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Systematic Review

Measurement Techniques, Calculation Methods, and Reduction Measures for Greenhouse Gas Emissions in Inland Navigation—A Preliminary Study

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Abstract: Emissions originating from inland navigation should be reduced to achieve climate targets. This paper aims to identify (1) onboard GHG emission measurement systems, (2) calculation methods for GHG emissions of inland vessels and (3) reduction measures. A systematic literature review, examining 6 databases, yielded 105 initial outcomes, with 17 relevant references. The review reveals a scarcity of studies, with the majority concentrated in Europe and Asia, while North America, Africa, Australia, and South America remain largely unexplored. Four of the seventeen relevant studies focused on real-world GHG emissions measurement. Future research should explore more efficient and calibrated approaches for real-time CO_2 insights in inland vessels. In the section on calculating GHG emissions, most papers attempt to adapt the EEDI or EEXI to inland navigation. Reduction measures for GHG emissions concentrate on alternative fuels, like LNG, methanol, hydrogen, or alternative power sources. As the research in this area is limited, prioritizing it in academic discourse is not only essential for advancing our understanding but also imperative for shaping a resilient and environmentally conscious future for inland navigation.

Keywords: CO_2e emissions; GHG; greenhouse gases; sustainable transport; emission measurement; inland navigation; inland vessel; emission calculation; emission reduction

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1. Introduction

The European Green Deal sets the goal of achieving a carbon-neutral European Union by 2050. This goal requires decarbonization across all sectors. In particular, the transport sector must achieve a 90% reduction in greenhouse gas (GHG) emissions by 2050 compared to 1990 levels [1]. Currently, the transportation industry is responsible for about a quarter of the EU's total GHG emissions [2] and is the second largest source of emissions in the European Union, after the energy supply sector. The transport sector was the only sector which recorded an increase in GHG emissions from 2013 to 2019, while the other sectors, specifically buildings, industry and energy, and the EU as a whole, have observed a decrease in GHG emissions levels [3,4]. Projections from the European Environment Agency suggest that domestic transport emissions will only fall below 1990 levels in 2029, despite the measures planned by EU Member States [5]. In 2021, road transportation constituted 76.2% of the GHG emissions related to transportation in the European Union (EU-27), while navigation emissions are responsible for 14.8% [6]. As the CO_2 reporting for inland navigation falls under the same IPCC guidelines as maritime vessels, emissions from inland navigation are reported together with maritime vessels under shipping emissions. As a result, the total emission data of solely inland waterway transport are not reported by European sources [7]. Although inland navigation vessels have lower greenhouse gas emissions per tkm compared to trucks, the European Union (EU) and the Central Commission for the Navigation of the Rhine (CCNR) are aiming for zero-emission vessels and the elimination of GHG emissions from inland navigation vessels by 2050 [8]. Individual companies and industry sectors will have to implement decarbonization strategies over the next few years. To identify how they can improve the performance of the logistics operations, they have to understand their current carbon footprint. The logical place to start is with detailed measurement of GHG emissions. The precision and usefulness of calculated emissions and emission intensities rely on the accessibility, specification, quality, and sharing of data [9]. While data collection for demonstrating environmental performance improvements in the road transportation sector has progressed, data availability for inland navigation is limited [2]. Therefore, to facilitate a reliable comparison with other modes of transportation, improving the qualitative and quantitative measurement of energy consumption and related emissions in inland navigation is essential and should be brought up to the standards of road transport [10]. Without accurate data, it is not feasible to establish science-based targets, assess decarbonization options, and oversee advancements in emissions reduction over time [11].

Given the significance of reliable GHG accounting methods in logistics and the dearth of data for inland navigation, the aim of this paper is to identify (1) onboard GHG emission measurement systems, (2) calculation methods for the GHG emissions of inland vessels, and (3) reduction measures. To reach the goal of this paper, the following research questions will guide our systematic literature review:

- RQ1: "Which onboard emission measurement systems are used to obtain real-world GHG emissions of inland vessels?"
- RQ2: "How are GHG emissions calculated for inland vessels, if no real-world/test data are available?"
- RQ3: "Which measures are discussed for the reduction in GHG emissions on vessels in inland navigation?"

The paper is organized as follows. After the introduction, we proceed with the methodology employed for the literature review in Section 2. Section 3 entails a descriptive, thematic, and content analysis of the identified literature. The results are deliberated in Section 4, and additional research requirements are outlined. The conclusions of this paper are encapsulated in Section 5.

