an impact on the environment in many ways. Emission pollution, especially caused by thermal pollution, is one of them. Motorlar için literatüre göre emisyon değerlendirmeleri için farklı yöntem ve tekniklerin olduğu görülmektedir [38–40]. Currently, the evaluation of emission potential is directly defined in all studies by the criteria set by the International Panel on Climate Change (IPCC). Nonetheless, this criterion presents issues because of the polluting influence of technology. To address this issue, impact analyzes were evaluated based on the Environmental Performance Index (EPI) and Sustainability Index (SI), developed by Ref. [41] and based on the entropy generation. Each of the two criteria is specifically dependent on the entropy generation caused by exergy destruction of fuels, as well as their engine performance. EPI is;

$$EPI = \left(\frac{\sum S_{gen}}{\sum \dot{E}x_{in}}\right) * T_0 \tag{10}$$

The EPI is considered acceptable when it falls within the range of zero to one. A value near zero is beneficial in terms of environmental sustainability but zero cannot represent a true lower bound, as it does not consider the continuity of entropy generation or the requirement for the environment to be in a dead state for reversible processes to occur. In real processes, it is important to consider boundary conditions related to operational loads or flows as key parameters for potential improvement. However, it is crucial to distinguish between reversible and irreversible changes when considering the limit of improvement. A modification has been developed to improve the potential, defined as Van Gool's equation, based on the Carnot efficiency. Accordingly;

$$IP = (\eta_{Carnot} - \eta_{\imath\imath}).(\dot{E}x_{in} - \dot{E}x_{out}) \tag{11}$$

The EPI value is the result of reversible processes and indicates the potential for pollution along with an understanding of boundary conditions. This metric shows the limit value for the rate of possible degradation of environmental sustainability. In contrast, SI is a measure of an improved potential for reversible conditions. Thus, it points to the lower limit value of the entropy produced for real systems that should be developed for the environment. In this case, SI;

$$SI = \left(\frac{\sum S_{gen.c}}{\sum \dot{E}x_{in}}\right) * T_0 \tag{12}$$

The framework expected in the analysis is based on an evaluation that prioritizes conditions related to reversibility for the environmental conditions in which the systems directly examined are located. In this regard, SI can serve as a standard and establish the limit for environmental pollution [41]. In terms of actual systems and processes, the establishment and performance characterization of irreversibility parameters are vital from an engineering perspective. The energy efficiency ratio is to reveal the main potential to reduce environmental pollution as represented and developed for enterprise target. Thus, it can be used as a decision measure of fossil fuel processes to ensure the manageability of energy and the environment. Accordingly.

$$\theta = \frac{\sum (EPI - SI).IP}{\sum Ex_{in}} \tag{13}$$

The corporate target of energy management is to establish application process for each step. It is seen that the efficiency rate achieved is a direct target for enterprises. This will improve operating processes and reduce entropy resulting from irreversibilities.

5. Results and discussion

In this study, the operational and thermophysical data of a two-stroke diesel engine to examine potential fuels for ships, as well as possible alternatives were considered. Firstly, the energy and exergy efficiencies of each fuel based on the RPM values generated under various operational conditions were evaluated. Secondly, the possible entropy potentials of the engine and the environmental effects caused by each fuel preference were separately calculated. The study was examined based on mass balance in the control volume for steady-state conditions. In the study, viscous effects due to fuel flow and kinetic and potential effects of flow were neglected. In addition to using diesel as the primary fuel for the ship, we also researched the thermophysical properties of seven other fuels. Their reference values separately were analyzed, and the findings are presented in Table 1.

In the energy and exergy analyses carried out in the study, the thermophysical properties of the fuel were evaluated for steady-state conditions, considering operational conditions. The thermal losses of the engine in the operating-induced contour structure were neglected and analyses have been developed over the engine's holistic system

Table 1
Reference alternative fuels and their thermophysical properties.

