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Evaluation of Decarbonization Methods on Ships

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ABSTRACT

Reducing CO_2 emissions from ships is regulated by the IMO due to global warming. The regulations aim to reduce carbon emissions gradually. This paper highlights the most recent developments for reducing carbon emissions from ships in compliance with the applicable regulations. Basically, three different techniques are used to reduce carbon emissions. These are the use of clean alternative fuels that do not contain carbon atoms, such as hydrogen and ammonia; the other is the use of ship propulsion systems that can be propelled by electricity; and finally, the use of carbon capture systems. As a result of the study, the potential, advantages, and disadvantages of the techniques used are mentioned. As a result of the study, it was found that carbon capture systems reduce carbon emissions by up to 90%. One of the findings is that CO2 emissions can be significantly reduced with appropriate storage practices.

Keywords: CO_2 reduction techniques, Sustainability, Alternative marine fuels, Marine diesel engines, Carbon capture

Gemilerde Karbonsuzlaştırma Tekniklerinin Değerlendirilmesi

ÖZ

Gemilerden kaynaklanan CO_2 emisyonlarının, küresel ısınma nedeniyle IMO tarafından getirilen düzenlemeler ile azaltması amaçlanmaktadır. Bu düzenlemeler, karbon salımını kademeli olarak azaltmayı hedeflemektedir. Bu çalışma, getirilen düzenlemelere uygun olarak gemilerden kaynaklanan karbon emisyonlarının azaltılmasına yönelik en son gelişmeleri ortaya koymaktadır. Karbon salınımını azaltmak için temel olarak üç farklı teknik kullanılmaktadır. Bunlar hidrojen ve amonyak gibi karbon atomu içermeyen temiz alternatif yakıtların kullanılması, diğeri ise elektrikli gemi sevk sistemlerinin kullanılması ve son olarak karbon yakalama sistemlerinin kullanılmasıdır. Çalışma içerisinde kullanılan tekniklerin potansiyelleri, avantaj ve dezavantajlarından bahsedilmiştir. Çalışma sonucunda karbon yakalama sistemlerinin karbon salımını %90 seviyelerine kadar azalttığı görülmüştür. Uygun depolama uygulamaları ile CO_2 emisyonlarının önemli ölçüde azaltılabileceği ortaya konulmuştur.

Anahtar Kelimeler: CO_2 azaltma teknikleri, Sürdürülebilirlik, Alternatif deniz yakıtları, Gemi dizel motorları, Karbon yakalama

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1. Introduction

The climate crisis, which has arisen due to global warming, is among the most crucial sources of concern today. The main reason for this situation is the high anthropogenic greenhouse gas emissions (GHG) released into the atmosphere. When the general greenhouse gas emissions are examined, the growth rate in greenhouse gas emissions between 2010 and 2019 is around 1.3%, and between 2000 and 2009, it is around 2.3%. Although the rate has been low in recent years, the situation is at alarming levels due to its incremental progress (Cachola et al., 2023).

When anthropogenic GHG emissions are examined between 1990 and 2019, the largest share is undoubtedly CO2. While its ratio among total anthropogenic GHG emissions was approximately 72% in 1990, this ratio increased to approximately 75% in 2019 (IPCC, 2022). Figure 1 represents anthropogenic greenhouse gas emissions between 1990 and 2019.

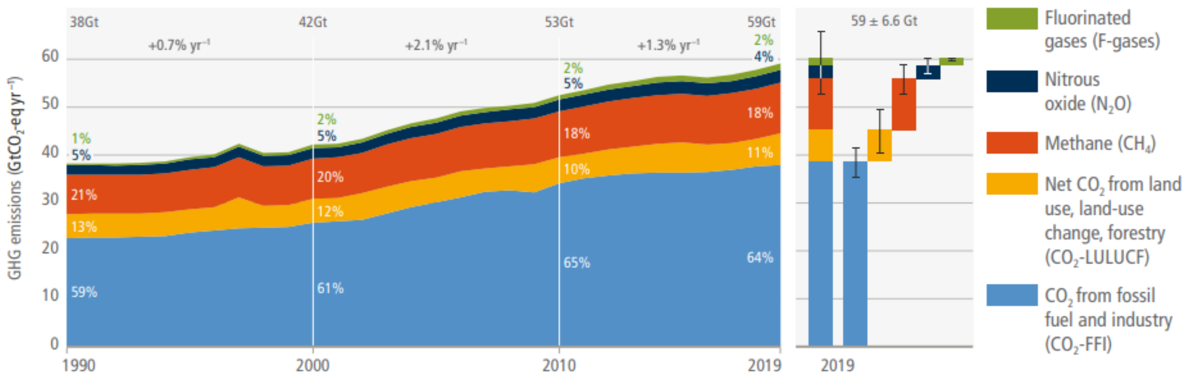

Figure 1: Anthropogenic greenhouse gas emissions (IPCC, 2022).

The fact that approximately 90% of the world's transportation is carried out by sea and the construction of ships with high power requirements in transportation shows that the role of ships in carbon emissions is high (Woodcock et al., 2007). It is thought that the annual CO_2 emissions in the world originating from maritime transport are approximately 940 million tons and this value constitutes 2.5% of the total CO_2 emissions (Eu, 2022).

