sustainability

MDPI

Review

A Global Analysis of Emissions, Decarbonization, and Alternative Fuels in Inland Navigation—A Systematic Literature Review

Charilaos Christodoulou Raftis *, Thierry Vanelslander and Edwin van Hassel

Department of Transport and Regional Economics, University of Antwerp, 13 Prinsstraat, 2000 Antwerp, Belgium; thierry.vanelslander@uantwerpen.be (T.V.); edwin.vanhassel@uantwerpen.be (E.v.H.)
* Correspondence: charis.christodoulouraftis@uantwerpen.be

Abstract: In response to the pressing need for transportation decarbonization, this paper examines 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. Employing a systematic literature review and regional analysis, this study identifies notable trends. 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; alternative power sources; LNG; batteries; hydrogen

check for updates

Citation: Christodoulou Raftis, C.; Vanelslander, T.; van Hassel, E. A Global Analysis of Emissions, Decarbonization, and Alternative Fuels in Inland Navigation—A Systematic Literature Review. *Sustainability* **2023**, *15*, 14173. https://doi.org/10.3390/su151914173

Academic Editors: Florian Kellner, Bernhard Lienland and Ulrike Plach

Received: 28 June 2023
Revised: 12 September 2023
Accepted: 22 September 2023
Published: 25 September 2023

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 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].

Many studies and much research have been focusing on more sustainable fuels for ocean-going vessels, as the transportation of goods by deep sea vessels represents almost 90% of the total global trade. In order to identify the most efficient alternative power sources for the vessel's propulsion systems, their emissions have been studied and investigated. Most of the current and past research is focused on emissions from ocean-going vessels, whereas inland waterway transport has not been the center of interest in a similar way. Air pollution generated by the shipping industry has predominantly been the focus of current research on seagoing vessels, with comparatively less attention given to inland waterway vessels. However, the impact of inland navigation vessels on air quality should not be underestimated, as these vessels operate along canals and rivers and directly affect the air quality of nearby communities [8]. According to Fan et al. [7], the current scenario in inland shipping reveals that over 95% of vessels still rely on diesel engines as their primary power source, leading to significant emissions of greenhouse gases and other pollutants. This situation has adverse effects on both human health and the environment. The emissions of nitrogen oxides (NOx) and particulate matter (PM) from these vessels have been identified as major contributors to health issues such as asthma, heart disease, and respiratory illnesses. Additionally, the emissions resulting from fuel ignition in inland waterway ships contribute to global warming and atmospheric acidification, among other environmental concerns [7].

Inland waterway transport (IWT) is considered a cost-efficient and sustainable transport solution that is expected to grow in the future, but the IWT ship fleet emits pollutants and therefore contributes to (urban) [9] air pollution. In comparison to other modes of transportation, inland waterway transport offers distinct advantages such as high transport volume, minimal environmental impact, cost-effectiveness, and overall environmental friendliness [7]. The transport capacity of inland waterway transport surpasses road transport by a factor of 17 and rail transport by a factor of 3. Additionally, pollutant emissions per unit are one-fifth of those produced by road transport and five-sixths of those generated by rail transport [7]. In the literature, the electrification of ships has emerged as a proposed solution for achieving carbon free shipping [10].

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. This research provides valuable insights into the current state of technology adoption in several countries around the world but also identifies critical research gaps. It provides a comprehensive view of the evolving alternatives within the inland waterway transportation sector worldwide, offering policymakers, researchers, and industry stakeholders the necessary guidance to navigate the complex terrain of sustainable transport solutions. The urgency of this paper lies in addressing the critical gap between current reliance on diesel engines in inland vessels and the pressing need for cleaner alternatives by answering the following question: what is the most promising alternative fuel or alternative power source for inland vessels?

This article focuses on alternative fuel sources and alternative power sources exclusively for inland vessels, a niche sector within the broader field of transportation, by addressing specific needs and challenges faced. Although there is an abundance of research worldwide on renewable energy sources and alternative fuels for internal combustion and diesel engines, it is crucial to underscore that this paper's scope is deliberately limited to the unique context of inland navigation, necessitating a more tailored approach.

The method used to answer the question is a systematic literature review along with an analysis that will provide an overview of the alternative fuels and alternative power sources that are mentioned in the literature review and the respective regions they are focused on.

The remainder of the paper is structured as follows: Section 2 describes the methodology. Section 3 presents the literature review. Section 4 provides the analysis of an overview of alternatives per region in the world, giving an answer to the research question. Section 5 provides the conclusion, which summarizes key takeaways and offers recommendations for a future research agenda.

2. Materials and Methods

The method applied in this study was a systematic literature review, which is a well-established methodology used to address research related to current issues. It aims to provide a thorough understanding of the current state of knowledge, identify research gaps and limitations, and suggest directions for future studies [11]. The systematic literature review aims to identify what the current status of decarbonization in inland navigation shipping is and what actions have been taken so far to reduce carbon emissions. The literature study presents examples from several countries (Bangladesh, Belgium, China, Croatia, Egypt, Germany, India, The Netherlands et al.) in the world, either by investigating the emissions that are produced by inland vessels or alternative power sources that are being tested or have been proposed to replace diesel engines. The financial side and barriers of implementing new technologies for decarbonization and alternative fuels in inland navigation shipping is not considered in this study.

For this literature review, more than 40 papers, studies, journals, websites, and reports were mainly reviewed in two databases, ResearchGate and ScienceDirect, between September 2022 and September 2023. The keywords used in the databases for this literature review were "inland navigation & fuel", "decarbonization & inland shipping", "decarbonization & inland waterways", "alternative fuels & inland waterways", "alternative fuels & inland navigation", "alternative fuels & barges", and "decarbonization & barges". The combined search provided more than 2000 results, while only 29 papers were relevant and matched the search terms as well as the chosen time frame. For this study, the papers that were selected were those that had been published since 2010 at the latest due to rapid development in policies, technologies, and innovations. The majority of the papers that were available focused either on ocean-going vessels, ship-to-ship bunkering, short-sea shipping, alternative fuel sources, greener infrastructure, and sustainable fuels for other modes of transport. In Figure 1, the total number of research studies by year can be seen.

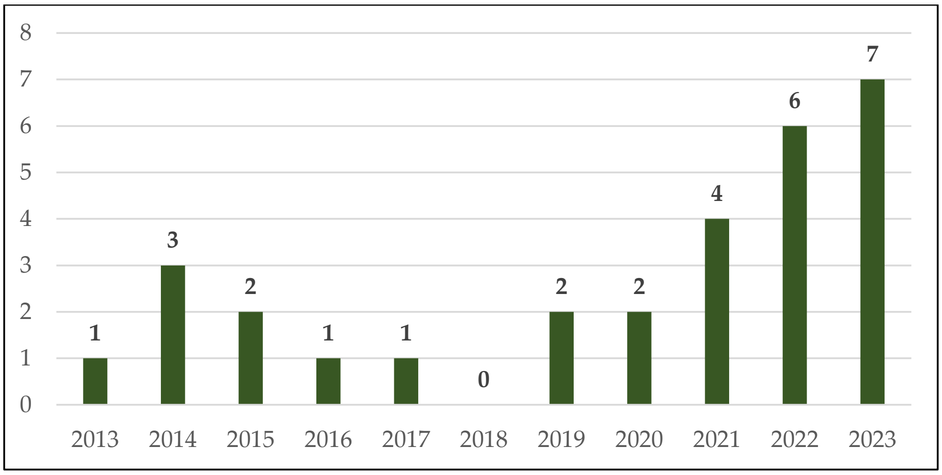

Figure 1. A summary of research studies by year.

3. Results

The literature review is split into two sections. The first section presents research papers about inland navigation emissions, while the second section presents research studies about alternative power sources, which are being used or tested in inland waterways in several countries around the world. Table 1 shows all the studies included in this literature review along with the subject and countries/regions of their research topic. In Figure 2, the total number of research studies by the countries/regions that the topic is related to can be seen.