2. Materials and Methods

The method used in this study was a systematic literature review (SLR), following the approach of Liberati et al. [12]. The SLR is a well-established methodology to map and assess the existing knowledge and gaps on specific issues. It deviates from conventional narrative reviews by embracing replicable, scientific, and transparent processes. This method aids in gathering all relevant publications and documents that align with our pre-defined inclusion criteria, facilitating the addressing of specific research questions [13]. Our review was carried out between May 2023 and February 2024 using six topic-relevant databases: Scopus, Science Direct, Emerald Collections, EBSCO Business Source Elite, IEEE, and Google Scholar. The keywords used in the databases in the first round were "inland waterway" OR "inland navigation" OR "inland vessel" OR "inland ship*" AND "greenhouse gas*" OR "CO_2*" AND "calculati*" OR "measure*" OR "reduction". In the second round we employed the keywords "inland navigation" OR "inland waterway" OR "inland vessel" OR "inland ship*" AND "carbon accounting" OR "carbon footprint" OR "onboard emission test" OR "portable emission measurement system" OR "CO_2 emission factor".

The precise search queries for the meta-analysis are provided in Table 1.

Table 1. Databases, metadata searched, and search strings used.

Database	Searched Metadata	Search String (First Round)	Search String (Second Round)
Scopus	Title, abstract, keyword	TITLE-ABS-KEY (“inland navigation” OR “inland waterway” OR “inland vessel” OR “inland ship*”) AND TITLE-ABS-KEY (“greenhouse gas*” OR “CO_2*”) AND TITLE-ABS-KEY (“calculati*” OR “measure*” OR “reduction”)	TITLE-ABS-KEY (“inland navigation” OR “inland waterway” OR “inland vessel” OR “inland ship*”) AND TITLE-ABS-KEY (“carbon accounting” OR “carbon footprint” OR “onboard emission test” OR “portable emission measurement system” OR “CO_2 emission factor”)
Science Direct	Title, abstract, keyword	(“inland navigation” OR “inland waterway” OR “inland vessel” OR “inland ship”) AND (“greenhouse gas” OR “CO_2”) AND (“calculate” OR “measure” OR “reduction”)	(“inland navigation” OR “inland waterway” OR “inland vessel” OR “inland ship”) AND (“carbon accounting” OR “carbon footprint” OR “onboard emission test” OR “portable emission measurement system” OR “CO_2 emission factor”)
Emerald Collections	Title, abstract	((title: “inland navigation” OR title: “inland vessel” OR title: “inland waterway” OR title: “inland ship”) OR (abstract: “inland waterway” OR abstract: “inland vessel” OR abstract: “inland ship” OR abstract: “inland navigation”)) AND ((title: “greenhouse gas*” OR title: “CO_2*”) OR (abstract: “greenhouse gas*” OR abstract: “CO_2*”)) AND ((title: “calculat*” OR title: “measure*” OR title: “reduction”) OR (abstract: “calculat*” OR abstract: “measure*” OR abstract: “reduction”))	((title: “inland navigation” OR title: “inland vessel” OR title: “inland waterway” OR title: “inland ship”) OR (abstract: “inland waterway” OR abstract: “inland vessel” OR abstract: “inland ship” OR abstract: “inland navigation”)) AND ((title: “carbon accounting” OR title: “carbon footprint” OR title: “onboard emission test” OR title: “portable emission measurement system” OR title: “CO_2 emission factor”) OR (abstract: “carbon accounting” OR abstract: “carbon footprint” OR abstract: “onboard emission test” OR abstract: “portable emission measurement system” OR abstract: “CO_2 emission factor”))
Ebsco Business Source Elite	Title, abstract, subject terms	((TI inland navigation OR SU inland navigation OR AB inland navigation) OR (TI inland waterway OR SU inland waterway OR AB inland waterway) OR (TI inland ship OR SU inland ship OR AB inland ship) OR (TI inland vessel OR SU inland vessel OR AB inland vessel)) AND ((TI greehouse gas* OR SU greenhouse gas* OR AB greenhouse gas*) OR (TI CO_2* OR SU CO_2* OR AB CO_2*)) AND ((TI calculat* OR SU calculat* OR AB calculat*) OR (TI reduction OR SU reduction OR AB reduction) OR (TI measure* OR SU measure* OR AB measure*))	((TI inland navigation OR SU inland navigation OR AB inland navigation) OR (TI inland waterway OR SU inland waterway OR AB inland waterway) OR (TI inland ship OR SU inland ship OR AB inland ship) OR (TI inland vessel OR SU inland vessel OR AB inland vessel)) AND ((TI carbon accounting OR SU carbon accounting OR AB carbon accounting) OR (TI carbon footprint OR SU carbon footprint OR AB carbon footprint) OR (TI onboard emission test OR SU onboard emission test OR AB onboard emission test) OR (TI portable emission measurement system OR SU portable emission measurement system OR AB portable emission measurement system) OR (TI CO_2 emission factor OR SU CO_2 emission factor OR AB CO_2 emission factor))