Parameters	Fuels							
	LNG	FT Synfuel	Diesel	Bio-diesel	Liquid h2	Liquid methane	Ethanol	Methanol
Density @15 °C (kg/m^3)	450	759	806.3	813.3	210	424	789	794
LHW (kJ/kg)	45000	44200	42803	38200	120000	50000	27200	19900
Fuel mix (%)	100	100	100	30	10	10	10	10
Mix LHW (kJ/kg)	45000	44200	42803	41422.1	50522.7	43522.7	41242.7	40512.7

structure. In addition, the combustion temperature of the engine, depending on diesel conditions, is assumed to be constant at ambient temperature. Depending on these conditions, the thermophysical properties of the engine are given in Table 2.

The reference engine has a six-cylinder structure and according to the test results, the unit cylinder load is 1003 kW in navigation full and 56 kW in dead slow ahead position. Mass flows were determined by taking the energy demand of the engine as a reference for each fuel. The mass flow rates related to the fuels were examined for each operation process of the engine. Mass flow rates of fuels are important in terms of the total fuel load demands of the ship. In this context, it is 10 % doped hydrogen with a capacity of 18.04 % less than diesel fuel. This demonstrates the advantage that can be achieved in the storage volume of the ship. This value shows a 5.14 % reduction in LNG, but a 3.77 % mass increase in ethanol. It can be said that the effect of storage volumes, especially on ships, will create a direct and indirect weight effect, indicating additional fuel consumption. In this study, energy analyses on this mass flow are handled separately over five defined positions. In the analyses made, the rate of change in energy efficiency depending on the type of fuel was also examined based on diesel fuel. Accordingly, the distributions are given in detail in Fig. 2.

When The efficiency performance of the alternative fuels compared to diesel fuel was examined, while liquid hydrogen and ethanol increased engine efficiency by 3.36 % and 5.56 %, respectively, it was observed that LNG and FT SYNfuel decreased it by 9.53 % and 6.13 %. The methanol contribution, which has become prominent in the maritime sector in recent years, has also been evaluated. Accordingly, while liquid methanol affects 0.01 %, gas phase methanol increases by 1.07 %. In fact, the most problematic area is that it reduces engine performance within the five positions that can be said for LNG. A similar study was carried out for exergy analyses and the distributions are given in Fig. 3.

The exergy efficiency of the engine depending on the diesel fuel preference was found to be 45.60 % on average, according to the defined positions. On the other hand, the exergy efficiency for prominent ethanol and liquid hydrogen was found to be 48.14 % and 47.13 %, respectively. The exergy efficiency of LPG usage, which stands out in sectoral preferences, was found to be 41.26 %, while liquid methanol and gas phase were found to be 46.09 % and 45.61 %, respectively. This situation shows important problem areas in terms of storage areas for methanol and LNG, which are used as alternatives. Based on the exergetic conditions of the engine, the exergy destruction and the related improvement potentials were evaluated separately for each fuel and position, and the distributions are given in Fig. 4.

While the average exergy destruction of the reference diesel engine was 6326 kW, the average IP potential was found to be 54.95 %, depending on the exergy destruction that occurred. This value represents a potential of 14.78 % for the total exergy flow. For liquid hydrogen, which stands out among the fuel preferences, this value depending on the exergy flow was found to be 11.40 %. However, in ethanol, which stands out in exergy efficiency, the IP ratio indicates an average of 13.14 % potential depending on the exergy flow. In fuel analysis, the IP potential of LNG, which stands out in the sector, shows a potential of 59.21 % for exergy destruction, while the IP ratio due to the Exergy flow shows that it is higher than expected with 16.75 %. However, this value indicates a potential of 15.15 % in methanol. For the defined positions of the engine, the entropy productions caused by the fuels were discussed over the reversibility and irreversibility conditions. The entropy production and possible pollution potentials of the engine were examined, and their distributions are given in Fig. 5.

When the pollution potentials of each fuel were examined in terms of reversibility conditions depending on the entropy produced in the study, the most problematic fuels for irreversible conditions were found to be 57.82 % for LNG, 56.67 % for FT Synfuel and 54.43 % for diesel, respectively. On the other hand, the lowest rates were found to be 52.19 % in Ethanol, 53.10 % in Hydrogen, and 54.01 in Methanol, respectively. On the other hand, while an average of 21.30 kW/K was found for diesel in entropy production, this value was 19.49 kW/K for liquid hydrogen and 18.25 kW/K for ethanol. On the other hand, this value is calculated as 28.05 kW/K for LNG and 25.39 kW/K for FT Synfuel. LNG and Methanol values are remarkable in all analyses. The average entropy production of ethanol according to the current positions has been determined as 20.67 kW/K. It is seen that these values have a remarkable effect on entropy productions or environmental pollution factors for the desired power generation according to the defined thermophysical properties of the fuels. This situation necessitates the evaluation of a new perspective, especially related to thermal diffusion. Exergy efficiency makes it necessary to examine operational values as a criterion along with fuel consumption. The EPI and SI values of each fuel were examined, considering the engine position, and the results are given in Fig. 6.