Table 1. The studies that are included in this literature review, their subjects, and respective regions.

Study	Authors	Year	Subject	Country
Analysis of the operational energy efficiency for inland river ships	Sun et al. [12]	2013	Emissions	China
Assessing the environmental impact of inland waterway transport using a life-cycle assessment approach: The case of Flanders	van Lier and Macharis [13]	2014	Emissions	Belgium
Impact of Inland Shipping Emissions on Elemental Carbon Concentrations near Waterways in The Netherlands	Keuken et al. [14]	2014	Emissions/Alternative Power Sources	Netherlands
The Use of Hydrogen as a Fuel for Inland Waterway Units	El Gohary et al. [15]	2014	Alternative Power Sources	Egypt
A green and economic future of inland waterway shipping	Sihn et al. [16]	2015	Emissions/Alternative Power Sources	Austria, Belgium, Germany, Hungary, Romania, Serbia, Slovakia
Liquefied Natural Gas as a Fuel in Inland Navigation: Barriers to Be Overcome on Rhine-Main-Danube	Simmer et al. [17]	2015	Alternative Power Sources	Germany
Emission fingerprint of inland navigation vessels compared with road traffic, domestic heating and ocean going vessels	Blasing et al. [18]	2016	Emissions	Global
Energy Efficiency Design Index (EEDI) for Inland Vessels in Bangladesh	Zakaria and Rahman [19]	2017	Emissions/Alternative Power Sources	Bangladesh
Challenges and opportunities for the development of river logistics as a sustainable alternative: a systematic review	Vilarinho et al. [20]	2019	Emissions/Alternative Power Sources	Serbia, China, Germany and EU
The evaluating on EEDI and fuel consumption of an inland river 800PCC integrated with solar photovoltaic system	Yuan et al. [21]	2019	Alternative Power Sources	China
LNG bunkering network design in inland waterways	Ursavas et al. [22]	2020	Alternative Power Sources	Netherlands
Reduction of CO_2 emissions of inland passenger and cargo vessels by alternative power system configurations	Perčić et al. [23]	2020	Alternative Power Sources	Croatia
Alternative fuel options for low carbon maritime transportation: Pathways to 2050	Xing et al. [24]	2021	Alternative Power Sources	Global
Decarbonizing inland ship power system: Alternative solution and assessment method	Fan et al. [7]	2021	Alternative Power Sources	China

Table 1. *Cont.*

Study	Authors	Year	Subject	Country
Energy Efficiency of Inland Waterways Transport for Agriculture: The Ukraine Case Study	Bazaluk et al. [25]	2021	Alternative Power Sources	Ukraine
Techno-economic assessment of alternative marine fuels for inland shipping in Croatia	Perčić et al. [8]	2021	Alternative Power Sources	Croatia
An Overview of Promising Alternative Fuels for Road, Rail, Air, and Inland Waterway Transport in Germany	Breuer et al. [26]	2022	Alternative Power Sources	Germany
Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation	Perčić et al. [10]	2022	Alternative Power Sources	Croatia
Power to gas technology: Application and optimization for inland transportation through Nile River	Ibrahim et al. [27]	2022	Alternative Power Sources	Egypt
Scrubber installation and green fuel for inland river ships with non-identical streamflow	Tan et al. [28]	2022	Alternative Power Sources	China
Carbon footprint model and low–carbon pathway of inland shipping based on micro–macro analysis	Fan et al. [29]	2022	Emissions/Alternative Power Sources	China
Carbon footprint prediction considering the evolution of alternative fuels and cargo: A case study of Yangtze river ships	Yan et al. [30]	2022	Emissions/Alternative Power Sources	China
Entering a new era for electrical vessels on inland waterways	Chatelier, J. M [31]	2023	Alternative Power Sources	Global
Holistic energy efficiency and environmental friendliness analysis of inland ships with alternative power systems	Perčić et al. [32]	2023	Emissions/Alternative Power Sources	Croatia
Enhancement method of series hybrid ship energy efficiency for speed and energy collaborative optimization	Yuan et al. [33]	2023	Emissions	China
Air Pollution by Inland Waterways Transportation in India	Mehrotra and Rai [34]	2023	Emissions	India
Speed and energy optimization method for the inland all-electric ship in battery-swapping mode	Zhang et al. [35]	2023	Emissions/Alternative Power Sources	China
Carbon footprint of hydrogen-powered inland shipping: Impacts and hotspots	Evers et al. [36]	2023	Emissions/Alternative Power Sources	Global
Measurement report: Inland ship emissions and their contribution to NOx and ultrafine particle concentrations at the Rhine	Eger et al. [37]	2023	Emissions	Germany

3.1. *Inland Navigation Emissions*

Sun et al. [12] 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.

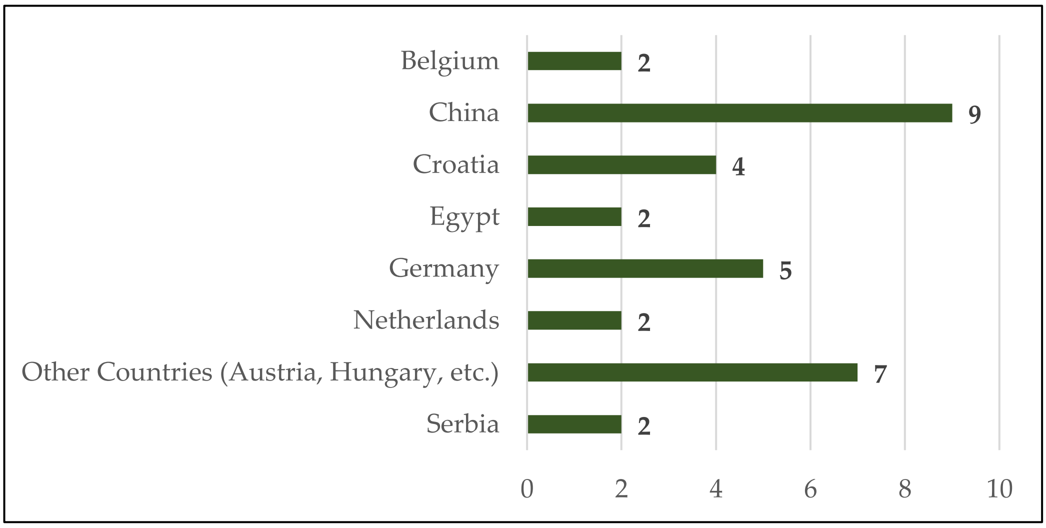

Figure 2. A summary of research studies by countries/regions related to the research.

Van Lier and Macharis [13] 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.

Keuken et al. [14] conducted a study that aimed to analyze the influence of inland shipping on air quality along inland waterways in the Netherlands, with a particular focus on the Amsterdam–Rhine Canal and the Waal. Their model used input emission factors specific to inland ships; these factors were derived from measurements conducted using the test banks of ship engines. The researchers concluded that the emission standards for shipping are not as stringent as those for road transport. Keuken et al. [14] recommended various measures to reduce emissions, including the implementation of LNG and fuel with lower sulfur content.

Sihn et al. [16] referred to many examples from around the world considering transportation greenhouse emissions and the ways states aim to reduce them and further take advantage of inland waterways. In the European region, a project called "Pollutant emissions of IWT ships on the Danube Corridor" took place in 2016, with the objective of collecting and analyzing the impact of greenhouse emissions along the Rhine–Danube Corridor and suggestions like an eco-friendly ship and "greener" ports as countermeasures [16]. According to their research, the World Bank launched a working paper for the "Development of a more energy efficient inland waterway transport in Bangladesh" in 2011 with the goal of reducing the modal share of road transport and switching to inland waterways. Another example of committing to the improvement and development of inland waterways is India, with the Inland Waterway Authority of India (IWAI). A policy was composed by IWAI, with the intention of expediting the development of inland waterways and fostering private sector involvement, all with the ultimate objective of reducing greenhouse gas emissions [16].