Table 1. *Cont.*

Database	Searched Metadata	Search String (First Round)	Search String (Second Round)
IEEE	Title, abstract	((“All Metadata”:inland navigation) OR (“All Metadata”:inland vessel) OR (“All Metadata”:inland ship) OR (“All Metadata”:inland waterway)) AND ((“All Metadata”:greenhouse gas) OR (“All Metadata”:CO_2)) AND ((“All Metadata”:calculate) OR (“All Metadata”:reduction) OR (“All Metadata”:measure))	((“All Metadata”:inland navigation) OR (“All Metadata”:inland vessel) OR (“All Metadata”:inland ship) OR (“All Metadata”:inland waterway)) AND ((“All Metadata”:carbon accounting) OR (“All Metadata”:carbon footprint) OR (“All Metadata”:onboard emission test) OR (“All Metadata”:portable emission measurement system) OR (“All Metadata”: CO_2 emission factor))
Google Scholar	Title, keyword	(((intitle:inland waterway OR keyword:inland waterway) OR (intitle:inland navigation OR keyword:inland navigation) OR (intitle:inland vessel OR keyword:inland vessel) OR (intitle:inland ship OR keyword:inland ship) AND ((intitle:greenhouse gas OR keyword:grennhouse gas) OR (intitle:CO_2 OR keyword:CO_2)) AND (intitle: calculat* OR keyword: calculat*) OR (intitle: reduction OR keyword: reduction) OR (intitle: measure* OR keyword: measure*)))	(((intitle:inland waterway OR keyword:inland waterway) OR (intitle:inland navigation OR keyword:inland navigation) OR (intitle:inland vessel OR keyword:inland vessel) OR (intitle:inland ship OR keyword:inland ship)) AND ((intitle: carbon accounting OR keyword:carbon accounting) OR (intitle:carbon footprint OR keyword:carbon footprint) OR (intitle:onboard emission test OR keyword:onboard emission test) OR (intitle:portable emission measurement system OR keyword:portable emission measurement system) OR (intitle: CO_2 emission factor OR keyword:CO_2 emission factor)))

The search provided 102 results. Table 2 shows the numbers of results for each of the databases used.

Table 2. Results of the literature search in each database.

Database	Scopus	Science Direct	Emerald Collections	Ebsco Business Source Elite	IEEE	Google Scholar
Number of studies	76	14	1	10	0	1

We incorporated three additional sources identified through alternative sources. The initial 105 results underwent systematic refinement by excluding duplicates (16). Articles not in English (2) and those lacking peer review (4) were omitted, along with publications without freely accessible full-text versions (6). After analyzing the abstracts, we excluded publications that did not align with our research questions (47). The remaining articles underwent a comprehensive assessment. Out of the 32 publications assessed in full, 13 were excluded due to content misalignment with our research questions. The literature review resulted in 17 papers focusing on inland vessels concerning GHG emission calculation, reduction, or measurement, which are further explored in this study. The flow chart in Figure 1 illustrates the entire review process, following the approach by Liberati et al. [12].

Descriptive and thematic analyses were conducted on the remaining 17 studies. The results and discussion of these analyses are presented in the next section.

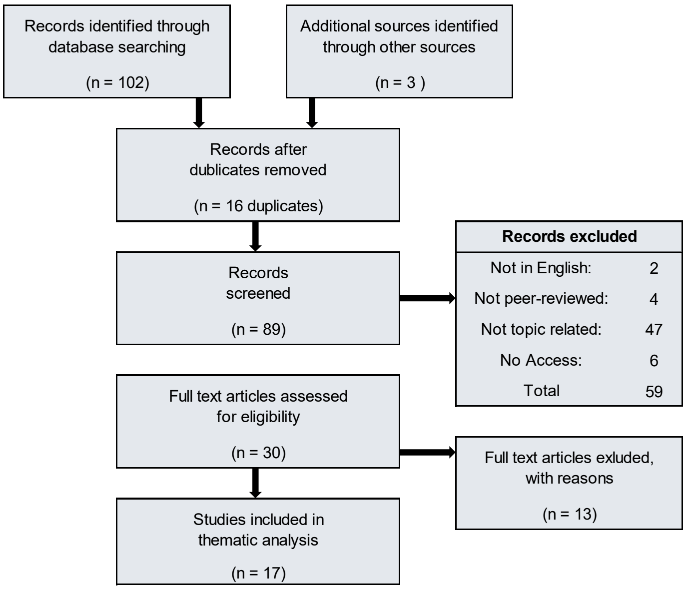

Figure 1. Review procedure within this literature review.

