Emissions, Decarbonization, and Alternative Fuels in Inland Navigation

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In response to the pressing need for transportation decarbonization, the often overlooked domain of inland waterway transport and seeks to answer which alternative fuel or power source is the most promising for that sector. As the shipping industry significantly contributes to global carbon emissions, it has been shifting towards alternative fuels and decarbonization measures in the effort to reduce them, whereas the inland waterways, operating predominantly on diesel engines, have not achieved equivalent substantial progress. Liquified natural gas (LNG) initially emerged as a favored alternative fuel, but recent studies emphasize a shift towards “greener” solutions like batteries and hydrogen. Europe and Asia lead in these developments. This investigation uncovers critical gaps in research and development, particularly in the Northern European countries that have extensive inland waterway networks. It also calls for future studies to explore the performance of vessels that have adopted LNG compared to other emerging alternatives and emphasizes the importance of considering the time lag between technology development and research publication.

Keywords: inland navigation ; emissions ; alternative fuel sources ; LNG ; Batteries ; Hydrogen

1. Introduction

The decarbonization of transportation is a crucial matter that has been part of our daily lives for almost 40 years now. The first scientific articles that dealt with the decarbonization of transportation, especially road transport, are dated back to 1984 [1]. There are currently global efforts aiming to cut down carbon emissions and reduce the carbon footprint from fossil fuels. Countries around the world are firstly committed to switching to alternative fuel sources and more sustainable ones by 2030 and then achieving net zero (Net zero refers to achieving a balance between the amount of greenhouse gases (GHGs) emitted into the atmosphere and the amount removed from it [2]) by 2050. One of the most important sectors is transportation—an area in which governments and states have adopted strict guidelines. Road traffic is among the worst causes of high carbon emissions, and this is why switching to more “greener” and more sustainable ways of transporting people and goods is a necessity. To cut greenhouse gas emissions from the transportation sector, the European Union has already presented a plan of action for low-emission mobility; the deadline set is 2050 [3].

The shipping industry plays a significant role in global carbon dioxide (CO_2) emissions, accounting for approximately 940 million tons annually; this amount represents at least 2.5% of the world’s total CO_2 emissions [4]. Therefore, the usage of alternative fuels and decarbonization in general is of crucial importance. On January 1, 2020, the International Maritime Organization (IMO) implemented a new regulation known as “IMO 2020”, which introduced a stricter limit on the sulfur content in fuel oil used by ships. The regulation aimed to improve air quality, protect the environment, and safeguard human health [5]. As a consequence, the shipping industry has been switching to other alternatives for marine fuels such as liquified natural gas (LNG) and installing scrubbers into their diesel engines, achieving lower carbon emissions through these means. Additionally, new energy technologies for vessel propulsion systems have been widely developed by scientists and engineers and have also been implemented on a prototype scale; some of these new energies are solar energy, wind energy, and fuel cells [6]. Amidst the drive for stringent emission control and the preservation of ecological environments, the shipping industry is undergoing a significant transformation and upgrade focused on embracing greener practices, decarbonization, and electrification [7].

Inland waterway transport offers a unique opportunity for sustainable, high-volume transportation with minimal environmental impact. However, its heavy reliance on diesel engines and associated emissions underline the urgent need for greener solutions.

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2.1. Inland Navigation Emissions

Sun et al. [8] conducted a study that focused on the energy consumption and greenhouse gas emissions of inland navigation against seagoing ships. Their research was based on a case study of container shipping on the Yangtze River in China, which is an important waterway in the region. The study found that inland navigation systems contribute significantly to air pollution. This highlights the need for the development of “low carbon shipping” policies to address these environmental concerns.

Van Lier and Macharis [9] utilized a comprehensive life-cycle assessment (LCA) framework to evaluate the complete environmental implications of inland shipping. Their study focused on assessing air pollution and greenhouse gas emissions associated with barge transport in the Flanders region of Belgium. The authors observed that as the size of the barge increased, the relative contribution of emissions from the vehicle fleet and waterway infrastructure became more significant, while the relative contribution from the vehicle operation decreased. The analysis of environmental discharges considered three main groups: barge travel, barge manufacturing, and barge maintenance. The findings highlighted that barge travel accounted for the largest proportion of air pollutants and greenhouse gas emissions, whereas emissions from barge manufacturing and maintenance were generally relatively minor in comparison.

