ENVIRONMENTAL FOOTPRINT OF DIESEL FUEL IN THE SHIPPING SECTOR

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ABSTRACT

Extensive use of fossil fuels is one of the most important environmental problems nowadays since their combustion results in different emissions, which negatively affect human health and the environment. In the shipping sector, diesel fuel in internal combustion engines represents the dominant power system. Its negative impact is more pronounced for the ships that operate in the short-sea shipping sector since they spend a lot of time near populated areas and in ports. In this paper, the environmental footprint of diesel fuel use in several countries is investigated through the life-cycle assessment. The analysis involved different environmental impact categories (climate change, acidification, eutrophication, human toxicity, etc.), and the results are illustrated on a ferry. It is concluded that alternative fuels represent a great alternative to diesel fuel, while e-fuels are highlighted as viable solutions for reducing life-cycle emissions.

Keywords: fossil fuel, environmental footprint, LCA, alternatives, shipping sector.

1 INTRODUCTION

Excessive use of fossil fuels is a major environmental problem. The gases emitted from fossil fuel combustion include nitrogen oxides (NO_X), sulphur oxides (SO_X), carbon monoxide (CO), particulate matter (PM) and greenhouse gases (GHGs) [1]. NO_X, SO_X and PM emissions are local pollutants that affect human health by causing respiratory diseases and environmental damage through acidification [2]. Increased concentrations of GHGs (i.e. emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and, to a lesser extent, fluorinated gases) have a global effect, contributing to the greenhouse effect that leads to global warming [3].

In the maritime sector, NO_X and SO_X emissions control depend on whether ships operate in Emission Control Areas (ECAs), where emission requirements are more stringent, or elsewhere [4]. SO_X emissions are regulated by the quality of fuel used in a ship's power system, where the sulphur content must meet certain requirements. NO_X emissions are limited by the speed of an engine, with Tier I and Tier II being global standards and Tier III being ECA-specific [5]. CO_2 emissions are regulated by the International Maritime Organization's (IMO) 2011 Energy Efficiency Regulation, which requires every ship of 400 gross tonnage or more engaged in international shipping to obtain an International Energy Efficiency certificate. To achieve this, ships must meet the requirements of the Energy Efficiency Design Index (EEDI) and have a Ship Energy Efficiency Management Plan. The EEDI is a technical measure that quantifies energy efficiency as a ratio of the mass flow of CO_2 per unit of transport work, calculated for each new ship, which must meet or be below the required EEDI level [6]. To further extend the energy efficiency regime to existing ships, the IMO has formulated the Energy Efficiency Existing Ship Index and the Carbon Intensity Indicator, which entered into force on 1 January 2023. These new measures aim to ensure that both new and existing ships contribute to the overall reduction of CO_2 emissions in the maritime sector [7].

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In order to combat the problem of global warming, significant decarbonisation should be achieved in every area of human activity, including the shipping sector. The maritime GHG emissions account for a small share of global anthropogenic emissions (2.9%), it is predicted that this share will increase significantly by 2050 if no action is taken to reduce them [8]. To address these challenges, in 2023 the IMO adopted the Strategy for the Reduction of GHG Emissions from Ships [9], which provides a framework for medium- and long-term decarbonisation measures and requires that international shipping must reduce its total annual GHG emissions by at least 20% by 2030, with the aim of achieving a 30% reduction. This reduction can be achieved through various technical and operational measures, especially by replacing conventional power systems with alternatives [10].

Although the use of alternative fuels for ship propulsion is increasing, most ships still use fossil fuels such as heavy fuel oil and marine diesel oil, whose high carbon content results in higher GHG emissions [11]. Many studies investigated the environmental footprint of conventional ship power systems and the alternatives for their replacement. Moreover, life-cycle assessment (LCA) is often used to compare environmental footprint of different power systems onboard different types of ships [12]–[16]. Perčić et al. [17] compared different power systems based on their life cycle GHG emissions and costs, where diesel-powered ferry represents a baseline scenario. Full electrification is indicated as the optimal powering option. Yan et al. [18] also performed LCA of different power systems focusing only on CO_2 emissions, i.e. they calculated the carbon footprint of different power systems for bulk carriers operating on the Yangtze River. Bilgili [19] conducted an LCA to evaluate the environmental impact of alternative marine fuels. The assessment encompassed a range of categories, including human health, ecosystems, resource use, emissions, and social costs. This comprehensive approach aims to provide a more holistic understanding of the environmental friendliness of a particular fuel, beyond the analysis of its GHG emissions.