3. Results

The literature review is divided into three sections. The first section presents research papers about onboard GHG emission measurement systems, while the second section presents research studies about the calculation of greenhouse gases for inland vessels and the third part deals with measures to reduce greenhouse gas emissions. Table 3 displays the comprehensive list of studies incorporated in this literature review, detailing their respective subjects and the regions under investigation. Nine out of seventeen studies were conducted in Asia and seven studies were realized in Europe. It is noticeable that no studies have North American, South American, Australian, or African origins.

3.1. Onboard GHG Emission Measurement Systems

In the following section, RQ1 "Which onboard emission measurement systems are used to obtain real-world GHG emissions of inland vessels?" is answered by examining the findings presented in four papers.

Wang et al. [14] described the research on the method of onboard emission tests. They refer to various studies that have measured emissions from vessels, focusing primarily on NOx, PM, VOC, THC, CO, and SO_2. Their conclusion highlighted the scarcity of Chinese research that specifically addresses the emission profiles of inland vessels with different engine types and model years, indicating a significant gap in this area of study. Their research examined the emission levels of 50 different vessels in China while they were actively sailing. They used a portable emission monitoring system (PEMS) to measure various vessel emissions, including carbon dioxide (CO_2), carbon monoxide (CO), total hydrocarbons (THC), particulate matter (PM), and nitrogen oxides (NOx). The PEMS consisted primarily of a SEMTECH-DS gas analyzer from the Sensor Company in the USA. The SEMTECH-DS gas analyzer specifically measured CO and CO_2 levels using the non-dispersive infrared (NDIR) technique. Their findings and conclusions focused mainly on the emissions of CO, THC, NOx and PM.

Jiang et al. [15] conducted a comparison between test data and model-calculated data to assess the precision of emission models based on the Automatic Identification System (AIS). Real-world emissions of CO_2, CO, HC, and NOx were measured from nine inland vessels utilizing a PEMS. The test system integrated a SEMTECH-DS gaseous pollutant analyzer from SENSORS, USA, with the detection of CO and CO_2 performed using NDIR. Furthermore, an emission model based on the Automatic Identification System (AIS) was utilized to project emissions from the examined inland vessels. The results indicated that, in the case of CO_2, the overall average ratios of test data to model-calculated data were

2.66 when engine loads were below 60%. During upstream cruise mode, the average CO_2 emission rates from the real-world test were observed to be between 1.91 and 6.48 times higher than those derived from the AIS-based model. Conversely, in downstream cruise mode, these rates showed a narrower range, being only 1.08 to 1.51 times higher than the predictions made by the AIS-based model.

The paper from Yang et al. [16] employed a PEMS to assess gaseous pollutants in various vessels, including oceangoing, harbor, offshore, and inland vessels. The PEMS setup comprised a navigation parameter recording system, a gaseous pollutant analysis system, and PM collection equipment. SEMTECH-DS, from Sensors USA, facilitated real-time measurement of contaminant concentrations (CO_2, CO, NO, NO_2, and THC). The detection of CO and CO_2 was carried out using NDIR. Fuel-based emission factors were determined through these on-board measurements across diverse vessel types and operating modes, offering foundational data for vessel emission studies.

Wang et al. [17] noted that while some researchers have measured emission factors from vessels in China, there is a scarcity of studies on gaseous and particulate pollutants from inland vessels, compared to offshore and oceangoing vessels. Therefore, they focused on quantifying fuel-based emission factors for gaseous pollutants and PM emitted by an inland cargo ship on the Huangpu River during daily operations. On-board measurements were conducted using a PEMS, with the main component being the Horiba OBS-2200 (On-Board Emission System 2200). Gaseous pollutants, such as CO, CO_2, THC, and NOx, were directly measured from the tube using a probe connected to the Horiba OBS-2200, employing a NDIR for CO and CO_2 concentrations.

In summary, the investigation into onboard emission measurement systems for real-world GHG emissions from inland vessels indicates the use of either a PEMS equipped with a SEMTECH-DS gas analyzer from the Sensor Company in the USA or a PEMS featuring a Horiba OBS-2200. The detection of CO_2 was carried out using NDIR.

3.2. Calculation of GHG Emissions in Inland Navigation

We found five studies dealing with the energy efficiency design index (EEDI) for new vessels and/or the energy efficiency existing ship index (EEXI) for existing vessels [18–22]. The International Maritime Organization (IMO) has developed the EEDI with the overarching objective of reducing CO_2 emissions as the first step towards shipping decarbonization.

The EEDI mandates a minimum energy efficiency level per capacity mile (e.g., ton mile) for various vessel types and size categories. Calculated through a formula based on the technical design parameters of a specific vessel, this benchmark is slated to undergo incremental tightening every five years. Consequently, the EEDI is anticipated to drive ongoing innovation and technical advancements across all components influencing the fuel efficiency of a vessel from its design phase.