Vilarinho et al. [10] aimed to identify the primary obstacles and potential advantages associated with the advancement of river logistics as an eco-friendly alternative. It is perhaps the only study that tried to approach the matter in a similar way as is performed in this study, with examples from around the world; thus, to avoid duplicating any work, international examples regarding inland navigation have not been mentioned, as they have already been or they will be analyzed at a later stage. The authors referred to the general framework with examples from Serbia, China, Germany, and the European Union. Moreover, inland transportation is regarded to be seven times more sustainable than other modes of transport [11]. Regardless of its significant potential in terms of cost-effectiveness and lower greenhouse gas emissions, waterway transport is still underdeveloped compared with roads and railways. This is primarily attributed to various constraints, including infrastructure weaknesses, limited investments, and institutional inefficiencies stemming from governance issues [12]. One of the major challenges in the inland waterway sector, as highlighted by the authors, is the adoption and increased use of renewable sources to further enhance its sustainability.

Evers et al. [13] investigated the carbon footprint of hydrogen-based maritime propulsion systems, with a particular focus on inland cargo shipping. The analysis reveals that renewable energy sources consistently outperform Methane Steam Reforming with carbon capture and storage, making them the preferred option for reducing emissions [13]. Hydrogen production through electrolysis, especially using wind power, yields lower carbon footprints compared to grid electricity mixes or Methane Steam Reforming without carbon capture and storage. The dominant contributor to the carbon footprint in all scenarios is fuel production, accounting for 80–98% of emissions [13]. The choice of renewable energy source significantly influences the carbon footprint of hydrogen production. Transportation considerations indicate that while hydrogen transport contributes to emissions, it is not the primary factor [13]. Pipeline transport proves efficient, and liquid hydrogen transport is preferable over liquified ammonia. Ports offer potential starting points for hydrogen developments to decarbonize inland shipping and reduce emissions in the maritime sector.

2.2. Alternative Fuel and Power Sources

El Gohary et al. [14] refer to hydrogen as “one of the most promising and abundant sustainable alternative energy sources”. The authors discussed the economic aspects and emissions impact by giving emphasis to how essential the usage of greener fuels is. Hydrogen was considered to be a suitable alternative. Hydrogen’s economic viability was examined in the study along with its technical specifications regarding production methods and storage techniques. In addition, a cost analysis was conducted to demonstrate the advantages of using hydrogen as a replacement for diesel-powered engines. According to the authors, the introduction of new alternative fuels such as hydrogen into the maritime industry is quite challenging because of the harsh environmental conditions in which the marine power plant operates. El Gohary et al. [14] express their belief that the hydrogen engine or gas turbine is a promising prospect that will soon become a reality, especially in inland navigation, given its suitability for short-distance trips. They conclude their research by stating that in order for hydrogen to become a dominant fuel and take over from diesel, it must offer equivalent advantages in terms of affordable operational expenses and extended travel distance on a single tank. The key takeaway from the analysis, which adds value to this study, is that hydrogen as a maritime fuel does not produce any harmful emissions.

Simmer et al. [15] conducted a comprehensive examination and evaluation of various factors that would impact the future implementation of LNG in the inland waterway sector. Although the research dates back to 2015, it still provides useful insights about alternative fuel sources into inland navigation shipping. One of the most important points of the paper is about the “LNG Masterplan for the Rhine-Main-Danube”, which was announced within the TEN-T (The Trans-European Transport Network (TEN-T) policy addresses the implementation and development of a Europe-wide network of railway lines, roads, inland waterways, maritime shipping routes, ports, airports, and railroad terminals [16]) in 2012. The project aimed to establish a strategic framework for the utilization of LNG as a fuel for inland vessels and the transportation of LNG cargo through waterways and inland ports. It also involved pilot deployments to test and evaluate the feasibility and effectiveness of these initiatives. [17]. The key takeaway of the study is that by embracing LNG as a fuel, the inland navigation sector can strengthen its competitive position in the transportation market and maintain its reputation as the most ecologically sustainable mode of transport [15].

Yuan et al. [18] present a photovoltaic (PV) generation system installed on a ship (In 2015, researchers from the Wuhan University of Technology achieved a successful implementation of solar energy in an inland river vessel named “Anji204”, an 800PCC (Pure Car Carrier)) and conducted navigation trials on the Yangtze River to assess its performance. The study found that the ship’s EEDI decreased from 55.09 g_CO_2/ton·nmile to 52.02 g_CO_2/ton·nmile, representing a reduction of approximately 5.57%. Moreover, an average fuel consumption reduction of 16 tons per year was attributed to the PV system. These findings indicate that the integration of solar energy in ships can play a significant role in aligning with the “low carbon shipping” policies within the inland river shipping industry. The study emphasizes that the implementation of new energy technologies enhances fuel efficiency, as evidenced by the decline in emissions after the installation of the PV generation system, primarily due to reduced fuel consumption [18].