To address difficulties with maritime pollution brought on by the shipping industry, the IMO established the maritime Environment Protection Committee (MEPC) in 1973. Similarly, in order to prevent environmental pollution from ships, the International Maritime Organization (IMO) adopted the MARPOL Convention in 1973. The MARPOL convention addresses a wide range of marine pollution issues arising from the shipping sector, including oil spills, the transit of poisonous liquids and other hazardous chemicals, sewage, rubbish, and ship air pollution. As a result, it has a considerable impact on the control of marine pollution associated with maritime transport and covers 99% of global commerce tonnage (IMO, 2005, 2022; Perera & Mo, 2016).

The regulations for reducing greenhouse gases, which have been in effect since 2011 within the scope of MARPOL, are generally related to energy efficiency. The arrangements given are generally carried out according to the flow chart given Figure 2.

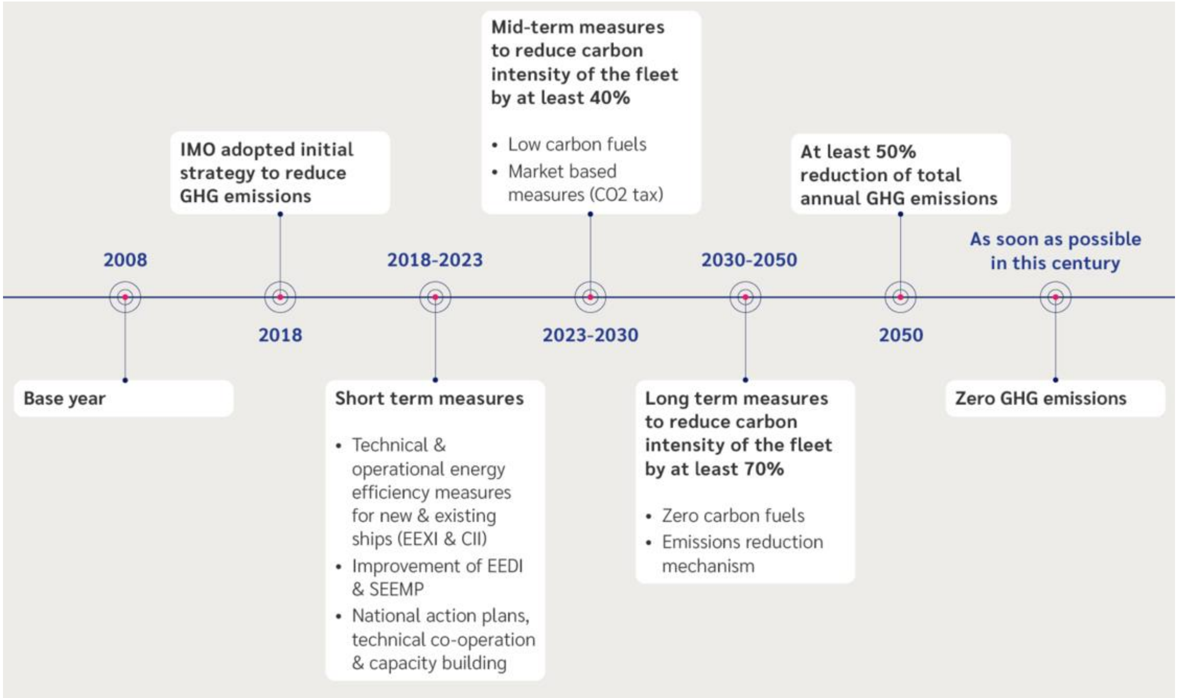

Figure 2: IMO CO_2 regulation (IMO, 2014).

In this context, carbon emissions from ships technically include the following regulations.

Energy Efficiency Design Index (EEDI): EEDI was implemented in 2011 with the goal of lowering CO_2 emissions from ships. It is basically a value related to ship design and expresses the amount of CO_2 that can be released per unit load carrying capacity. The EEDI value, which calls for a significant change in how new ships emit CO2, must be assessed during the design phase and then confirmed through navigational testing. Figure 3 represents the EEDI reference value until 2025 (Eyring et al., 2010).