Existing vessels of 400 GT and above are required to calculate their EEXI, which reflects the "technical" or "design" efficiency of the vessel and must meet a "required EEXI". Ship owners or charterers can choose the most suitable means to fulfill these IMO regulatory objectives. Existing technologies available to satisfy the required EEXI encompass engine/shaft power limitation, waste heat recovery, wind-assisted propulsion, and other viable alternatives [23,24].

Simić and Radojcic [20] presented an attempt to calculate the EEDI for inland self-propelled dry cargo vessels and to establish EEDI baselines for new vessel designs. They developed a mathematical model for the power evaluation of self-propelled inland vessels. Moreover, they recommend a procedure for more precise determination of propulsive coefficients, based on the findings of full-scale measurements.

Karim and Hasan [19] attempted to propose EEDI baseline for inland vessels. They calculated CO_2/ton mile for cargo vessels and oil tankers and verified these data with data measured and calculated in different methods by several world-recognized research organizations. The comparison showed that the calculated result ranges are mostly consistent with the existing results. It is important to highlight that the existing results are calculated for inland vessels of different countries (mostly European). The differences observed in the results are largely attributed to varying geographical conditions and the effective technical strategies implemented by European countries, among other factors.

In Hasan and Karim [21], they addressed the differences in conditions for inland vessels in contrast to maritime vessels (like shallow and restricted water effects, different fuel quality, reduction in speed, increase in engine power, and reduction in carrying capacity) to calculate the EEDI for inland cargo vessels in Bangladesh.

In Hasan and Karim [18], they proposed an EEDI baseline for inland vessels in Bangladesh. Their investigations and field studies found that the actual measurement varies from the available inland ship data in several government organizations. The main differences are observed in the principal particulars, the power of the main and auxiliary engines, and the design speed. These variations in vessel information have a significant impact on the EEDI values. Therefore, vessel data should be verified to find the correct data. Accurate data regarding the emitted CO_2, vessel speed under service conditions, and the deadweight capacity are essential to determine the EEDI value for a vessel. They described different CO_2 estimation methods (the carbon balance method, activity-based approach, and stoichiometric method (energy-based approach)) and their effectiveness. Using verified vessel physical and operational data, EEDI baselines have been proposed for Bangladesh's inland cargo, oil tanker, and passenger vessels.

Kalajdžić et al. [22] attempted to compile and offer a review of endeavors aimed at establishing energy efficiency criteria for inland vessels. Moreover, a typical Danube cargo inland vessel's data are used to evaluate their current energy efficiency levels with respect to provisional criteria. Two approaches adapted from the IMO energy efficiency framework specifically for inland vessels were used. These methodologies showed significant differences in their applicability and posed challenges in comparison. The final results showed inconsistencies in the energy efficiency ratings for identical vessels, indicating a need for further refinement and standardization of the methodology.

Fan et al. [25] investigated the carbon footprints of inland vessels from both a micro and macro perspective, introducing a comprehensive life cycle perspective on CO_2 emissions from vessels. Throughout the vessel's life cycle, carbon emissions from the WTT and TTW phases constituted 89.48–95.15% of their total emissions. Emission factors were calculated using data from the GREET® 2021 database and other studies.

3.3. Reduction in GHG Emissions in Inland Navigation

Pauli [26] outlined strategies aimed at diminishing fuel or energy consumption, consequently reducing air emissions. These strategies are categorized into technical aspects of the vessel, vessel operation, measures pertaining to the design and equipment of vessel engines (engine internal measures and exhaust after treatment), adoption of alternative energy sources (methane, biofuels, synthetic fuels, hydrogen, electricity), infrastructure improvements, and transport management measures. The technical aspects are optimization of vessel design, resistance reduction, weight reduction, optimization of conventional propulsion systems, diesel–electric propulsion, hybrid propulsion, more efficient or alternative propulsion organs, energy recovery, and energy efficient equipment.

Pauli and Boyer [8] provide an overview of the current regulations and standards applicable to various technologies. These technologies, which have a technology readiness level (TRL) of 5 or higher, are potential solutions for reducing carbon emissions of inland vessels. The technologies described are stage V diesel, liquefied natural gas (LNG), stage V hydrotreated vegetable oil (HVO), liquefied biomethane (LBM), battery electric propulsion systems, hydrogen stored in liquid or gaseous form, and used in fuel cells (H_2 FC), hydrogen stored in liquid or gaseous form and used in internal combustion engines (H_2 ICE), methanol used in fuel cells (MeOH FC), and methanol used in internal combustion engines (MeOH ICE). They determined that for the technical requirements of vessels, essential standards for the implementation of LNG, hydrogen, methanol, and electric batteries are either already in draft form or currently being developed. In terms of policies and crew-related requirements, the necessary efforts are planned in the respective work programs, though they are still in the stage of assessing needs. Moreover they mention a study from Ushakov et al. [27] where on-board measurements indicate that marine engines using LNG show a significant methane slip, especially at low loads, which are typical for the operation of inland vessels. Therefore, opting for LNG to reduce pollutant emissions may result in higher greenhouse gas (GHG) emissions compared to conventional diesel engines.