The fuel preference of the engine depending on entropy production and its environmental effects has very effective results. In the study, the values of alternative fuels were examined by comparing them with diesel fuel. In particular, 10 % hydrogen additive showed a decrease of 2.82 % in the general framework, while 10 % Ethanol additive had a reduction value of 4.66 %. In addition, especially LNG and FTSynfuel values have results that need attention. It was observed that their EPI values were 7.99 % and 5.14 %, respectively. It can be said that both fuel preferences increase the EPI value of the engine and create a problem area due to high entropy production. In the analyses, the entropy

Table 2
Thermophysical properties of the reference diesel engine.

Position of engine	Speed	Engine Fuel Load	Engine Speed	TC	Ambient Air Temp.	Humidity	Pressure	Inlet Air	
	(knots)	(%)	RPM	RPM	°C	(%)	mm Hg	°C	mm Hg
Navigation Full	12.9	66	105	11853	22	60	750	33.5	755
Full Ahead	12	40	85	7850	22	60	750	30.9	754
Half Ahead	10.1	32	75	7605	22	60	750	28.3	754
Slow Ahead	8.7	20	58	6680	22	60	750	25.4	755
Dead Slow Ahead	7	10	38	5507	22	60	750	24.3	754

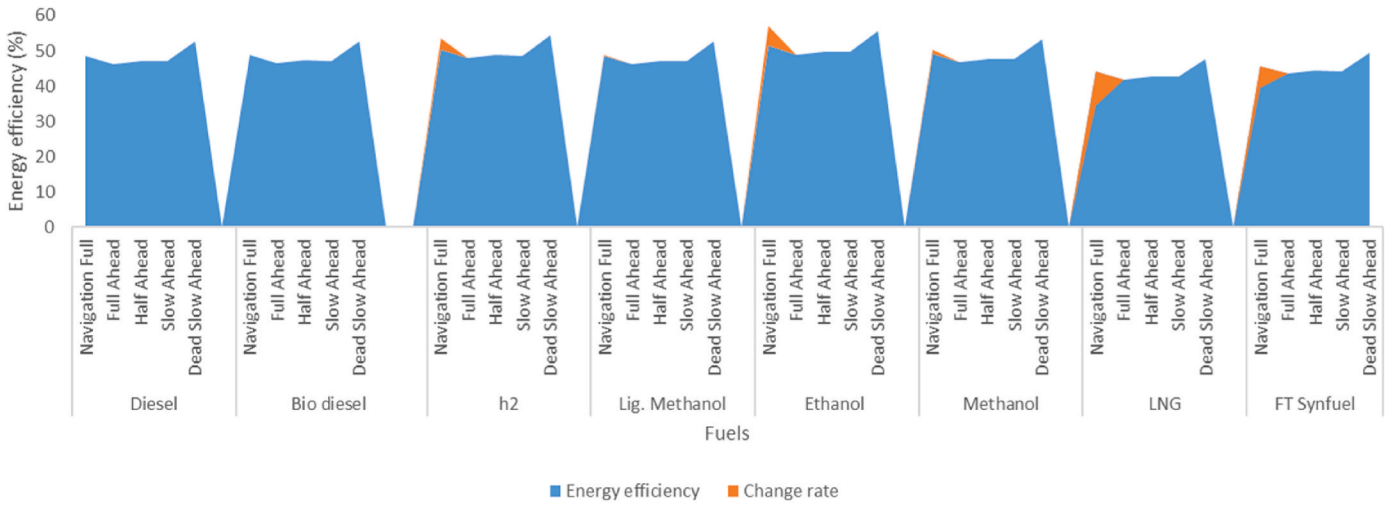


Fig. 2. Energy efficiency of fuels according to operational positions.