Bläsing et al. [18] focused on the emission fingerprint of inland navigation vessels. A comparison and identification of patterns from metals and parent, thio-, and alkylated Polycyclic aromatic hydrocarbons (PAH) in aeriform and particulate matter from inland navigation ships was carried out. The researchers compared these emission patterns with those from road traffic, domestic heating (solid fuels), and ocean-going vessels. They collected data from their own study, as well as from existing literature, to conduct this analysis. The authors concluded that metal and PAH discharges from inland ships were always lower than from domestic heating and road traffic. Additionally, they were incapable of determining values from inland vessels emissions and diesel-powered road traffic or sea-going vessels.

Vilarinho et al. [20] 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 [38]. 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 [39]. 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.

The study conducted by Fan et al. [29] focuses on reducing carbon emissions in China's inland shipping industry. It employs a comprehensive approach, utilizing micro and macro perspectives, Life Cycle Assessment, and an improved turnover method. Notably, LNG emerges as a promising alternative fuel, reducing emissions by 6.83% compared with diesel. In 2019, inland shipping emitted 20.924 million tons of CO_2, with a slight 0.98% reduction in 2020. Fan et al. [29] underscore the importance of careful fuel selection, the consideration of raw materials, ship construction optimization, and adjustments in energy consumption structures. Overall, in their research, the authors provide valuable insights to support China's efforts in achieving its carbon reduction targets.

Yan et al. [30] explored the importance of reducing carbon emissions in the shipping sector by utilizing alternative low-carbon and zero-carbon fuels. The study focuses on calculating annual carbon emissions for various alternative fuel-powered ships under different cargo growth scenarios and power system structures, with a particular case study on Yangtze River bulk carriers. According to Yan et al. [30], LNG hybrid, LNG, and methanol fuels are currently suitable choices, reducing life cycle carbon emissions by 31.5–38.1% compared with diesel. Green hydrogen and green ammonia offer substantial carbon reduction potential, with emissions reduced by 78.8% and 91.3%, respectively, compared with hydrogen and ammonia, thus concluding that alternative low-carbon and zero-carbon fuels are crucial for reducing carbon emissions in the shipping industry [30]. The choice of fuel, power system structures, and cargo growth rates all play significant roles in achieving carbon reduction goals.

Yuan et al. [33] address the urgent concerns of environmental pollution and energy consumption in the transportation sector, specifically greenhouse gas emissions in waterway transportation and their contribution to global warming. The study introduces an innovative approach to enhance the energy efficiency of hybrid ships. The subject of this study was a diesel–electric hybrid cruise ship operating on the Yangtze River, which provided valuable data and insights into enhancing energy efficiency and optimizing its power system. The study utilized real sailing data from this specific hybrid ship to develop and validate the proposed energy efficiency enhancement method. Results demonstrated effective power source balancing, extended supercapacitor lifespan, and stable ship speeds for passenger comfort [33]. Despite slightly longer navigation times, significant fuel savings were achieved. This research substantially contributes to ship energy efficiency optimization, emphasizing impressive outcomes in terms of fuel conservation, reliability, and passenger satisfaction. Yuan et al. [33] conclude that reducing fuel consumption in hybrid ships helps lower greenhouse gas emissions and supports environmental sustainability efforts.

Mehrotra and Kumar G [34] address the growing challenges of urban cargo traffic and its impact on the environment, with a specific focus on inland waterway transportation in India. Inland waterways emerge as a cost-effective and congestion-free solution for bulk cargo transportation. The study analyzes environmental implications and compares the costs, carbon dioxide (CO_2) emissions, and time efficiency of inland waterway transport against road transport in India [34]. The research highlights that ship emissions, especially in harbor-based cities, significantly contribute to air pollution. These emissions include sulfur dioxide (SO_2), nitrogen oxides (NOx), volatile organic compounds (VOCs), particulate matter (PM), carbon dioxide (CO_2), and greenhouse gases (GHGs) [34]. The number of mechanized boats in India has surged over the years, leading to increased fuel consumption and CO_2 emissions [34]. The paper suggests several measures to reduce ship emissions, including the use of low-sulfur fuels, ultra-low sulfur fuels, alternative fuels like biofuels and natural gas, and water-emulsified fuel. It also mentions the importance of distillate fuel but notes its potential for increased CO_2 emissions. Mehrotra and Kumar G [34] emphasize the need for stricter regulatory policies in the maritime sector to mitigate air pollution and achieve zero-carbon emissions.

Evers et al. [36] 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 [36]. 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 [36]. 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 [36]. 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.

In their study, Eger et al. [37] investigated emissions from inland shipping along the Rhine River, specifically in the vicinity of Worms, Germany, offering valuable insights into real-world emissions factors and their potential impact on air quality. The research covers a comprehensive range of pollutants, including NOx, PM, PNC, UFP, PM1, and BC, utilizing peak analysis algorithms and AIS data to assess the monthly contributions of shipping to atmospheric pollution [37]. Key findings include variable emission levels influenced by wind conditions, the predominance of ultrafine particles (UFP), and the dependence of emissions on engine characteristics such as age, power, and RPM [37]. Moreover, the study highlights the potential for significant emission reductions through the adoption of modern engine technologies, emphasizing the importance of fleet modernization for improving air quality along heavily frequented waterways. These findings underscore the need for targeted strategies to address inland shipping emissions and emphasize the relevance of UFP measurements in future studies.

3.2. Alternative Fuel and Power Sources

El Gohary et al. [15] 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. [15] 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.

According to Sihn et al. [16], Central European waterways are underutilized, and at the same time road, rail traffic keeps rising. Road transport generates high volumes of air pollutants due to increased congestion. The answer to this issue was the construction of a new and more ecological vessel called NEWS (Development of a Next-generation European Inland Waterway Ship and Logistics System). The diesel-/gas-/LNG-electric propulsion of the vessel boosted efficiency by 30%, and at the same time, there was a 10% decrease in fuel consumption due to the new hull [16]. The aim of that new development was the reduction in greenhouse gas emissions and the shifting of the majority of cargo transportation from road and rail traffic to inland waterways. Back then, the NEWS LNG-power management system was considered highly innovative and was believed to contribute to more ecologically safer and sustainable inland waterways. Sihn et al. [16] states that two other projects for "greener" solutions have been developed and both take liquified natural gas (LNG) into consideration as a marine fuel for inland waterways. The project "LNG Masterplan for Rhine-Main-Danube", which was finished in 2015, delivered the so-called LNG Masterplan. Sihn et al. [16] highlight that the Masterplan had a primary objective of establishing a collaborative platform for authorities and industry stakeholders to promote the development of a harmonized European regulatory framework for LNG as a maritime fuel. Another notable project related to LNG was the "LNG Power Train for Danube Inland Navigation", which was concluded in 2011. This project played a significant role in promoting the adoption of alternative fuels in Danube navigation and contributed to the implementation of LNG usage in the region.

Simmer et al. [17] 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 [40]) 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. [30]. 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 [17].

Zakaria and Rahman [19] evaluated the Energy Efficiency Design Index for inland vessels in Bangladesh. According to these authors, inland waterway ships in Bangladesh often navigate through densely populated regions and their carbon footprint, energy efficiency, and comparable environmental characteristics will soon be of great significance. Zakaria and Rahman [19] state that there is a lack of suggested benchmarks that can be utilized to assess the energy efficiency of inland waterway vessels. The analysis conducted by the researchers included a comprehensive database comprising inland waterway general cargo ships, oil tankers, passenger vessels, and passenger ferries in Bangladesh. One of the main conclusions from their research, which is important to this study, is that according to Zakaria and Rahman [19], the EEDI shows a decrease when using fuel types with low carbon content. Therefore, the adoption of LNG as the primary fuel can lead to a substantial reduction in the EEDI.