The LCA provides a comprehensive evaluation of the environmental effects associated with all stages of a ship's life cycle. This encompasses the extraction and processing of raw materials, fuel production, operation, maintenance, and finally, disposal [20], [21]. LCA is a tool for understanding and mitigating the environmental impacts of ships powered by fossil fuels [22]. The results of an LCA can differ significantly based on regional and national contexts. This paper aims to comprehensively investigate the environmental impact of a diesel-powered ferry trough performing LCA. This assessment will consider a range of environmental indicators, including acidification, global warming, eutrophication, human toxicity, etc. The analysis investigates and compares the environmental impact of diesel fuel from nine different countries/regions.

2 METHODOLOGY

2.1 The LCA of a diesel-powered ship

The environmental impact of diesel-powered ships is quantified by performing a LCA, which follows the well-to-wheel life cycle model. This model is suitable for the transportation sector. To align more closely with shipping terminology, the model is renamed to the well-to-wake (WTW) model, comprising two distinct phases: well-to-tank (WTT) and tank-to-wake (TTW). The WTT phase covers the extraction, production, and transportation of fuel, while the TTW phase includes the actual use of the fuel by the ship during operation [23] (Fig. 1).

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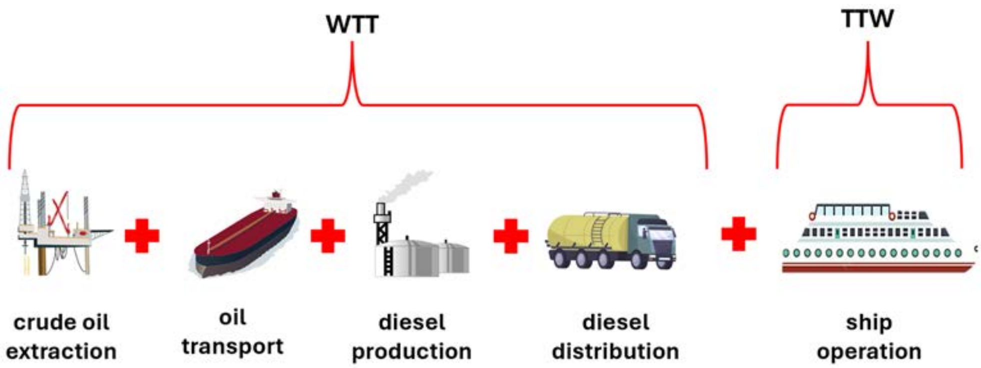

Figure 1: LCA of a diesel-powered ship.

The life-cycle emissions of diesel-powered ships are calculated by means of LCA software, GaBi [24]. While TTW emissions are practically the same regardless of the country in which the ship operates, they are calculated by multiplying fuel consumption with emission factors for diesel fuel [25]. In contrast, WTT emissions differ. This paper examines the production of diesel fuel in nine countries and regions: Germany (DE), the United Kingdom (UK), France (FR), the Netherlands (NL), the United States of America (US), Brazil (BR), China (CN), Australia (AU) and Europe (EU).

Within LCA, data on emissions, waste and material production is gathered and then processed into a numerical format suitable for interpretation. Life-cycle impact assessment (LCIA) methods are used to organise and classify the different environmental impacts of processes, where emissions contributing to the same type of impact are standardised into a single unit that reflects a specific impact category [26]. One of the key reasons for the complexity of LCA results is the extensive number of impact categories found in common LCIA methods [27]. In this paper, the comparison of LCA results using two different LCIA methods, ReCiPe 2016 v1.1 (18 impact categories) [28] and TRACI 2.1 (10 impact categories) [29], is conducted to gain insight into their variability.

2.2 Illustrative example

The results of the conducted LCA are illustrated for a ferry that operates in the Adriatic Sea and is engaged in international shipping (connecting Croatia with Italy), thus is subject to IMO's regulations (Fig. 2).