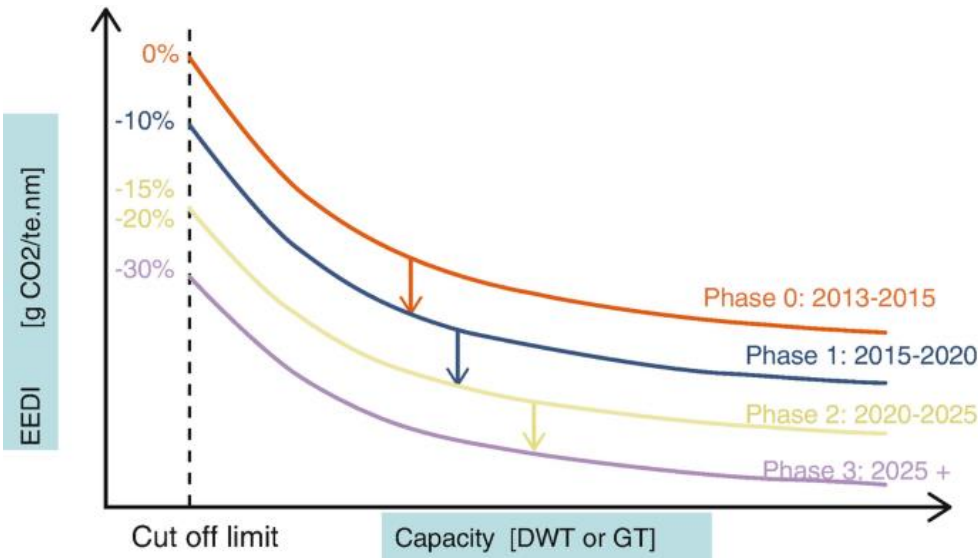

Figure 3: EEDI values (Zheng et al., 2013).

The EEDI was developed for various ship types and must be equal to or less than the reference line. IMO aims to reduce CO_2 emissions by 10% compared to the first phase and 30% by 2025, starting in 2015. For this reason, the development of more efficient ships will be encouraged by applying various technologies to meet the specified EEDI value (Polakis et al., 2019).

Energy Efficiency Existing Ship Index (EEXI): IMO introduced EEXI in its revision approved in 2020 under MARPOL Annex IV on the prevention of air pollution from ships. As of 2023, EEXI is valid for ships larger than 400 GT and regulates the calculation of the standardized CO_2 emissions based on installed engine power, payload, and ship speed (DNV GL, 2022; Rutherford et al., 2020).

Energy Efficiency Operational Index (EEOI): The Energy Efficiency Operational Index (EEOI), an important IMO metric of ship energy efficiency, came into effect in 2011 (Hou et al., 2019). Ship speed, resistance, specific consumption of fuel, operational effectiveness, and further energy efficiency are all directly related to operational operating parameters. Consequently, speed optimization and research of engine speed on ships is the most important of reducing EEOI, energy saving and emission reduction.

SEEMP: SEEMP is an operating strategy that creates a framework to increase the efficiency of energy on board by tracking the performance of the ship and installing energy-efficiency solutions. Since 2013, the plan for management, which includes four phases: planning, implementation, tracking, self-evaluation and enhancements, has included an important mechanism that encourages ship owners to take various measures that promote economical in fuel operation (MEPC.213(63), 2012; Nuchturee et al., 2020)**.**

Basically, these regulations play an important role in reaching the carbon-zero target to prevent global warming by 2050. To decrease the release of CO_2 from ships, the amount of carbon that is aimed to being reduced by different energy efficiency applications is given in Figure 4.

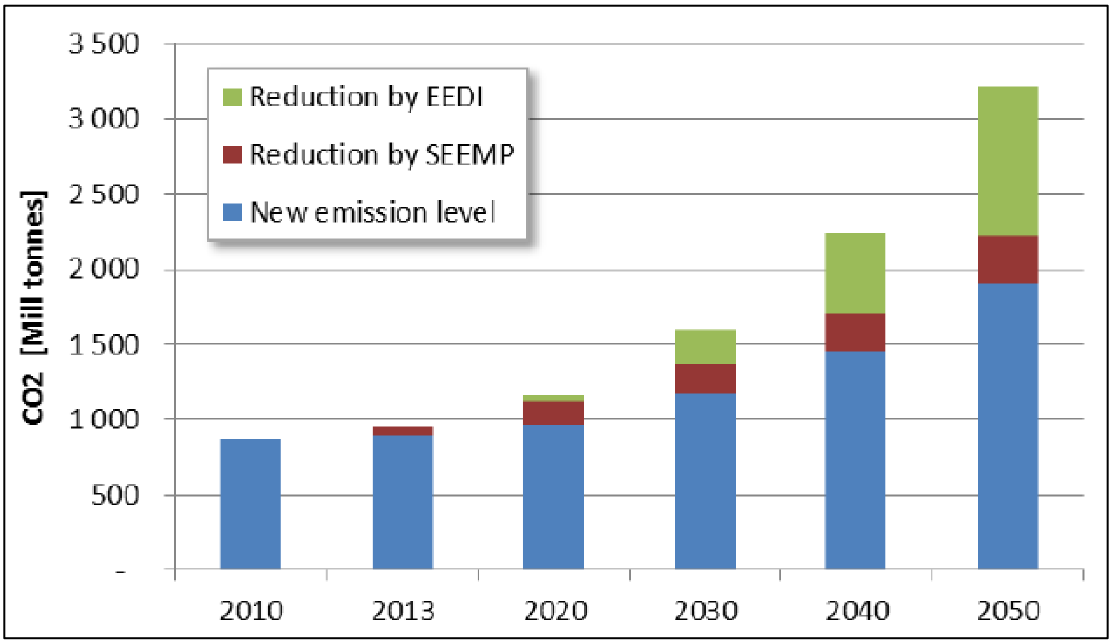

Figure 4: Rates of CO_2 emitted from maritime transport per million tons per year (IMO, 2020).