Hasan and Karim [28] focused on the possibility of CO_2 emissions reduction in inland oil tankers in Bangladesh by implementing a revised EEDI formulation (=$EEDI_{INLAND}$). They performed a sensitivity analysis for the different vessel design parameters of oil tankers and made suggestions for the design of inland oil tankers in Bangladesh for reducing CO_2 without any major cost involvement. The computational fluid dynamics (CFD) analysis of those redesigned vessels using 'Shipflow' demonstrated a decrease in CO_2 emissions through increasing $EEDI_{INLAND}$ by 7.54–13.65%.

Litwin et al. [29] investigated the efficiency of a parallel diesel–electric hybrid propulsion system across two modes of operation (electric and diesel) considering various engine speeds and loads. The impact of employing a hybrid propulsion system on fuel consumption was analyzed using a case study vessel and six actual journeys. In the case of the analyzed vessels, the power demand at 7 km/h was more than seven times lower than at the economic speed of 13 km/h. The utilization of hybrid propulsion in the electric engine operation mode enabled achieving up to a fourfold increase in the drive's energy efficiency while reducing CO_2 emissions. However, attention should be directed to the notable rise in power demand as a function of speed, particularly beyond 13 km/h. To reach the maximum speed (set as 15 km/h) the power of the propulsion system must increase twice, leading to a substantial rise in fuel consumption and, consequently, a significant increase in exhaust emissions.

The study conducted by Lebkowski [30] answered the question "To what extent will the use of different configurations of hybrid systems, affect the reduction in fuel consumption and reduce poisonous gases to the atmosphere?" by modelling and vessel simulation. The simulation shows that a lower energy consumption can be seen with respect to the diesel–propeller (DP) drive in the diesel–battery–electric–propeller (DBEP) and diesel + LNG–battery–electric–propeller drives (DLBEP) (−13.1%), along with diesel–electric–propeller (DEP) and diesel + LNG–electric–propeller (DLEP) drives (−9.3%). At the same time, the emissions of CO_2 into the atmosphere decreased relative to the DP drive, respectively: DLBEP by 29.2%; DLEP by 26.2%; diesel + LNG-Propeller (DLP) by 18.6%; DBEP by 13.1%; DEP by 9.3%.

Perčić et al. [31] summarized the literature for alternative fuels in shipping and mentioned that the possibility of applying alternative fuels in inland navigation has not been adequately investigated. Therefore, they undertook a technical, environmental, and economic analysis of alternative fuels (electricity, methanol, LNG, hydrogen, ammonia, and biodiesel) to reduce the environmental footprint of inland navigation. The adoption of ship electrification (using Li-ion batteries) stands out as the most environmentally friendly choice for each evaluated vessel, achieving a potential reduction in carbon emissions of up to 51%.

Evers et al. [32] focused on the carbon footprint of hydrogen-based maritime propulsion systems, emphasizing inland cargo shipping. Their three-step approach included a literature review, harmonization of studies for comparability, and in-depth analyses. The results indicated that maritime fuel drivetrains relying on renewable energy-based electrolysis or carbon capture and storage can notably decrease carbon footprints, attaining around 10–30 k tons of CO_2 over a vessel's lifespan. Conversely, hydrogen production through electrolysis with a grid electricity mix substantially escalates emissions compared to the diesel scenario and is advised against.

Table 4 summarizes the reduction strategies of GHG emissions in inland navigation.

Table 3. Studies included in this literature review, their subjects, and regions.