According to Fan et al. [7], it is of utmost importance to urgently explore actions for the decarbonizing of inland waterways, along with proposing different options for the power systems of inland vessels. The authors present the current progress of inland shipping in China, taking into consideration the assessment of shipping assets, prevailing obstacles, and catalysts for sustainable growth. They analyze the power requirements of inland ships and the characteristics of new power systems, and they suggest alternative options for inland ship power systems [7]. Two case studies were conducted that focused on battery-powered and hybrid-powered ships in a canal and in the Yangtze River, respectively. The results of their study demonstrate that battery power and hybrid power are more cost effective and have lower lifetime CO_2 emissions versus diesel power [7]. In the past few years, increasing global and domestic emphasis on environmental protection and emission reduction has prompted the promotion of low-carbon energy usage in inland ships, such as lithium batteries, fuel cells, shore-side electricity, solar energy, and LNG. The majority of the inland fleet comprises dry bulk carriers, particularly on the Yangtze River, where they account for nearly 75%; passenger ships and tankers are the other two big groups [7]. According to Fan et al. [7], cell-powered ships will likely be a promising alternative along with battery-powered ships in the years to come. However, the usage of fuel cells, even for on-road vehicles, is currently limited. Additionally, wind-assisted propulsion is currently out of the question in many waterway corridors worldwide due to the air draught restrictions of the bridges.

Fan et al. [7] propose the following power systems based on different vessel sizes:

- In the case of large and long-range ships, the authors propose that only ships with reliable sailing patterns be nominated for the use of LNG powered systems. However, for ships with robust sailing patterns, a combination of batteries and LNG-powered systems would be a better option.
- Regarding small ships, the research recommends LNG power for long-range ships. Fast-charging batteries or super capacitors would be preferable for short-range ships or point-to-point transport.
- When it comes to specialized ships, according to the authors, a hybrid-powered system should be employed for engineering ships and public service ships, which typically have vastly diverse operational modes. A combination of LNG and battery cells should power engineering ships with high-rated power, whereas a combination of battery and supercapacitor modules should power public service ships with low-rated power.

From the standpoint of lowering emissions, the alternative options that are suggested indicate a development path. Fan et al. [7] mention that based on their case study of a hybrid-powered ship in the Yangtze River and a battery-powered ship in a canal, the outcome demonstrated that these alternative options generally exhibited lower CO_2 emissions and were cost effective throughout their life cycle versus traditional diesel power. The decarbonization of vessel activities can be fully achieved by the use of low-carbon and hydrogen energy.

3. Summary

The research that was taken into consideration is focused on three regions of the world: Africa, Asia, and Europe. This can be easily explained, as the majority of the countries from around the world that utilize their inland waterways are located in these regions.

It is obvious that the research on the topic is not extensive, and there is room for further studies and analysis. The number of papers regarding emissions, decarbonization, and alternative fuel and power sources for the inland navigation market is limited compared with similar research for other modes of transport and ocean-going vessels. This generates an opportunity for researchers to fill in the gaps that are available for further study and to push the entire inland waterway network such as authorities, entities, and companies to switch to "greener" solutions.

In conclusion, transportation via inland waterways presents a unique chance for eco-conscious, large-scale shipping. The research [19] not only exposes critical areas where further investigation is needed but also provides valuable insights into the current state of technology adoption across various countries. It serves as a recommendation for policymakers, researchers, and industry players, offering them essential guidance for navigating the intricate terrain of sustainable transportation solutions.

On a final note, although this is not taken from the analysis made, it is important to emphasize the time lag between technology developments such as alternative fuel and power sources and the publication of research findings. As a result, the information presented in research papers may not always reflect the most current state of technological development. The implementation of technologies in the real world may differ from scientific research, as they always include the practical challenges and limitations of real-world applications such as cost-effectiveness and regulatory frameworks. Technology development in all sectors is driven by various factors like market demands, government policies, and industry trends. Therefore, when analyzing any technological advancements, it is important to consider the time lag between technology developments and research publication, as well as the potential differences between research findings and real-world implementation.

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