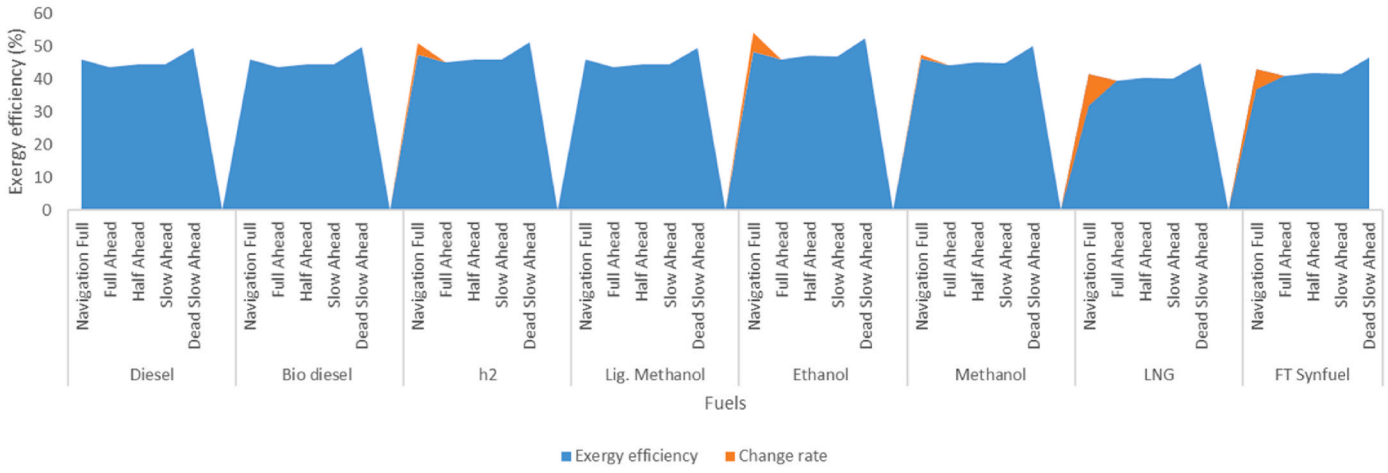


Fig. 3. Exergy efficiency of fuels according to operational positions.

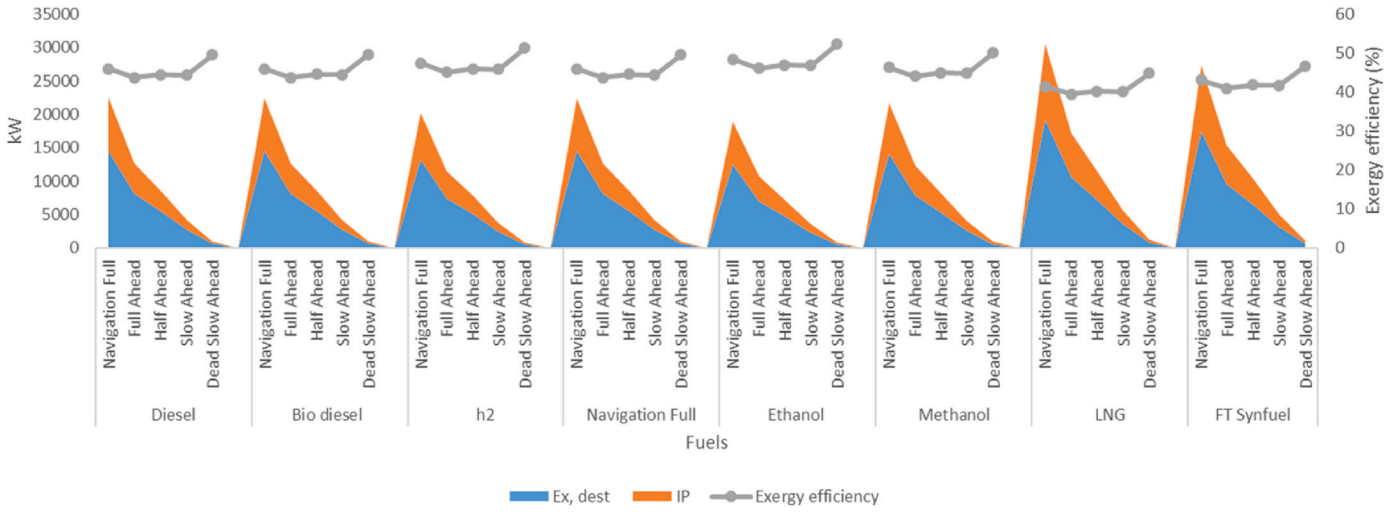


Fig. 4. Exergy destruction for fuel and IP for each fuel.