Yuan et al. [21] 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 [21].

Ursavas et al. [22] investigated the LNG bunkering network based on several parameters in the inland waterway sector and validated their approach in the Arnhem–Nijmegen region in the West European river network. Ursavas et al. [22] state that LNG is considered one of the most auspicious solutions for pollution contraction in both inland shipping and short-sea shipping. As a conclusion, Ursavas et al. [22] mention that the usage of LNG as a maritime fuel is expected to increase further in the near future, but a notable expansion in the advancement of the LNG supply network is further expected and must be set in place.

Perčić et al. [23] investigated the feasibility of alternative power system configurations for passenger and cargo ships in the Croatian inland waterway fleet. They focused on the environmental effect of three potential power system setups: a ship powered by a diesel engine, a battery-powered ship, and a ship powered by a combination of photovoltaic cells and batteries. The results of their analysis revealed that the ship powered by a combination of photovoltaic cells and batteries demonstrated the highest level of environmental friendliness. Throughout its lifecycle, this configuration emitted fewer greenhouse gases compared with the other power system configurations, resulting in a lower overall carbon output [23].

Xing et al. [24] highlight the significance of alternative marine fuels for achieving low carbon emissions in the shipping industry by 2050, in conjunction with a range of technological and operational strategies. In their paper, the authors conducted a comprehensive technological assessment to identify the most auspicious alternative maritime fuels that would contribute at the same time to a reduction in sulfur oxides, nitrogen oxides, and carbon dioxide emissions, as well as increase in sustainability. Although their study primarily investigates the short-sea shipping sector, it is pertinent to consider their findings in the context of inland waterway navigation. The results of their research suggest that green hydrogen and green ammonia could play a crucial role in promoting environmentally friendly practices in domestic and short-sea shipping [24]. Their research concludes with the assumption that hydrogen, compressed natural gas and ammonia, and bioethanol and biodiesels from renewable energy sources are recommended and could act as alternative options for short-sea shipping [24].

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.

Bazaluk et al. [25] identify prospective energy-saving technologies for IWT. They highlight that there is limited knowledge on methods to decrease the energy usage of inland shipping. They utilize metrics such as traction efficiency, theoretical fuel consumption, and actual specific fuel consumption to assess and measure energy efficiency. In their results, Bazaluk et al. [25] reveal that self-propelled vessels exhibit a lower energy efficiency compared with towing barges, with the actual specific energy consumption being five times higher than the theoretical value. As a next step, they compare the effectiveness of the energy utilization of inland waterway transport to rail and road haulage. In their conclusion, Bazaluk et al. [25] state that IWT demonstrates superior traction efficiency (ranging from 1.88 to 11.82 t/kW) compared with road transportation (ranging from 0.07 to 0.145 t/kW) and rail transportation (ranging from 0.68 to 1.35 t/kW). Barges exhibit the most favorable average specific fuel consumption, with approximately 100 kJ/tkm. However, dry cargo ships have lower efficiency compared with rail transport.

Perčić et al. [8] conducted a comprehensive analysis of alternative fuels (electricity, methanol, LNG, hydrogen, ammonia, and biodiesel) with the aim of reducing the environmental impact and lifetime costs of inland waterway transportation. The study encompasses technical, environmental, and economic aspects to evaluate the feasibility and benefits of each fuel option. The analysis focuses on Croatia, whose aging inland waterway fleet must satisfy the objectives of the Republic of Croatia's Low-Carbon Development Strategy. The researchers also conducted a case study to assess how a carbon tax may affect Croatia's 2030 carbon emission reduction goal. Perčić et al. [8] state that the electrification of ships emerges as the most ecologically friendly for all the vessels considered, resulting in a decrease in carbon emissions by up to 51%. However, the cost-effectiveness choice is linked to the type of the vessel. Perčić et al. [8] suggest replacing a diesel engine with a Li-ion battery, as this power system configuration does not release exhaust emissions during its operation. They conclude the research by proposing other substitute fuels that could be utilized in Croatia's inland waterways with a lower carbon footprint than a diesel-powered vessel, such as methanol, LNG, and B20 (a blend of 20% biodiesel and 80% petroleum diesel).

Breuer et al. [26] mention that a wide range of alternative fuels based on various principles, including Power-to-Gas and Power-to-Liquid, as well as propulsion technologies, have been developed to address the challenge of decarbonizing the transportation industry. By offering a comprehensive examination of the available fuel and drivetrain options spanning production to utilization, their study seeks to reduce this gap. Breuer et al. [26] identify Methanol-to-Gasoline, Fischer–Tropsch diesel and kerosene, hydrogen, battery-electric propulsion, HVO, DME, and natural gas as promising sustainable marine fuels. In their study, Breuer at al. [26] defined the inland waterways based on the situation in Germany, as it was easier to come to a conclusion based on inland vessel types. Cargo barges, liquid cargo barges, pushed barges, and pushed tankers were the ship groups they divided freight transport into. Pusher boats are used in the operations of the last two ship classes. In addition to freight transport, they also considered passenger transport, specifically referring to cabin vessels [26]. Based on their research, they found that compressed natural gas (CNG) was a more appealing fuel option for pusher boats, due to their smaller size and lower daily distances. In Germany's inland waterway sector, diesel engines with higher RPMs are predominantly used, which have a maximum efficiency of 44% [41]. On the other hand, electric drivetrains offer significantly higher efficiencies, with a maximum of 85% [42]. Breuer et al. [26] propose LNG as an alternative source for marine fuel, but because of their great efficiency, fuel cell- and battery-electric propulsion technologies are also attractive. Breuer et al. [26] state that "it is promising to deploy a fuel cell-electric powertrain for passenger and cargo transportation in inland navigation since it delivers modest energy consumption benefits and a high gravimetric energy density". In Germany's inland navigation industry, battery–electric propelled vessels are already in use. On the other hand, Kasten et al. [43] state that due to the low volumetric and gravimetric energy density and the ensuing large weight of the batteries, battery–electric inland waterway barges are rarely thought of as choices for inland transportation. Hydrogen was rated as a promising alternative option for inland transport in a viability assessment by the MariGreen project [44]. The advantages of using hydrogen in combustion engines is advantageous for the cargo/liquid cargo barges and pushed barges/tankers, while ferries and cabin ships could utilize more fuel cell–electric propulsion. By 2024, ten inland hydrogen-powered vessels between Rotterdam and Duisburg will be operated by the Rhine Hydrogen Integration Network of Excellence (RH2lNE) [45].

Another study that focused on alternative fuel sources for short-sea shipping was conducted by Perčić et al. [10]. A comparative analysis was conducted to assess the suitability of different power systems for achieving zero-emission shipping, focusing on ro-ro passenger vessels in Croatian short-sea transportation. The comparison involved evaluating the diesel-powered conventional power system against a battery-powered alternative system. The goal was to identify the most advantageous technology based on both environmental and economic criteria. The findings highlighted the electrification of ships using a Lithium-ion battery as the most suitable alternative, considering its favorable performance in terms of environmental impact and economic viability.