In order to calculate the real energy needs of a ship operating on a given route, the operating speed, v_{op} (km/h), is determined by dividing the route length by the trip duration. This speed may differ from the design speed, v_{de} (km/h) due to a number of factors, including weather conditions and weather routing, adherence to the schedule and other operational considerations. By applying the cubic relationship between ship speed and power and considering that ships are designed to operate at speeds corresponding to 70%–80% of the main engine load, the average power of the main engine, of a ship, P_{MEave} (kW), which sails at the calculated operating speed, is calculated as follows [23]:

$$P_{ME,ave} = (P_{ME} \cdot 0.8\,) \cdot \left(\frac{v_{op}}{v_{de}}\right)^3. \tag{1}$$

Ship name	Marko Polo
Route	Split-Ancona
Length (m)	128.1
Breadth (m)	19.6
Draught (m)	5.7
Main engine power, P_{ME} (kW)	15,016
Auxiliary engine power, P_{AE} (kW)	3,136
Design speed, v_{de} (km/h)	36.1
Trip duration, t (min)	660
Route length, l (km)	245
Annual number of return trips, N	116
Vehicles capacity	270
Passenger capacity	1,100

Figure 2: Ferry's route and its technical and operational data [30].

It is assumed that the average load of the auxiliary engine, $P_{AE,ave}$ (kW), is 50%. The average ship power, P_{ave} (kW), is calculated by summing up the $P_{ME,ave}$ and $P_{AE,ave}$. The annual fuel consumption, FC_A (kg), is then calculated according to the following equation:

$$FC_A = \frac{P_{ave} \cdot SFC \cdot N \cdot 2 \cdot l}{v_{op}}, \tag{2}$$

where *SFC* refers to the specific fuel consumption of 0.215 kg/kWh [17], *N* denotes the number of return trips annually, and *l* is the length of a one-way trip.

Since GaBi software does not have diesel fuel mix production for Croatia, LCA will be conducted with data for Europe.

3 RESULTS AND DISCUSSION

LCA examines different environmental impacts of diesel fuel production and the final results depend on the methods used for LCIA. In this paper, using the ReCipe 2016 v1.1 midpoint method, climate impact, fine PM formation, fossil fuel depletion, freshwater consumption, human toxicity (cancer) and photochemical ozone formation are considered. On the other hand, using the TRACI 2.1 method, the paper investigates acidification, eutrophication, ozone depletion, smog formation, PM formation and human health impact and global warming impact. For 1 kg of fuel produced, the results of the WTT emissions are shown in Fig. 3 for the ReCiPe 2016 v1.1 midpoint method, and Fig. 4 for the TRACI 2.1 method.

The LCA results indicated that the environmental footprint of diesel fuel production differs significantly between countries. This is primarily attributable to the efficiency and quality of the production process, the proportion of domestic and imported diesel fuel in a mix, the quality of the raw material (crude oil), the transportation modes of crude oil and the final product to the refuelling station, among other factors. The impact on global warming