productions depending on the SI value for these fuels were found to be 16.33 kW/K and 14.50 kW/K in LNG. The energy efficiency ratios (EER) depending on the fuel preferences of the engine were also evaluated. This value indicates the target value that is developed based on environmental impact conditions and can be defined for possible opportunities in energy efficiency. According to these data, the exergy

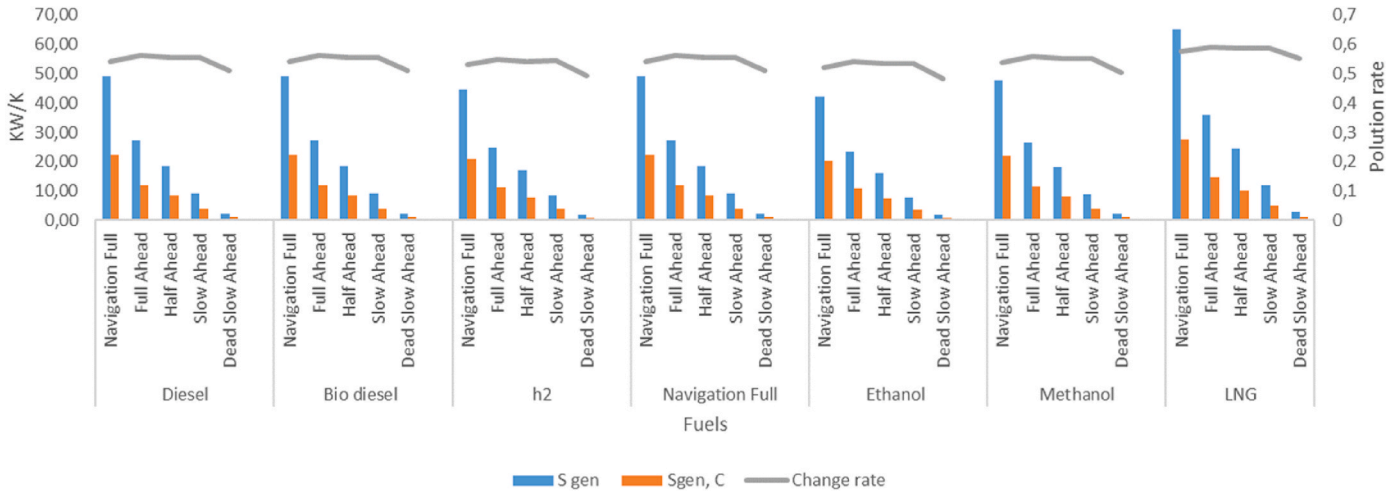


Fig. 5. Entropy production and pollution rate of fuels according to operational positions.