Ibrahim et al. [27] discuss the replacement of the typical diesel engines of a pushed and pusher bulk carrier barge, and they examined the viability of a renewable energy-based system from both a technical and financial standpoint. They explain that the selected renewable energy-based system for the pushed and pusher bulk carrier barge is primarily based on photovoltaic panels. Excess energy generated by these panels is stored using a combination of hydrogen (H2) gas produced through electrolysis and batteries, utilizing power-to-gas technology. This configuration enables the utilization of fuel cells to convert hydrogen gas into electrical energy, providing a sustainable and efficient power source for the barge. Their research investigates an innovative solution to achieve zero-emission propulsion for an 800-ton cargo barge operating in the Nile River. The proposed solution combines three key elements: solar energy, hydrogen generation, and fuel cell propulsion. The aim is to pave the way for energy transformation and promote green propulsion in the Nile River cargo transport sector. In conclusion, the study highlights the promising potential of power-to-gas technology for the future of renewable energy generation and utilization. The innovative system combining photovoltaic panels, electrolysis, and fuel cells demonstrated an efficiency of 57.9%. Due to this great efficiency, the amount of energy required to travel from Aswan to Alexandria was significantly reduced from 21,964 kW/h to 11,980 kW/h. The results indicate that the efficiencies of solar cells, electrolysis, and fuel cells are projected to increase even more while becoming more accessible as these technologies evolve. This suggests that in the foreseeable future, overall system efficiency will significantly rise.

Tan et al. [28] conducted a theoretical and comprehensive analysis of the decision-making process of a container ship in an inland river by taking the influence of streamflow velocity into consideration. A numerical example using the Yangtze River was presented to illustrate their method and results. The researchers found that green fuel consumption and scrubber installation are two main adaption techniques for reducing emissions by ships. Utilizing costly, low-sulfur oil as green fuel raises the cost of shipping. By contrast, installing scrubbers is a long-term solution that necessitates a substantial capital outlay to set up desulfurization plants. However, it permits ships to keep utilizing cheap oil [41]. Tan et al. [41] indicate that "in contrast to ocean going vessels, an inland vessel's fuel consumption is closely linked to its engine speed. The actual sailing speed of the ship is determined by a combination of the engine speed and the velocity of the streamflow".

Chatelier [31] highlights the urgent need for low-carbon and zero-carbon propulsion systems in the maritime sector, particularly for inland vessels. The paper explores a range of solutions to achieve sustainability and regulatory compliance. Inland vessels are identified as early adopters due to their size. Batteries are a mature technology suitable for smaller ships, offering pollution, noise, and cost reduction when paired with renewable energy [31]. Fuel cell technology, while promising, faces adaptability challenges. The source of electricity for battery charging is crucial for environmental benefits, emphasizing the importance of green energy. Swappable batteries and hydrogen fuel cells are noted as options [31]. The choice of propulsion system depends on various factors, including vessel type and safety regulations. Electrical propulsion systems play a crucial role in reducing emissions, especially on inland waterways. However, each solution must be tailored to specific vessel needs and operational considerations, alongside advancements in alternative fuels according to Chatelier [31].

Perčić et al. [32] delve into the critical issue of global warming caused by greenhouse gas (GHG) emissions primarily from fossil fuel use in the shipping sector. The research underscores that a significant reduction in GHG and other harmful emissions can be achieved by transitioning from conventional fossil fuels to alternative, low-carbon, or zero-emission power systems [32]. Natural gas, hydrogen, methanol, and electricity are examined as potential alternative marine fuels, with a focus on inland navigation. In their research they address this context, particularly within Croatia, where aging inland navigation vessels primarily operate. They evaluate the energy efficiency and environmental impact of various power systems, considering fuels like diesel, electricity, methanol, liquefied natural gas (LNG), hydrogen, and ammonia [32]. The analysis reveals that full electrification with Li-ion batteries stands out as the most environmentally friendly and energy-efficient option for both cargo and passenger ships in the Croatian inland waterway fleet. These electrified vessels have significantly lower Energy Efficiency Indices (EEI) compared with their diesel-powered counterparts. While Perčić et al. [32] conclude that fully electrified vessels are the most favorable choice in terms of decarbonization, they also highlight the limitations of using fossil hydrogen and ammonia, which are less viable options for reducing GHG emissions compared with diesel.

Zhang et al. [35] investigated the critical challenge of optimizing the operational efficiency of battery-powered inland vessels, specifically those employing battery-swapping mechanisms in the Yangtze River region. To harness the full potential of this technology, a holistic approach is required that considers diverse factors such as environmental conditions, cargo loads, and battery-swapping pricing dynamics [35]. The study's primary contributions are twofold. First, it introduces an intricate energy consumption model tailored to inland battery-powered vessels operating in the Yangtze River, offering a comprehensive understanding of power dynamics during operation. Second, it proposes an innovative optimization model that simultaneously addresses sailing speed and energy consumption. Importantly, this model integrates the variable nature of battery-swapping prices, which significantly impacts operational costs. The results are compelling, revealing a remarkable 14% reduction in battery-swapping costs compared with conventional methods using fixed batteries [35]. Furthermore, with their research, Zhang et al. [35] provide valuable insights into how variations in navigational conditions such as water speed, water depth, and cargo load influence energy consumption and overall operational costs.

4. Discussion

The literature review showed that 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 a surprise, though, that America—especially North and South America—are missing from this review, as both regions make use of their inland waterways for the transportation of passengers and cargo.

It has become apparent that the fuels that were proposed as the most suitable alternative solutions are LNG, as it is mentioned in 10 different studies, and electric batteries, which are mentioned 9 times. Hydrogen and Photovoltaic (PV) solutions are proposed as alternative solutions in six and three studies, respectively. Figure 3 shows a recap of the times the fuels were mentioned in the studies. An overview of the alternative fuels and alternative power sources per country and per region can be seen in Table 2.

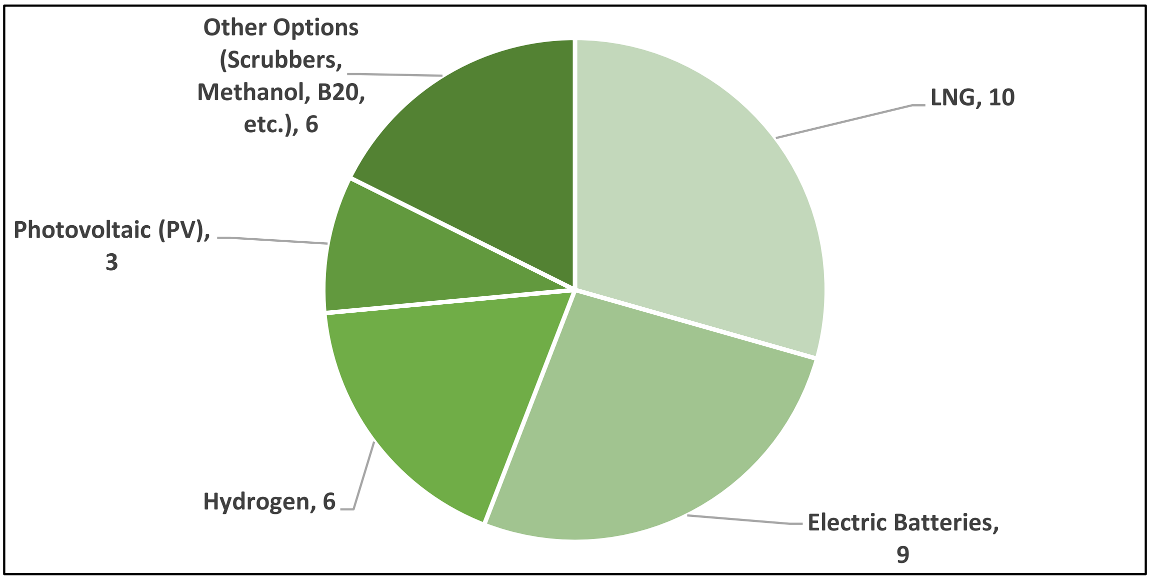

Figure 3. A recap of the times the fuels were mentioned in the studies.

Table 2. Alternative Fuels and Alternative Power Sources as per the literature review and the respective regions.