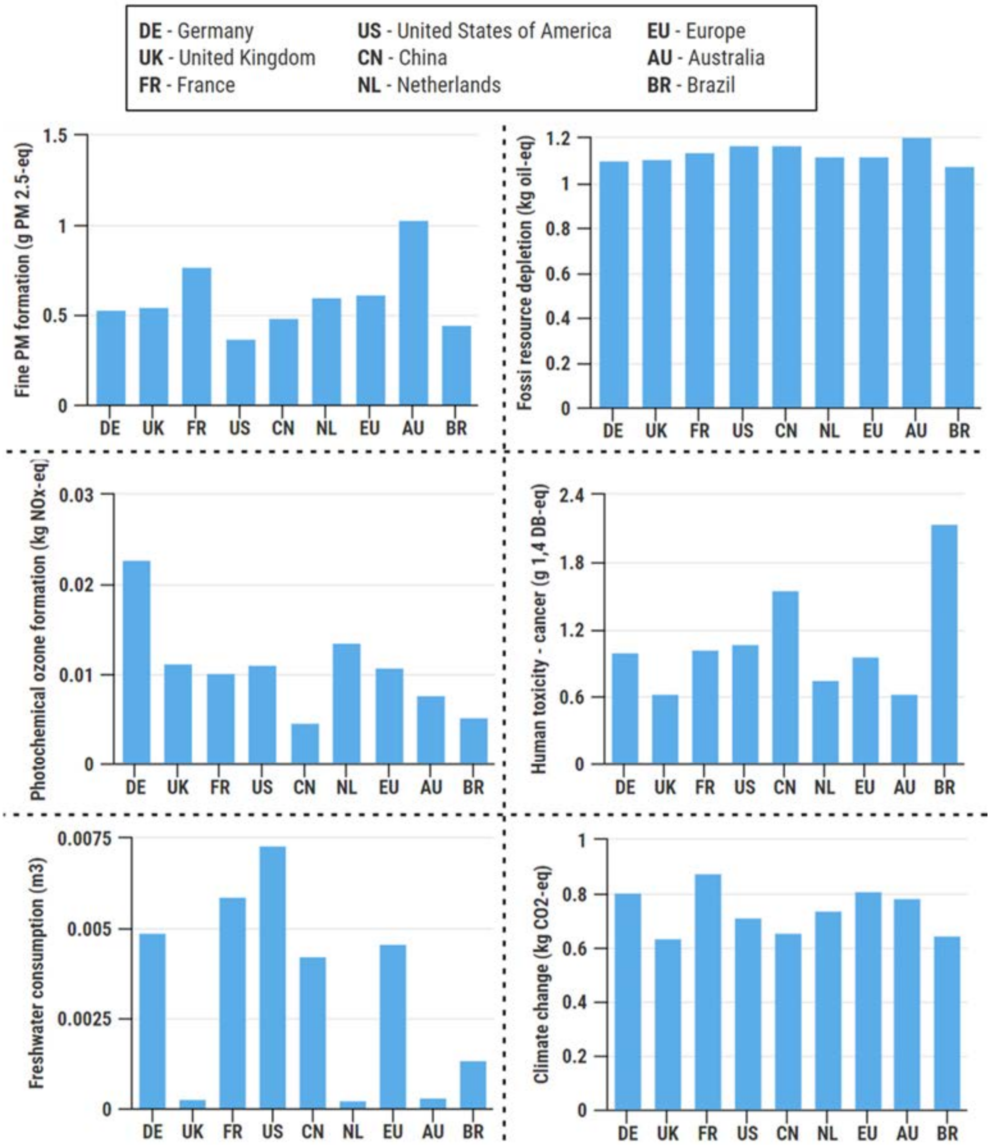

Figure 3: WTT results of diesel fuel production for different countries/regions using the ReCiPe 2016 v1.1. midpoint method.

(i.e. climate change) yielded comparable results for the various investigated LCIA methods. The LCA also indicated significant deviations between the results. For example, Fig. 3 demonstrates that the BR results in significantly higher emissions that contribute to the development of cancer in humans. Moreover, the US has the highest per unit of fuel freshwater consumption, whereas the UK has a consumption rate that is 96% lower. In Fig. 4, BR is identified as a significant contributor to eutrophication, while AU demonstrated the