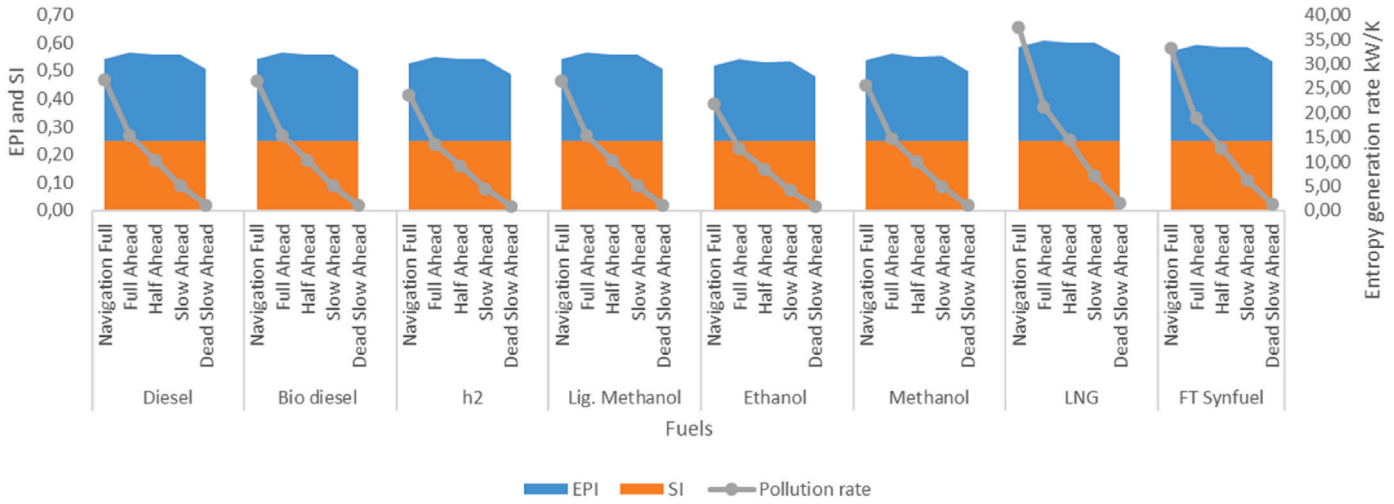


Fig. 6. EPI and SI values and entropy generation rate of fuels according to operational positions.

efficiency, IP ratio, and Energy Efficiency ratio (EER) of the engine were evaluated together, and their distributions are given in Fig. 7.

The EER values depending on the fuel preferences of the engine show that it varies between 5.20 % and 13.10 % on average, depending on the operating position of the engine. In diesel usage, this rate was found to be 8.87 % on average. While this rate is 7.95 % in the hydrogen-assisted use of the engine, it has an average value of 7.39 % in the Ethanol preference. In the use of LNG, which has high inefficiency in the fuel

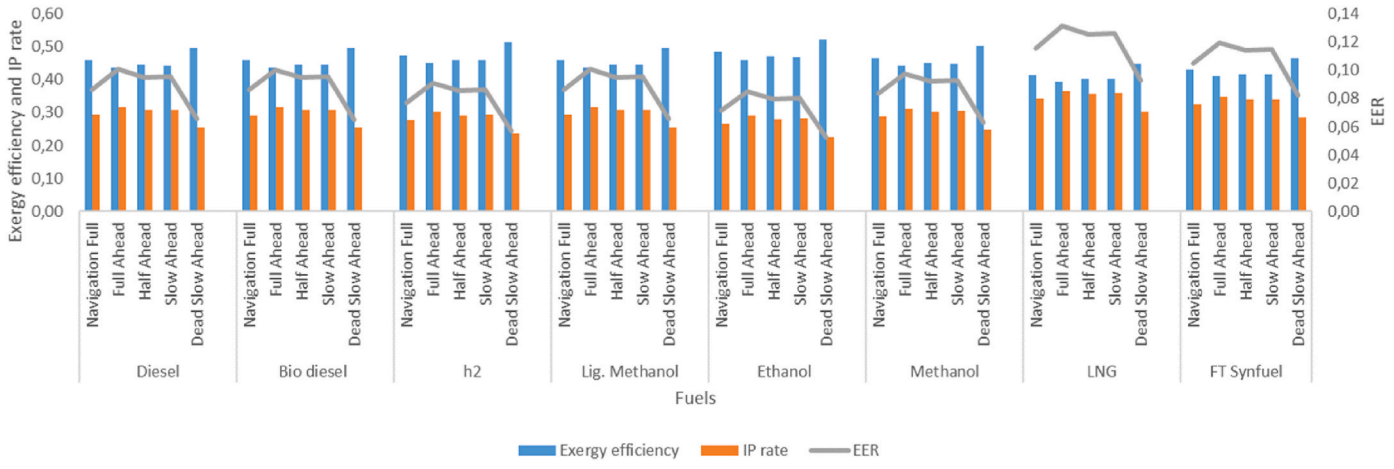


Fig. 7. Exergy efficiencies and EER values of fuels according to operational positions.