Study	Authors	Year	Fuel	Region	Country
The Use of Hydrogen as a Fuel for Inland Waterway Units	El Gohary et al. [15]	2014	Hydrogen	Africa	Egypt
Power to gas technology: Application and optimization for inland transportation through Nile River	Ibrahim et al. [27]	2022	Photovoltaic (PV)/Batteries		Egypt
Energy Efficiency Design Index (EEDI) for Inland Vessels in Bangladesh	Zakaria and Rahman [19]	2017	LNG	Asia	Bangladesh
The evaluating on EEDI and fuel consumption of an inland river 800PCC integrated with solar photovoltaic system	Yuan et al. [21]	2019	Photovoltaic (PV)		China
Decarbonizing inland ship power system: Alternative solution and assessment method	Fan et al. [7]	2021	LNG/Batteries (Hybrid)		China
Scrubber installation and green fuel for inland river ships with non-identical streamflow	Tan et al. [28]	2022	Green Fuels/Scrubbers		China
Carbon footprint model and low–carbon pathway of inland shipping based on micro–macro analysis	Fan et al. [29]	2022	LNG		China
Carbon footprint prediction considering the evolution of alternative fuels and cargo: A case study of Yangtze river ships	Yan et al. [30]	2023	LNG, LNG Hydrid, Methanol, Hydrogen, Ammonia		China
Speed and energy optimization method for the inland all-electric ship in battery-swapping mode	Zhang et al. [35]	2023	Electric Batteries		China
Impact of Inland Shipping Emissions on Elemental Carbon Concentrations near Waterways in The Netherlands	Keuken et al. [14]	2014	LNG/Scrubbers	Europe	Netherlands
A green and economic future of inland waterway shipping	Sihn et al. [16]	2015	LNG/Batteries		Austria, Belgium, Germany, Hungary, Romania, Serbia, Slovakia
Liquefied Natural Gas as a Fuel in Inland Navigation: Barriers to Be Overcome on Rhine-Main-Danube	Simmer et al. [17]	2015	LNG		Germany
Reduction of CO_2 emissions of inland passenger and cargo vessels by alternative power system configurations	Perčić et al. [23]	2020	Photovoltaic (PV)		Croatia
LNG bunkering network design in inland waterways	Ursavas et al. [22]	2020	LNG		Netherlands
Techno-economic assessment of alternative marine fuels for inland shipping in Croatia	Perčić et al. [8]	2021	LNG/Methanol/B20		Croatia
Energy Efficiency of Inland Waterways Transport for Agriculture: The Ukraine Case Study	Bazaluk et al. [25]	2021	Diesel/Batteries		Ukraine
Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation	Perčić et al. [10]	2022	Electric Batteries		Croatia
An Overview of Promising Alternative Fuels for Road, Rail, Air, and Inland Waterway Transport in Germany	Breuer et al. [26]	2022	LNG/Hydrogen/Batteries		Germany
Holistic energy efficiency and environmental friendliness analysis of inland ships with alternative power systems	Perčić et al. [32]	2023	Electric Batteries		Croatia
Alternative fuel options for low carbon maritime transportation: Pathways to 2050	Xing et al. [24]	2021	Hydrogen/Ammonia/Biofuels	Global	Global
Entering a new era for electrical vessels on inland waterways	Chatelier, J. M [31]	2023	Electric Batteries, Hydrogen		Global
Carbon footprint of hydrogen-powered inland shipping: Impacts and hotspots	Evers et al. [36]	2023	Hydrogen		Global

An interesting observation from Table 2 is that LNG was considered the most promising alternative fuel in studies dated 8 to 3 years ago, whereas there was a switch to LNG along with electric batteries only in the last 2 years of research. Additionally, the majority of the studies that suggest LNG as the most suitable solution came from the European region and are followed by Asia. In the African region and the two Egyptian studies, LNG was not considered at all. Contrary to the suggestions from the papers reviewed, the Central Commission for the Navigation of the Rhine's (CCNR) forecasts for the most promising fuels in inland navigation by 2050 demote LNG as an option. CCNR currently considers two pathways for the development of the fuel share by 2050: a conservative and an innovative pathway as depicted in Figures 4 and 5. For CCNR, the most promising alternative fuels and power sources are biofuels and batteries.

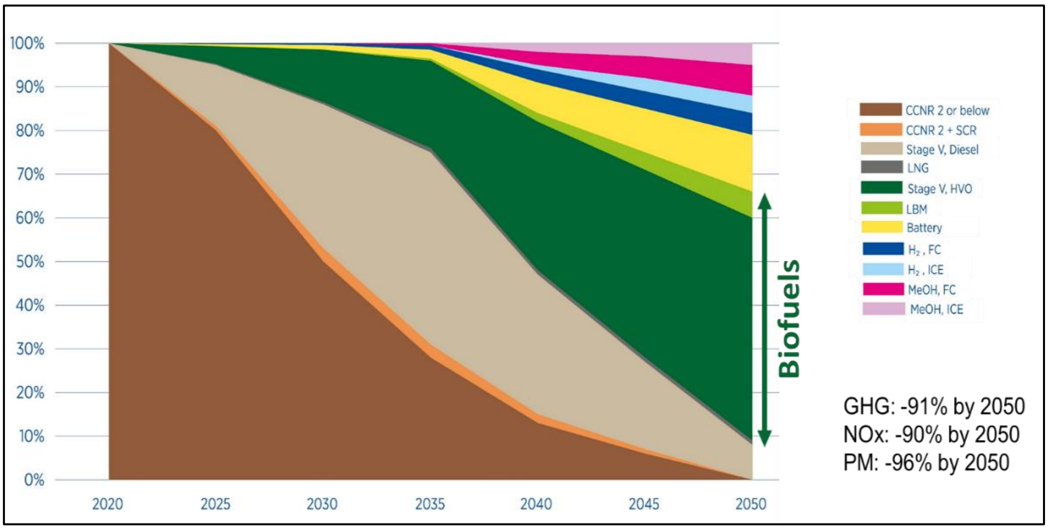

Figure 4. The development of the fuel share by 2050 in the conservative pathway [46].

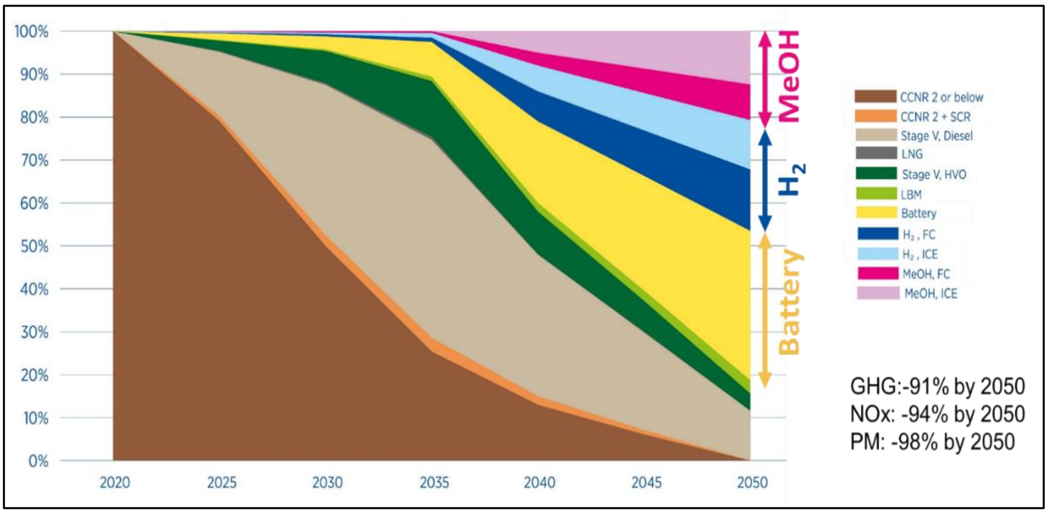

Figure 5. The development of the fuel share by 2050 in the innovative pathway [46].