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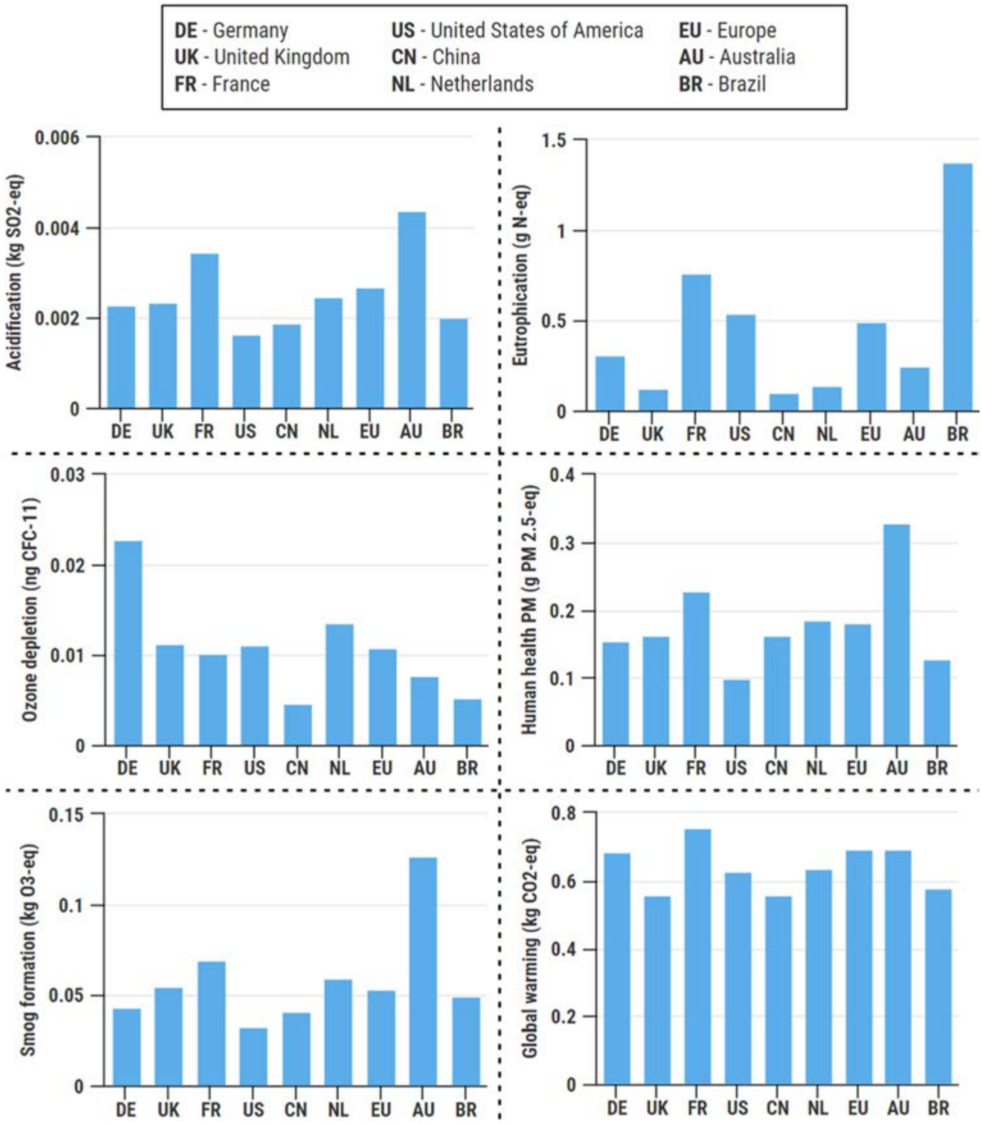

Figure 4: WTT results of diesel fuel production for different countries/regions using the TRACI 2.1 method.

greatest impact of PM on human health, acidification, and the formation of smog, among the investigated regions.

The results of performed LCA are presented in the context of a Croatian ferry operating in the Adriatic Sea. The annual fuel consumption of the vessel is 2.4 million kg, which is used to calculate the environmental footprint of a diesel-powered ship on an annual basis. Given that the geographical scope of the TRACI 2.1 method is limited to North America, whereas the ReCiPe 2016 v1.1 method is designed with a global perspective, the latter is employed for the investigation of the Croatian diesel-powered ferry, using EU data from the GaBi database. The results of selected environmental impact categories, in which the contribution of WTT and TTW emissions can be indicated, are presented in Fig. 5.