preferences of the engine, the EER value was found to be 11.83 % on average, depending on the operating position. The engine's use of FTSynfuel has shown that it has similar negativities. The EER value for this fuel shows a potential of 10.71 %. These values indicate the extent of opportunities that can be provided to the engine for possible maintenance liability. However, the reference boundary condition for design and corporate responsibilities is the IP rate. This value is a measure of the combustion performance depending on the structural features and operational conditions of the engine. For the IP values of the engine, while the ratio in diesel fuel was 29.64 % on average, this ratio was found to be 34.54 % in 100 % LNG use. It has been observed that the possible IP rate values of the engine in the use of 10 % hydrogen and ethanol are on average 28 % and 29.11 %, respectively. All these results show that it produces an environmental pollution problem even with all kinds of fuel preferences in engines. In this context, it can be said that the optimization of possible operating parameters has become valuable. Developing engine operating processes with environmental indicators and examining the related results can be perceived as another evaluation that should be taken into account.

6. Conclusion

This study primarily aims to investigate the energy, exergy, and environmental impacts of different fuel preferences on a two-stroke ship engine, as well as their potential effects on sustainability and sectoral decarbonization. Information on fuel preferences is crucial for sustainable and environmentally friendly ship propulsion. The study focused on diesel fuel performance, and comparatively analyzed results with seven possible fuel options. The study provides a concise performance comparison of the reference engine, focusing on the potential power output of each fuel at five different positions that represent the boundary conditions of 5507 RPM and 11853 RPM. The specific outputs obtained for each position are presented below.

a. While an increase of 5.13 % was observed in the mass demand for 100 % LNG, a decrease of 18.04 % was found for 10 % hydrogen.
b. While the average energy efficiency of the engine for a diesel engine was 48.34 %, this value was found to be 51.02 % for Ethanol and 49.97 % for liquid hydrogen. However, in LNG, this value is 43.73 % on average. Especially Ethanol performance is remarkable.
c. The energy efficiency for the liquid and gas phases of methanol, which stands out in sectoral preferences, was found to be 48.35 % and 48.86 % on average, respectively.
d. When the exergy efficiency of fuels is examined, while this value is 45.60 % for diesel, it indicates an increase of 3.36 % and 5.56 % for liquid hydrogen and ethanol, respectively. This value was found as an average of 0.02 % and 1.07 % increase for liquid and gas methanol. In contrast, for LNG, this value has an average of 9.53 % reduction in efficiency.

Considering the reversible conditions, the entropy generation for fuels shows an increase of 122 % for diesel, while this value indicates a potential of 116 % and 112 % for liquid hydrogen and ethanol. On the other hand, this value was found as 139 % for LNG. For liquid and gaseous methanols, this value was found to be 122 % and 120 % on average, respectively.

f. Considering the emission effects of fuels, it shows a cumulative reduction potential of 27.01 %. This value indicates a potential improvement of 34.96 %.
g. On the other hand, when the SI values of 0.248 are taken as reference, the rate of increase in the EPI value for diesel fuel is 120 %, while this value is 114 % for liquid hydrogen and 110 % for ethanol. While this value was on average 137 % for LNG, it was found to be 119 % and 117 % for liquid and gas methanol, respectively.
h. The EER value, which defines the ratio of opportunities depending on fuel preference in the engine, is 8.87 % for diesel, while this value is 7.45 % for liquid hydrogen and 7.38 % for ethanol. While this value was 11.83 % for LNG in the study, this value was 8.86 % and 8.57 % for liquid and gas methanol, respectively.

Many studies have highlighted the potential of LNG, methanol, and hydrogen as transition fuels in piston engines, to achieve decarbonization targets. However, when operational data and energy demands are taken into account, it appears that their decarbonization potential is limited. In this case, devising strategies to enhance engine efficiency via operational optimization can be seen as an important step for increasing the potential of these fuels. Also, this could help to alleviate potential concerns regarding the suitability of transition fuels for decarbonization targets. For this purpose, to ensure energy manageability, it's important to develop an EER rate that prioritizes the operational efficiency of the engine and encourages continuous improvement. Furthermore, supporting this study through exergo-economic and exergo-environmental analyses could offer an alternative viewpoint for making decisions about fuel preference.

CRediT authorship contribution statement

M. Ziya Sogut: Writing – original draft, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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