In this study, approaches that can be used to reduce carbon emissions that cause global warming, especially from ships, and emission reduction amounts will be evaluated comparatively."

2. Techniques of CO_2 Emission Reduction

To achieve the carbon zero target until 2050 to reduce CO_2 emissions from ships, different technologies are used that can meet the regulations within the scope of MARPOL Annex IV. These methods include the utilization of alternative fuels and renewable energy sources, ship energy-efficient technologies, and the use of carbon capture devices (Hoang et al., 2022).

2.1 Using Alternative Fuels

Alternative fuels used to reduce CO_2 emissions from ships can basically be grouped into two main groups. The first is conventional ship fuels with low carbon content, and the second is fuels that do not contain carbon atoms in their structure. In this study, mainly hydrogen and ammonia will be examined for carbon zero purposes.

Ammonia: Because it excludes carbon atoms in its structure, ammonia is one of the most likely fuels to be employed in the objective of reducing greenhouse gases by approximately 50% and CO2 emissions by 70% by 2050 in order to avert global warming. (Yapicioglu & Dincer, 2018). Liquid ammonia storage, transportation, and distribution are easier and less dangerous than hydrogen. Ammonia is easily liquefied and held at ambient temperature at comparatively low pressure (1030 kPa) or at ambient pressure at a low temperature (240 K). Hydrogen, on the other hand, must be held at greater temperatures (Dimitriou & Javaid, 2020). Ammonia is traded globally and is mostly produced in China, India, Russia, and the United States. Consisting of 17.6% hydrogen and 82.4% nitrogen components by weight, ammonia also undertakes the task of carrying hydrogen (Machaj et al., 2022).

Hydrogen: One of the most important fuels foreseen to be used in ship diesel engines is Hydrogen. Because of its abundance, cleanliness, and high efficiency, hydrogen is a promising future fuel. It can be electrochemically turned into electricity via fuel cells or burned in internal combustion engines. Despite the fact that fuel cells represent a potential future technology, the usage of hydrogen in internal combustion engines remains critical, primarily for power production or heavy-duty applications. Various investigations on the feasibility and advantages of hydrogen as a form of fuel for internal combustion engines have been done in this direction (Bayramoğlu & Yılmaz, 2021; Dimitriou et al., 2018). It has become vital to use alternative carbon-free fuels in combustion systems in order to reduce carbon emissions and achieve the zero-carbon emission target. Since fuel cannot be lost during burning, it is also the most efficient strategy. Due to its lack of carbon, hydrogen is one of the most widely used carbonless fuels (Chai et al., 2021). Since hydrogen cannot be obtained naturally and must be created to be used, it cannot be used widely. The costly equipment required to liquefy hydrogen and transport it as liquid are additional factor (Kojima, 2019). Table 1 shows the thermodynamic properties of alternative fuels (Dotto et al., 2023).

Table 1*:Specifications of alternative fuel* (Dinesh & Kumar, 2022; Song et al., 2022).

Property	H_2	CH_3OH	NH_3	LNG
Density [kg/m^3]	71.1	805	683	422.6
Calorific value [MJ/kg]	120	20	19	50
air-to-fuel ratio	34	6.5	6	17.2
Storage temperature [°C]	−253	25	−34	−162
pressure of storage [bar]	1	1	1	1
h_{vap}[kJ/kg]	450	1199	1371	512

2.2 Using Renewable Energy Sources

The usage of alternative energy sources on ships means the elimination of all harmful gases released into the atmosphere. There are basically two types of green energy sources, solar and wind. According to the statistics made in 2021, by the end of 2020, the renewable energy generation capacity will have reached a level of approximately 2799 GW (Huang et al., 2021). The share of solar and wind among the renewable energy sources produced is 25.5% (714 GW) and 26.1% (733 GW), respectively. (Jathar et al., 2022). However, although renewable energy sources are used alone in small-sized vessels today, they are mostly used as hybrid energy sources with solar and wind. Hybrid systems are widely used on naval vessels, tugboats, offshore vessels, research vessels and yachts. Figure 5(a) depicts the "Greenline 33 Hybrid Yacht" built together with Slovenia and Italy in January 2010. The boat is powered by a battery package, solar and diesel power, and it can run in both diesel and electricity configurations. Feadship, a Dutch constructor, constructed the 274-foot (83.5 m) boat "Savannah" in 2015, as seen in Figure 5(b). This yacht's power system consists of a four-stroke diesel engine, three electricity producers and a bank of 1 MW lithium-ion batteries. There are three operating modes for the boat's power system: diesel-powered, hybrid diesel-electric, and power-only. A system that uses hybrid power has benefits such as long-term dependable performance at high speed and power levels and long-term stable operation at low speed and power levels.