Another key highlight of this literature review is that out of the 10 scientific papers focusing on the European region, only half of them concern the biggest maritime nations in terms of moving cargo and passengers via inland waterways, with the biggest focus being in Germany. It has been as a surprise that the Netherlands and Belgium, which both have an extensive network of inland waterways, are not the center of extensive research for this topic. On the other hand, alternative fuel and power sources can be considered a hot topic in Croatia, as in the last 3 years, four different papers have been published with respect to this matter. Another key outcome from the analysis is that the majority of the research papers are based on suggestions and "real" applications for their results. Out of 22 papers (as presented in the analysis section), only 7 of them are based on scientific research, adopting either a systematic literature review or a theoretical approach. The remaining 15 papers either use technologies under development, which are in a concept stage, or real-life case studies to justify their results.

5. Conclusions

This research paper investigates the issue of emissions from inland navigation, recognizing the environmental impact of traditional fuel sources like diesel used in inland vessels. It adopts a systematic literature review approach, taking under consideration a wide range of scientific papers from various regions around the world such as Egypt, China, the Netherlands, Croatia, Ukraine, Austria, Belgium, Germany, India, Hungary, Romania, Serbia, and Slovakia. All these regions have important inland waterways. The research question aims to identify the most promising alternative fuel or power source for these vessels. This research paper, after conducting a thorough analysis, presents the options considered more sustainable and environmentally friendly, as they will potentially significantly reduce emissions and contribute to a cleaner and greener inland navigation industry.

Based on the systematic literature review, 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.

One important point that has to be taken into consideration is the amount of studies regarding alternative fuel sources and decarbonization in inland waterways with respect to the European region. The majority of the studies that have been analyzed and presented in this literature review come from other parts of the world, especially in China, where it seems that the government along with researchers have been putting much effort into utilizing inland corridors and switching to alternative power sources for inland vessels and their propulsion systems. As the European region has extensive networks of inland waterways and the European Commission has set a goal for net zero, it seems that there is plenty of space for additional actions. There are many projects that concern decarbonization in transportation and a further utilization of inland waterways, but based on the literature review, it seems that they focus on the optimization of the inland corridors as a first step, and the focus on switching to alternative power sources for inland vessels is only a second step.

In conclusion, transportation via inland waterways presents a unique chance for eco-conscious, large-scale shipping. This research 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. By delivering a comprehensive evaluation of emerging alternatives within the global inland waterway transportation sector, this study equips stakeholders with the necessary knowledge to make informed decisions in the pursuit of environmentally friendly transport solutions. From the analysis, it is obvious that LNG is still a fuel that is most preferable for inland navigation and short-sea shipping, but it lacks infrastructure, especially in inland corridors. Additionally, batteries and green fuels such as ammonia and biodiesel seem quite promising for the future along with hydrogen, which is considered the most sustainable one under the correct conditions and based on a few studies, but there is still a long way for it to go in order for it to replace diesel oil. As indicated by the systematic literature review, the analysis in the previous section, and the conclusion, there is plenty of space for similar research in Northern European countries. As mentioned earlier, countries such as Belgium, France, Germany, and the Netherlands, which have an extensive network of inland waterways and are currently making coordinated efforts for the maximum utilization of them, should be the center of focus for this topic. It is understandable that this kind of research is missing, and they should be considered for future research. Additionally, another interesting research topic for future analysis should be a comparison of the performance of inland vessels that have already invested in LNG with those that have invested in alternative solutions. The literature review showed that a majority of the research topics focused on LNG as the most suitable solution a few years ago but that they switched to greener fuels and batteries in the last two years. It would be interesting to see if any owners have already invested in LNG and how the results of their choices so far compare to other options.

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. Research papers are carefully reviewed and evaluated by experts in each respective field, ensuring their quality and reliability, and this process takes time. 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.

Author Contributions: Conceptualization, C.C.R.; methodology, C.C.R.; validation, C.C.R. and T.V. and E.v.H.; formal analysis, C.C.R.; investigation, C.C.R.; data curation, C.C.R.; writing—original draft preparation, C.C.R.; writing—review and editing, C.C.R. and T.V. and E.v.H.; supervision, T.V. and E.v.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors would like to express their appreciation to the CCNR—Central Commission for the Navigation of the Rhine for their permission to use their material.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Meyer, T. Decarbonizing Road Freight Transportation—A Bibliometric and Network Analysis. *Transp. Res. Part D Transp. Environ.* **2020**, *89*, 102619. [CrossRef]
2. What Is Net Zero? National Grid Group. Available online: https://www.nationalgrid.com/stories/energy-explained/what-is-net-zero (accessed on 12 September 2022).
3. 2050 Long-Term Strategy. Climate Action. Available online: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en (accessed on 12 September 2022).
4. Shipping Industry Reduces Carbon Emissions with Space Technology. Available online: https://www.ukri.org/news/shipping-industry-reduces-carbon-emissions-with-space-technology/ (accessed on 12 September 2022).
5. IMO 2020—Cutting Sulfur Oxide Emissions. IMO. Available online: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx (accessed on 12 September 2022).
6. Arief, I.S.; Fathalah, A. Review of Alternative Energy Resource for the Future Ship Power. *IOP Conf. Ser.* **2022**, *972*, 012073. [CrossRef]