Study	Authors	Year	Journal	Subject	Country
Carbon footprint model and low-carbon pathway of inland shipping based on micro–macro analysis	Fan et al. [25]	2023	*Energy*	Calculation	Asia
Regulation for the decarbonization of IWT in Europe	Pauli et al. [8]	2022	*Sustainability*	Emission reduction	Europe
Energy efficiency design index baselines for ships of Bangladesh based on verified ship data	Hasan and Karim [18]	2022	*Climate Policy*	Calculation	Asia
Comparison of inland ship emission results from a real-world test and an AIS-based model	Jiang et al. [15]	2021	*Sustainability*	Measurement and Calculation	Asia
Proposed inland oil tanker design in Bangladesh focusing CO_2 emission reduction based on revised EEDI parameters	Hasan and Karim [28]	2020	*J. Mar. Sci. Eng.*	Emission reduction	Asia
Revised energy efficiency design index parameters for inland cargo ships of Bangladesh	Hasan and Karim [21]	2020	*J. Eng. Marit. Environment*	Calculation	Asia
Experimental research on the energy efficiency of a parallel hybrid drive for an inland ship	Litwin et al. [29]	2019	*Energies*	Emission reduction	Europe
Reduction of fuel consumption and pollution emissions in inland water transport by application of hybrid powertrain	Lebkowski [30]	2018	*Energies*	Emission reduction	Europe
Establishment of EEDI baseline for inland ship of Bangladesh	Karim and Hasan [19]	2017	*Procedia Engineering*	Calculation	Asia
On energy efficiency of inland waterway self-propelled cargo vessels	Simić and Radojčić [20]	2013	*FME Transaction*	Calculation	Europe
Evaluating an inland waterway cargo vessel's energy efficiency indices	Kalajdžić et al. [22]	2022	*Polish Maritime Research*	Calculation	Europe
Analysis of ship emission characteristics under real-world conditions in China	Wang et al. [14]	2019	*Ocean Engineering*	Measurement of emissions	Asia
Techno-economic assessment of alternative marine fuels for inland shipping in Croatia	Perčić et al. [31]	2021	*Renewable and Sustainable Energy Reviews*	Emission reduction	Europe
Carbon footprint of hydrogen-powered inland shipping: Impacts and hotspots	Evers et al. [32]	2023	*Renewable and Sustainable Energy Reviews*	Emission reduction	-

Table 3. *Cont.*

Study	Authors	Year	Journal	Subject	Country
Real-world emission characteristics of Chinese fleet and the current situation of underestimated ship emissions	Yang et al. [16]	2023	*Journal of Cleaner Production*	Measurement of emissions	Asia
Quantification of gaseous and particulate emission factors from a cargo ship on the Huangpu River	Wang et al. [17]	2023	*J. Mar. Sci. Eng.*	Measurement of emissions	Asia
Emissions and inland navigation	Pauli [26]	2016	Book: *Green Transportation Logistics*	Emission reduction	Europe

Table 4. Summary of reduction strategies per literature review.

Reduction Strategies	Source
Stage V diesel	Pauli and Boyer [8]
Liquefied natural gas (LNG)	Pauli and Boyer [8], Perčić et al. [31], Pauli [26]
Stage V hydrotreated vegetable oil (HVO)	Pauli and Boyer [8]
Liquefied biomethane (LBM)	Pauli and Boyer [8], Pauli [26]
Battery electric propulsion systems	Pauli and Boyer [8], Perčić et al. [31]
Hydrogen	Pauli and Boyer [8], Perčić et al. [31], Evers et al. [32], Pauli
Methanol	Pauli and Boyer [8], Perčić et al. [31]
Vessel design	Hasan and Karim [28], Pauli [26]
Diesel electric propulsion system	Litwin et al. [29], Lebkowski [30], Pauli [26]
Diesel–battery–electric–propeller	Lebkowski [30]
Diesel + LNG–battery–electric–propeller	Lebkowski [30]
Diesel + LNG–electric–propeller	Lebkowski [30]
Biodiesel	Perčić et al. [31]
Ammonia	Perčić et al. [31]
Energy recovery	Pauli [26]
Energy efficient equipment	Pauli [26]

4. Discussion

Measuring actual emissions from inland vessels is challenging due to several factors. These include the variety of vessel types, sizes, and auxiliary engines (varying in installed power and speed, with or without after-treatment systems), different hull designs, and propulsion systems that affect hydrodynamic drag. External conditions, such as current wind direction, draft, keel clearance, and varying loads and speeds, also play a significant role. Unfortunately, the large number of parameters affecting a vessel's emission performance has resulted in only a few monitoring projects in inland navigation over the past decade [33]. This might also explain why only four studies focusing on obtaining real-world GHG emissions of inland vessels were identified. All four studies took place in Asia and utilized a PEMS. The PEMS included a SEMTECH-DS gas analyzer from the Sensor Company in the USA or a Horiba OBS-2200. The detection of CO_2 was carried out using an NDIR (non-dispersive infrared detector).