Combination diesel-electric power technology has advanced in tandem with the advancement of power electronics technology. Using this kind of technology, all power generating and storage devices for energy have primarily been utilized in the design of propulsion systems onboard tugboats, yachts, ferryboats, research vessels, navy and offshore ships. The watercraft depicted in Figure 5(c) became operational in November 2017 as the world's first 2000-tonne new energy electric ship. The ship used two electric motors to operate the flat-bladed omnidirectional propellers as the control and power system, which was powered by a hybrid energy storage system (a supercapacitor and a lithium-based battery). The California Air Resources Board (CARB) announced in June 2018 the production of a 70-foot aluminum catamaran ferry called the "Water-Go-Round" in the Bay Area, as depicted in Figure 5(d). This vessel is powered by a hybrid of hydrogen fuel cells and lithium-ion batteries. It was the world's first ship to use ~~a~~ hybrid fuel cell technology. Furthermore, this ship is the world's first to use fuel cells (Jathar et al., 2022).

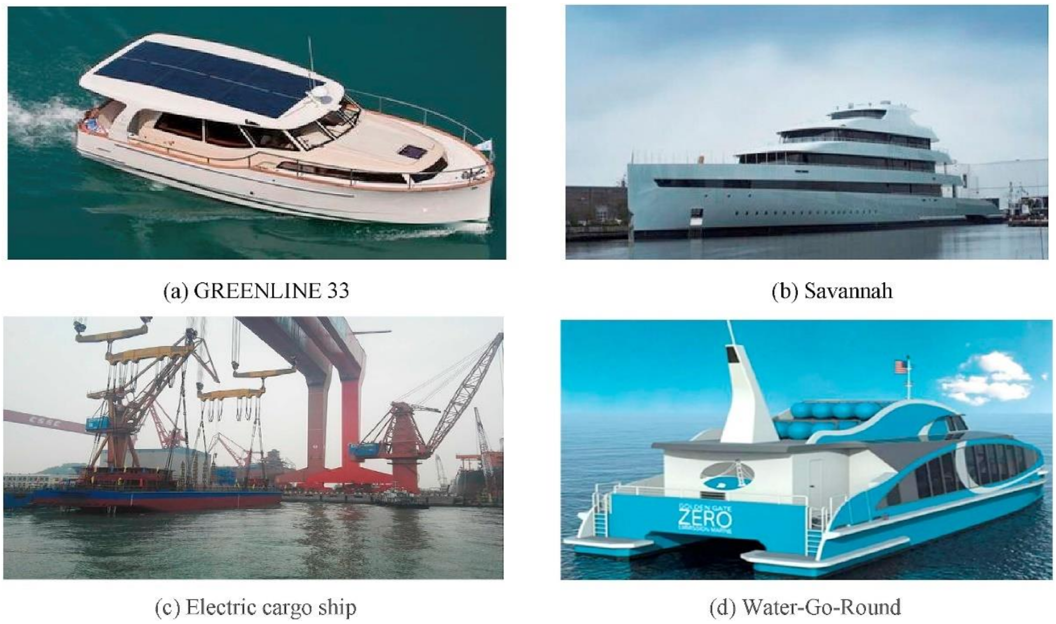

Figure 5: Hybrid ships (Yuan et al., 2020).

2.3 Carbon Capture and Storage Systems

Carbon capture and storage (CCS) systems on ships can be considered as a technology used to achieve standards related to decarbonisation, in the case of using conventional fuels. CCS can be used in ships to treat all carbon-containing fossil, electrical and biofuels, which can have a medium- to long-term impact on ship decarbonization. However, the viability of CCS is dependent on a number of variables, such as the advancement of CCS technology, commercial feasibility, the cost and accessibility of alternative fuels, and future emission-related policies (Howell et al., 2022).

There are primarily three different types of carbon capture techniques. These are pre-combustion carbon capture, post-combustion carbon capture and oxygen combustion and carbon capture systems. A post-combustion carbon capture system has been proposed by Pi-Innovation, where water acts as a physical mass transfer solvent. This CO_2 Capture may be utilized on land or at sea. Decarbonization that is largely complete of flue gases provides low cost and ease of usage in numerous different flue gas sources with partial CO_2 content. Also, The fact that post-combustion CO_2 capture produces a solubility difference between CO_2 and N_2 at lower temperatures and higher pressures is a significant benefit (Blount et al., 2017; Malekli & Aslani, 2022) . Figure 6 represents the post-combustion carbon capture process.