7. Fan, A.; Wang, J.-T.; He, Y.; Perčić, M.; Vladimir, N.; Yang, L. Decarbonizing Inland Ship Power System: Alternative Solution and Assessment Method. *Energy* **2021**, *226*, 120266. [CrossRef]
8. Perčić, M.; Vladimir, N.; Fan, A. Techno-Economic Assessment of Alternative Marine Fuels for Inland Shipping in Croatia. *Renew. Sustain. Energy Rev.* **2021**, *148*, 111363. [CrossRef]
9. Ramacher, M.O.P.; Aulinger, A.; Matthias, V.; Helmholtz-Zentrum, H. Current and Future INLAND SHIPPING Emissions Impacts on Urban Air Quality Based on REAL-WORLD EMISSION Factors. In Proceedings of the 13th International Conference on Air Quality—Science and Application, Thessaloniki, Greece, 27 May–2 June 2022. [CrossRef]
10. Perčić, M.; Frković, L.; Pukšec, T.; Ćosić, B.; Li, O.L.; Vladimir, N. Life-Cycle Assessment and Life-Cycle Cost Assessment of Power Batteries for All-Electric Vessels for Short-Sea Navigation. *Energy* **2022**, *251*, 123895. [CrossRef]
11. Govindan, K.; Soleimani, H. A Review of Reverse Logistics and Closed-Loop Supply Chains: A Journal of Cleaner Production Focus. *J. Clean. Prod.* **2017**, *142*, 371–384. [CrossRef]
12. Sun, X.; Yan, X.; Wu, B.; Song, X. Analysis of the Operational Energy Efficiency for Inland River Ships. *Transp. Res. Part D Transp. Environ.* **2013**, *22*, 34–39. [CrossRef]
13. Van Lier, T.; Macharis, C. Assessing the Environmental Impact of Inland Waterway Transport Using a Life-Cycle Assessment Approach: The Case of Flanders. *Res. Transp. Bus. Manag.* **2014**, *12*, 29–40. [CrossRef]
14. Keuken, M.; Moerman, M.M.; Jonkers, J.; Hulskotte, J.H.J.; Van Der Gon, H.A.C.D.; Hoek, G.; Sokhi, R.S. Impact of Inland Shipping Emissions on Elemental Carbon Concentrations near Waterways in The Netherlands. *Atmos. Environ.* **2014**, *95*, 1–9. [CrossRef]
15. Gohary, M.M.E.; Welaya, Y.M.A.; Saad, A.S. The Use of Hydrogen as a Fuel for Inland Waterway Units. *J. Mar. Sci. Appl.* **2014**, *13*, 212–217. [CrossRef]
16. Sihn, W.; Pascher, H.; Ott, K.O.; Stein, S.L.; Schumacher, A.; Mascolo, G. A Green and Economic Future of Inland Waterway Shipping. *Procedia CIRP* **2015**, *29*, 317–322. [CrossRef]
17. Simmer, L.; Pfoser, S.; Schauer, O. Liquefied Natural Gas as a Fuel in Inland Navigation: Barriers to Be Overcome on Rhine-Main-Danube. *J. Clean Energy Technol.* **2015**, *4*, 295–300. [CrossRef]
18. Bläsing, M.; Kistler, M.; Lehndorff, E. Emission Fingerprint of Inland Navigation Vessels Compared with Road Traffic, Domestic Heating and Ocean Going Vessels. *Org. Geochem.* **2016**, *99*, 1–9. [CrossRef]
19. Zakaria, N.M.G.; Rahman, M.S. Energy Efficiency Design Index (EEDI) for Inland Vessels in Bangladesh. *Procedia Eng.* **2017**, *194*, 362–369. [CrossRef]
20. Vilarinho, A.; Liboni, L.B.; Siegler, J. Challenges and Opportunities for the Development of River Logistics as a Sustainable Alternative: A Systematic Review. *Transp. Res. Procedia* **2019**, *39*, 576–586. [CrossRef]
21. Yuan, C.; Pan, P.; Sun, Y.; Yan, X.; Tang, X. The Evaluating on EEDI and Fuel Consumption of an Inland River 800PCC Integrated with Solar Photovoltaic System. *J. Mar. Eng. Technol.* **2021**, *20*, 77–92. [CrossRef]
22. Ursavas, E.; Zhu, S.X.; Savelsbergh, M.W.P. LNG Bunkering Network Design in Inland Waterways. *Transp. Res. Part C Emerg. Technol.* **2020**, *120*, 102779. [CrossRef]
23. Perčić, M.; Vladimir, N.; Fan, A.; He, Y. Reduction of CO_2 Emissions of Inland Passenger and Cargo Vessels by Alternative Power System Configurations. *Energy Proc.* **2021**, *11*, 453. [CrossRef]
24. Xing, H.; Stuart, C.A.; Spence, S.; Chen, H. Alternative Fuel Options for Low Carbon Maritime Transportation: Pathways to 2050. *J. Clean. Prod.* **2021**, *297*, 126651. [CrossRef]
25. Bazaluk, O.; Havrysh, V.; Nitsenko, V. Energy Efficiency of Inland Waterways Transport for Agriculture: The Ukraine Case Study. *Appl. Sci.* **2021**, *11*, 8937. [CrossRef]
26. Breuer, J.L.; Scholten, J.; Koj, J.C.; Schorn, F.; Fiebrandt, M.; Samsun, R.C.; Albus, R.; Görner, K.; Stolten, D.; Peters, R. An Overview of Promising Alternative Fuels for Road, Rail, Air, and Inland Waterway Transport in Germany. *Energies* **2022**, *15*, 1443. [CrossRef]
27. Ibrahim, M.M.; Abdou, M.; Bakhit, M.; Mansour, P.; Dewidar, M.; Hussein, M.; Warda, H.A.; Haddara, S.H.; Wahba, E.M.; El-Gayar, D.A. Power to Gas Technology: Application and Optimization for Inland Transportation through Nile River. *Int. J. Hydrogen Energy* **2022**. [CrossRef]
28. Tan, Z.; Zeng, X.; Shamsaei, N.; Chen, J.; Wang, H. Scrubber Installation and Green Fuel for Inland River Ships with Non-Identical Streamflow. *Transp. Res. Part E-Logist. Transp. Rev.* **2022**, *161*, 102677. [CrossRef]
29. Fan, A.; Xiong, Y.; Yang, L.; Zhang, H.; He, Y. Carbon Footprint Model and Low–Carbon Pathway of Inland Shipping Based on Micro–Macro Analysis. *Energy* **2023**, *263*, 126150. [CrossRef]
30. Yan, X.; He, Y.; Fan, A. Carbon Footprint Prediction Considering the Evolution of Alternative Fuels and Cargo: A Case Study of Yangtze River Ships. *Renew. Sustain. Energy Rev.* **2023**, *173*, 113068. [CrossRef]
31. Chatelier, J.M. Entering a New Era for Electrical Vessel on Inland Waterways. *Cienc. Tecnol. Buques* **2023**, *16*, 21–32. [CrossRef]
32. Perčić, M.; Vladimir, N.; Fan, A.; Jovanović, I. Holistic Energy Efficiency and Environmental Friendliness Analysis of Inland Ships with Alternative Power Systems. Available online: https://www.piancamerica2023.org/ (accessed on 6 September 2023).
33. Yuan, Y.; Wang, X.; Tong, L.; Yuan, C.; Shen, B.; Long, T. Enhancement Method of Series Hybrid Ship Energy Efficiency for Speed and Energy Collaborative Optimization. *IET Electr. Syst. Transp.* **2023**, *13*, e12085. [CrossRef]
34. Mehrotra, P.; Rai, V.K. Air Pollution by Inland Waterways Transportation in India. *Int. J. Sci. Res. Sci. Technol.* **2023**, *10*, 975–986. [CrossRef]

35. Zhang, Y.; Sun, L.; Fan, T.S.; Ma, F.; Xiong, Y. Speed and Energy Optimization Method for the Inland All-Electric Ship in Battery-Swapping Mode. *Ocean Eng.* **2023**, *284*, 115234. [CrossRef]
36. Evers, V.H.M.; Kirkels, A.F.; Godjevac, M. Carbon Footprint of Hydrogen-Powered Inland Shipping: Impacts and Hotspots. *Renew. Sustain. Energy Rev.* **2023**, *185*, 113629. [CrossRef]
37. Eger, P.; Mathes, T.; Zavarsky, A.; Duester, L. Measurement Report: Inland Ship Emissions and Their Contribution to NOx and Ultrafine Particle Concentrations at the Rhine. *Atmos. Chem. Phys.* **2023**, *23*, 8769–8788. [CrossRef]
38. Krčum, M.; Plazibat, V.; Mrčelić, G.J. Integration Sea and River Ports—The Challenge of the Croatian Transport System for the 21st Century. *Naše More* **2015**, *62*, 247–255. [CrossRef]
39. Bank, A.D. *Promoting Inland Waterway Transport in the People's Republic of China*; Asian Development Bank: Manila, Philippines, 2016.
40. Trans-European Transport Network (TEN-T). Mobility and Transport. Available online: https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en (accessed on 12 September 2022).
41. Van Basshuysen, R.; Schäfer, F. *Handbuch Verbrennungsmotor: Grundlagen, Komponenten, Systeme, Perspektiven*; Springer Vieweg: Berlin/Heidelberg, Germany, 2017.
42. Kramer, U.; Ortloff, F.; Stollenwerk, S. *Defossilisierung des Transportsektors: Optionen und Voraussetzungen in Deutschland*; FVV: Frankfurt am Main, Germany, 2018.
43. Kasten, P.; Mottschall, M.; Köppel, W.; Degünther, C.; Schmied, M.; Wüthrich, P. *Erarbeitung Einer Fachlichen Strategie zur Energieversorgung des Verkehrs bis zum Jahr 2050: Endbericht*; Umweltbundesamt Texte: Dessau, Germany, 2016.
44. Project-MariGreen. Available online: https://keep.eu/projects/17598/MariGreen-EN/ (accessed on 12 September 2022).
45. RH2INE. RH2INE Awarded Co-Funding of the EU Connecting Europe Facility! Available online: https://www.rh2ine.eu/latest-news/253/ (accessed on 12 September 2022).
46. Central Commission for Navigation on the Rhine. *CCNR Roadmap for Reducing Inland Navigation Emissions*; Central Commission for Navigation on the Rhine: Strasbourg, France, 2022.