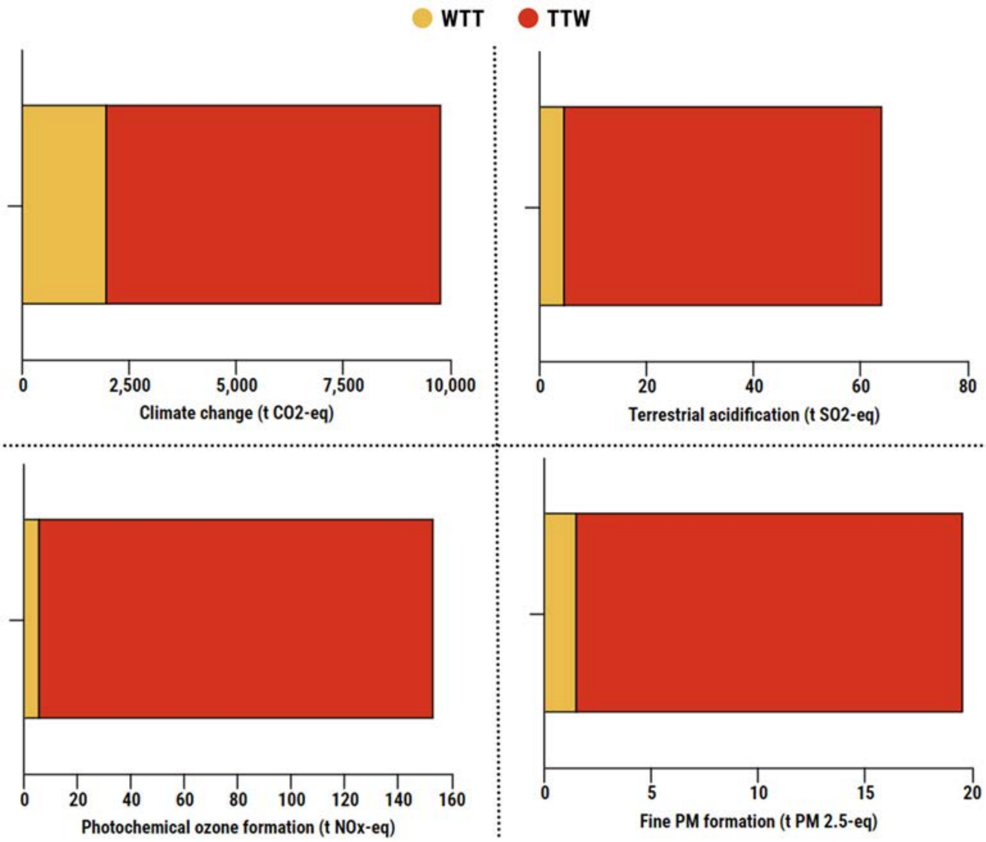

Figure 5: Environmental footprint of diesel-powered ferry.

The results presented in Fig. 5 indicate that WTW emissions are significantly lower than TTW emissions. It can be concluded that the primary environmental and human health impact is the operation of the diesel-powered ship. In order to reduce the TTW emissions, conventional marine fuels like diesel fuel must be replaced by alternatives. In the context of global warming problems, the preferred alternatives are zero-carbon powering options (electrification, hydrogen, ammonia, etc.). Nevertheless, while the use of these fuels on board does not result in GHG emissions, it often results in high GHG emissions in the WTT phase. Furthermore, the use of some of them on board is not yet technically feasible or requires the development of infrastructure, among other factors [13].

Electrofuels (e-fuels) are produced using renewable energy sources, offering a carbon-neutral alternative to conventional marine fuels. The production of e-fuels involves two principal stages. The initial step is the electrolysis of water using renewable energy to generate hydrogen. This is followed by the synthesis of hydrogen with captured CO_2 to create hydrocarbons or other fuels. E-fuels offer a number of advantages for marine applications. It is possible to reduce CO_2 emissions significantly when e-fuels are produced using renewable energy. Some e-fuels can be used in existing engines with minimal modifications, while e-fuels such as e-diesel provide energy density comparable to that of conventional marine fuels. Nevertheless, the current high production costs of e-fuels in comparison to conventional fuels represent a significant challenge. It is possible that technological advancements may reduce these costs over time. Moreover, the development of refuelling infrastructure and storage facilities is essential for the widespread adoption of e-fuels [31], [32].

4 CONCLUSION

The extensive use of fossil fuels in the shipping sector has a negative impact on the environment and human health. This paper examines the environmental footprint of diesel fuel production in nine different countries and regions using LCA. The results indicate that the footprint differs from country to country, with some deviations observed in high freshwater consumption, PM formation and their impact on human health, etc. The analysis involved different environmental impact categories (based on two different LCIA methods), and the results are illustrated on the Croatian ferry. The emissions during the operation of the ship are considerably greater than those associated with the WTT phase of the diesel fuel cycle.

In order to reduce these emissions, conventional marine fuels such as diesel fuel must be replaced by alternative fuels. E-fuels represent a viable pathway towards the decarbonisation of the marine industry. Although current economic and infrastructural challenges exist, ongoing research and development, in conjunction with supportive policies, could facilitate the transition to e-fuels, thereby contributing to sustainable maritime transport. Further research will be conducted to investigate the environmental footprint of ships powered by e-fuel.

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