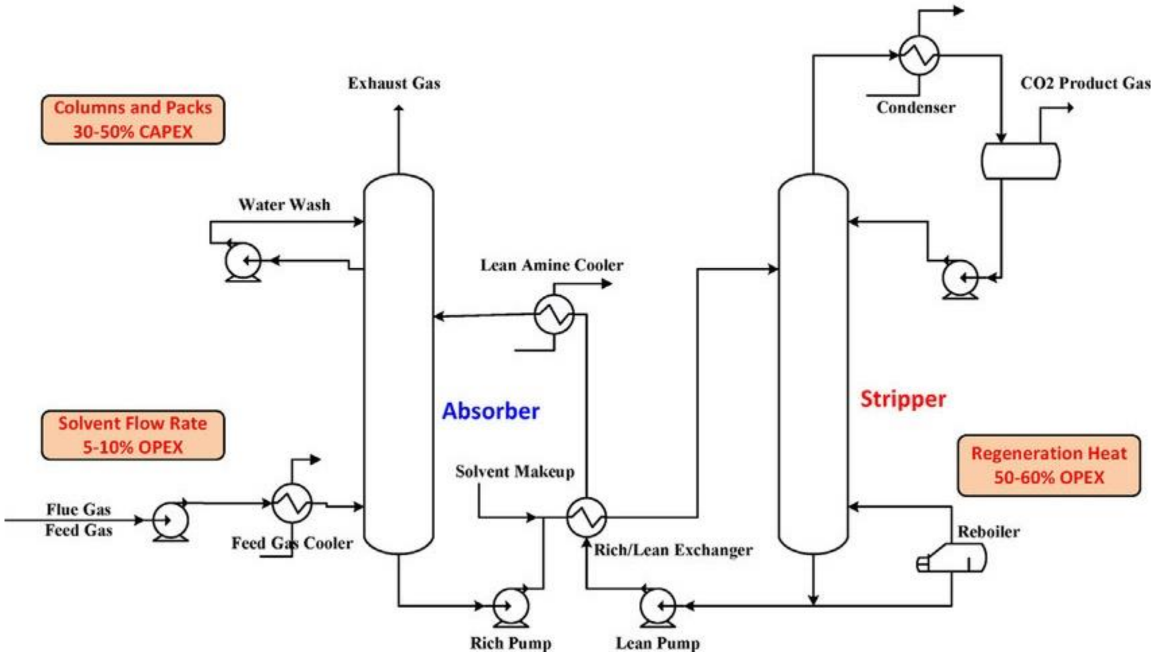

Figure 6: Post-combustion carbon capture process (Liang et al., 2015)

Pre-combustion carbon capture involves the process of removing carbon dioxide from a fossil fuel or biomass fuel before the combustion process is complete. It is mainly based on the gasification process of fuels in the form of biomass, natural gas, and coal (Theo et al., 2016). To reduce the CO_2 components formed as a result of the combustion of fossil fuels such as natural gas, the CO_2 and H_2 components in its structure are separated with the help of a membrane. As a result, the CO_2 components in its structure will be separated without requiring gasoline to be sent to the ship's diesel engines. The purified gas, which the mixture is made up of about 40% CO_2 and 60% H_2 separated from natural gas prior to combustion, will undergo CO_2 separation treatment to produce pure H_2, which will then be fed to gas turbines for the purpose of generating electricity. The methods used to remove CO_2 from a fuel gas mixture include absorption, adsorption, membrane separation, and cryogenic separation (Babu et al., 2016). Figure 7 represents the pre combustion carbon capture process.

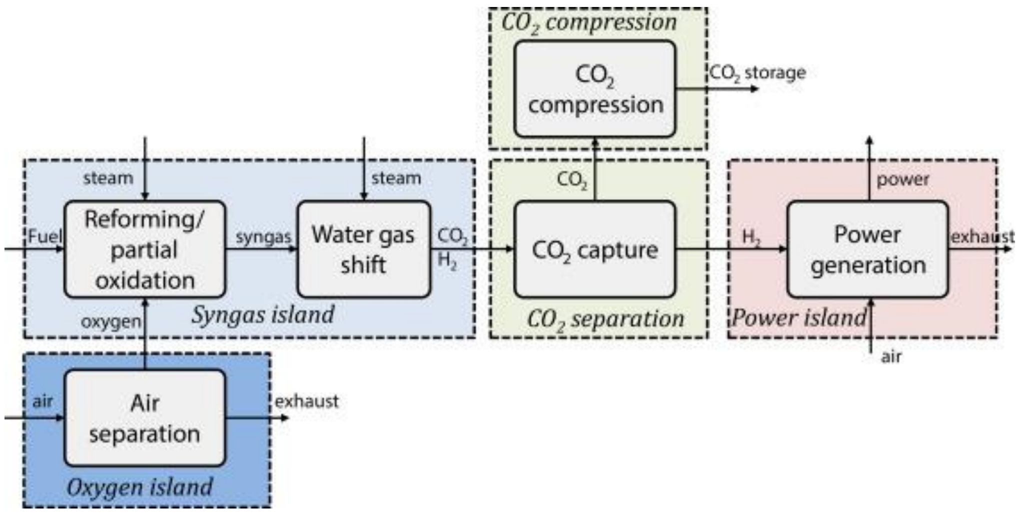

Figure 7: Carbon capture process pre-combustion (Jansen et al., 2015)

As a result of pure oxygen combustion, combustion takes place by using pure oxygen instead of air in the carbon capture process. After combustion, the exhaust gas consists of CO_2 and H_2O vapor. The flue gas is cooled so that the water turns into liquid and is separated from the carbon dioxide. Combustion with pure oxygen produces very high temperatures. This process simplifies carbon dioxide capture as it contains no nitrogen. This process can compete with the post-combustion capture process, but experience with this process is limited (Albazzaz, 2020). Figure 8 represents the oxy-combustion carbon capture process.

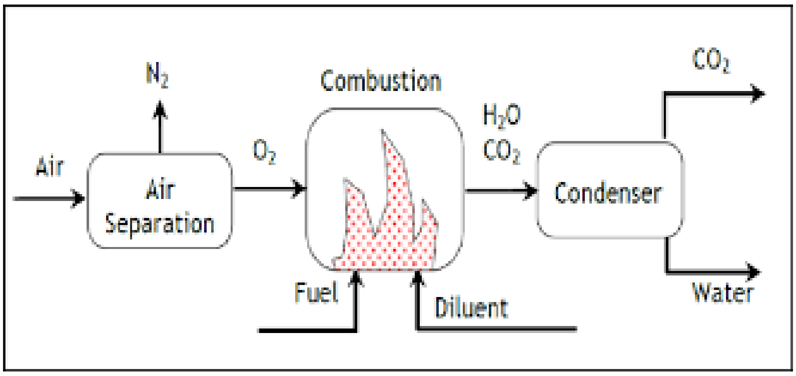

Figure 8: oxy-combustion carbon capture systems (Albazzaz, 2020)

3. Comparison of Carbon Reduction Systems on Ships

Different methods are used to reduce the CO_2 gases that cause global warming from ships. These technologies, in addition to lowering CO_2 emissions, have a significant influence on the performance of engines and other emissions.

In the study conducted by Seddiek and Ammar (Seddiek & Ammar, 2023), the effect of ammonia use on CO_2 emissions in diesel engines versus conventional ship fuel was evaluated. As a result of the study, 1052 tons of CO_2-eq. Against the emission of ammonia, this rate was determined as 202.8 tons CO_2-eq. Likewise, in the case of diesel fuel combustion, the percentage ratio of CO_2, CH_4 and N_2O components is determined as 96.3%, 2.7% and 1%, while only CO_2 components are formed in the use of ammonia. The chemical process used to produce ammonia is the primary cause of the synthesis of carbon compounds. The determined EEDI and EEOI in the case of diesel fuel use were 20.32 gCO_2/ton·nm and 39.68 gCO_2/ton·nm, respectively, while the EEDI and EEOI were determined as approximately 1 gCO_2/ton·nm in the case of ammonia usage.

Although hydrogen as a fuel combines with different gases, it is not found alone in nature. Therefore, it is necessary to separate the structures in the form of compounds with different techniques (Bayramoğlu et al., 2022). Even though it does not create a CO_2 component as a result of combustion in diesel engines, it causes CO_2 formation in the chemical processes during its production. Wang et al. (Wang et al., 2023) intended to investigate the full maritime hydrogen fuel technology chain. Figure 9 represents six different technologies of hydrogen production.

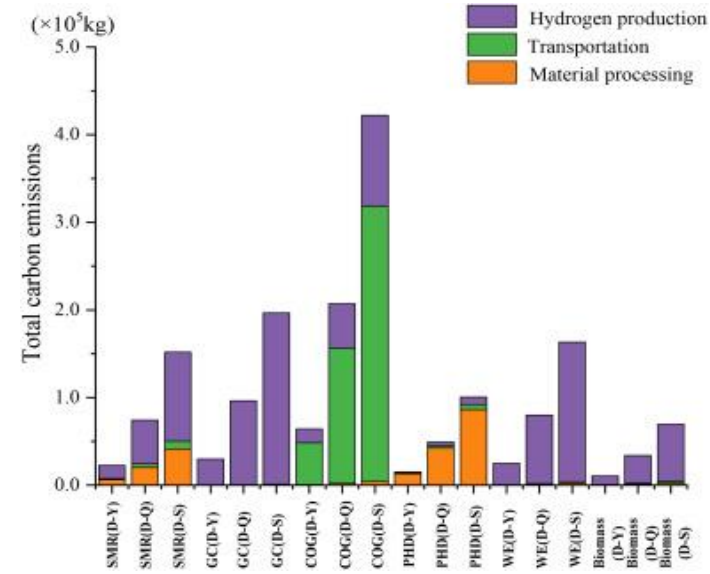

Figure 9: Carbon emissions of six types of hydrogen production (Wang et al., 2023)

Different techniques applied in hydrogen production are defined as steam methane reformer (SMR), gasification of coal (GC), coke oven gas (COG), propane dehydrogenation (PDH), water electrolysis (WE), and biomass gasification. According to the findings, the use of the biomass for hydrogen supply technique has a substantial benefit with regard to of CO_2 emissions.

Renewable energy sources are systems that are sensitive to both human health and the environment. However, the fact that a large part of maritime transport is carried out by ships has made it necessary to optimize higher carrying capacity and lower costs. Therefore, renewable energy sources can be used either in small marine vehicles that require less energy or with hybrid systems in addition to diesel engines (Caliskan et al., 2013; Jeong et al., 2022). Furthermore, clean energy is critical to effectively meeting energy-saving targets and lowering emissions. However, due to the very nature and functioning of ships, utilizing one energy source or one energy form simultaneously has some limitations has restrictions, particularly for ships with high power capacities. Solar energy, for example, is affected by ship structure, operational circumstances, and meteorological variables, making it unsuitable for all ship types (Diab et al., 2016; Nasirudin et al., 2017).

Stec et al. (2021) evaluated the impact of post-combustion carbon capture systems on CO_2 and EEDI reductions in marine applications. Reducing CO_2 components in ships directly leads to a decrease in the EEDI value (Stec et al., 2021). In parametric studies, it has been determined that CO_2 emissions have been reduced by approximately 90%. The study mainly investigates the potential of reducing the EEDI of a 47,000 DWT intermediate tanker (Handymax class tanker) using HFO. In addition, Feenstra et al. (2019) demonstrated the Ship-Based Carbon Capture idea as a transitional solution to notably reduce CO_2 emissions on ships. The concept of Ship-Based Carbon Capture has been shown to be technically feasible. Theoretical design ideas for two sample instances, an inland ship and a cargo ship, are presented. Balances of mass and energy reveal the probability of ships aptitudes of up to 90% of their pollutions. In addition, it emerged that the dimensions as well as the weight of the equipment were suitable for the cargo ship's design and did not impair its stability's.

Comparisons between the EEDI values of a ship currently in operation and those in which three different carbon reduction techniques are applied are given in Figure 10. The results obtained basically reveal that the EEDI values of the ships that are shipped with hydrogen fuel, carbon capture and storage systems, and electrical power, which do not contain carbon in their structure, are close to zero. In addition, basic parameters such as CAR, Es and CS used in EEDI calculations were also investigated in the study (Law & Othman, 2022).

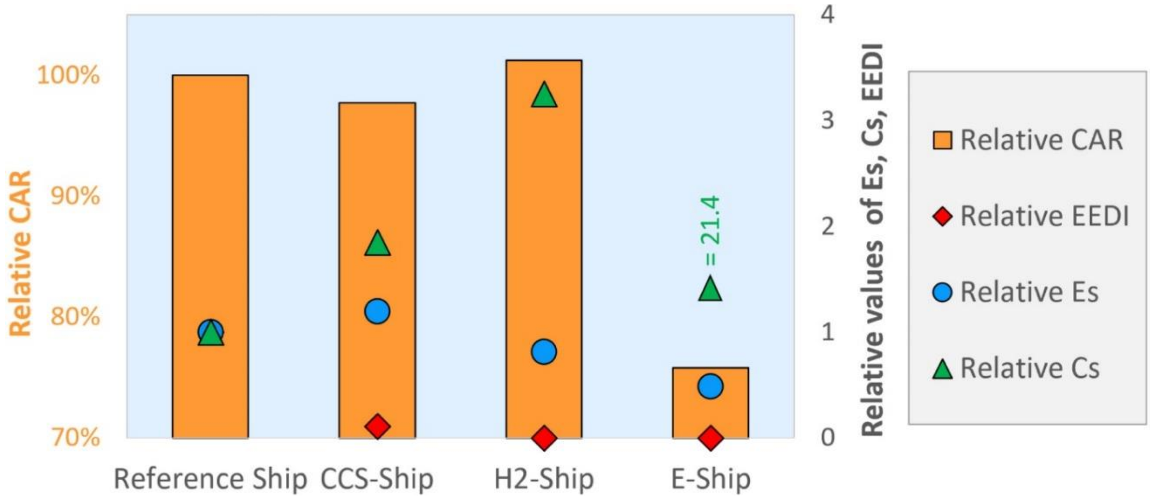

Figure 10: EEDI for variable configurations (Law & Othman, 2022)

4. Conclusion

For the first time in 2011, the IPCC was implemented to reduce carbon emissions from ships. Implementations will be carried out gradually until 2070, ultimately aiming to achieve carbon zero by reducing carbon emissions from ships by approximately 70%. With the introduced regulations, it is aimed to apply alternative fuels with a low carbon ratio, which allows carbon emissions to be reduced by 25%, such as LNG, until 2030 in the first place.

In the second stage, it is necessary to apply clean fuels such as ammonia and hydrogen, which do not contain carbon atoms in their structure, to reduce it by approximately 50% until 2040. However, some difficulties arise due to the low calorific energy of ammonia and the release of carbon emissions during its production. If hydrogen is used as a diesel fuel, engine modifications are also required if it is used directly as a stand-alone fuel due to its high energy value and rapid flammability. In addition, although hydrogen is the lightest metal and makes compounds with most metals, it is not found alone in nature. This makes it necessary to obtain hydrogen with different techniques. In addition, it prevents the usage of H_2 as a energy sources in the storage and transportation problems of hydrogen obtained by chemical means.

In the third stage, in reducing carbon emissions by 70%, it removes the obstacles to carbon zero in carbon capture and storage systems, as well as clean fuels. Carbon capture and storage systems only remove the Barriers to fuel prices and reduce emissions from the usage of fossil sources. However, the initial installation and operating costs also raise questions about the use of these systems on ships.

5. Declarations

5.1. Competing Interests

There is no conflict of interest in this study.

5.2. Author Contribution

Kubilay BAYRAMOĞLU: Conceptualization, Writing- Original draft preparation, Writing - Review & Editing.

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