The need to reduce emissions from freight transport activities increases the necessity of acquiring knowledge on actual emissions as the basis for actionable improvements and effective policies. Policymakers should allocate funds and resources to support research initiatives similar to PROMINENT and the IWT Footprinting project, encouraging on-board measurements and data collection for a diverse range of vessels. In PROMINENT, a project funded through the Horizon 2020 program, on-board measurements were conducted for a total of 12 cargo vessels. Information was gathered on certain aspects, such as fuel consumption and emissions, focusing on representative vessels and journeys [34]. The other project is the IWT Footprinting project ("Meten op Schepen"). The project was initiated by Topsector Logistics in the Netherlands to measure and record important parameters and outputs in the reality of inland shipping, focusing both on CO_2 emissions and air pollutant (NOx). Twenty vessel owners allow their vessels to be equipped with sensors and telematics to record and share their data for at least one year. The results of this project should be published soon [33]. Encouraging the sharing of data encompassing fuel consumption, emissions, and operational parameters is essential to foster a more comprehensive comprehension of emissions in inland navigation. Furthermore, it is crucial to acknowledge the varied conditions across different regions and customize research efforts to tackle specific challenges encountered by inland vessels and to take into account external factors, such as river conditions, vessel types, and navigation constraints to offer recommendations tailored to each region. In conclusion, it is imperative for policymakers, industry stakeholders, and researchers to prioritize efforts in collecting data pertaining to greenhouse gas emissions from inland vessels.

Another possibility to obtain an understanding of the GHG emissions of a vessel is via calculation. One objective of calculating GHG emissions is to generate estimates that are uniform, transparent, and comparable across all modes of transportation, operators, commodities, supply chains, and geographical regions [10]. The quality of calculated emissions and emission intensities and their subsequent use in corporate reporting and logistics emissions reduction decision making, depends on the availability, specification, quality, and exchange of data [9]. The availability of data for inland vessels is scarce [2] and requires qualitative and quantitative improvement [10]. Policymakers should invest in initiatives that improve the quality and quantity of data available for inland vessels. They could encourage collaboration between stakeholders to create a centralized and accessible database for emissions-related data.

In our literature review, we found five studies dealing with the EEDI and/or EEXI and only one study [24] focusing on the carbon footprints of inland vessels, using emission factors utilizing data sourced from the GREET® 2021 database and additional research. When reviewing the 105 papers, we noticed that some of them deal with the calculation of greenhouse gases for so-called emission inventories for a specific area or river section. However, we did not include these papers in our research, as they attempt to calculate the fuel consumption of many vessels and obtain an average, and our focus in this paper is on the exact determination of the GHG of individual vessels.

The third focus in our study answered the question "Which measures are discussed for the reduction of greenhouse gases in inland navigation?". The review on countermeasures for CO_2 emissions from ships from Xing et al. [35] revealed that several researchers have presented decarbonization options for shipping in recent years. They divided the potential measures for shipping CO_2 emissions reduction into technical measures (propulsion efficiency, ship resistance, and marine power plants), operational measures (voyage optimization, supply chain and logistics, slow steaming, cold ironing, optimized maintenance, and human factors), eco-friendly fuels (biofuels, LNG, synthetic fuels, and carbon capture and storage) and alternative power sources (wind energy, solar energy, nuclear energy, and fuel cells). Despite the range of different reduction measures in the shipping sector, we found only seven studies dealing with the reduction in GHG emissions in inland navigation. These measures were ship design, stage V diesel, LNG, stage V hydrotreated vegetable oil (HVO), liquefied biomethane (LBM), battery electric propulsion systems, hydrogen stored in liquid or gaseous form and used in fuel cells (H2 FC), hydrogen stored in liquid or gaseous form and used in internal combustion engines (H2 ICE), methanol used in fuel cells (MeOH FC) and methanol used in internal combustion engines (MeOH ICE), diesel–electric hybrid propulsion system, diesel–battery–electric-propeller (DBEP) and diesel + LNG–battery–electric–propeller drives (DLBEP), diesel–electric–propeller (DEP), diesel + LNG–electric–propeller (DLEP), methanol, hydrogen, ammonia, biodiesel, energy recovery, and energy-efficient equipment. Focusing the literature review on eco-friendly fuels or alternative power sources may result in more papers. Raftis et al. [36] scrutinized 23 papers within the domain of alternative fuels and power sources, determining that LNG and electric batteries emerge as the most viable alternatives. Hydrogen and photovoltaic (PV) solutions were proposed as alternatives in six studies. However, they also emphasize that the research in this field is not extensive, and the number of papers is limited compared to similar investigations in other transportation modes and maritime vessels.

5. Conclusions

The goal of this literature review was to identify (1) onboard GHG emission measurement systems, (2) calculation methods for GHG emissions of inland vessels, and (3) reduction measures. As a result of the literature review, we identified 17 relevant studies. Four of the identified studies dealt with onboard GHG emission measurement systems, five with calculation methods for the GHG emissions of inland vessels, and eight with reduction measures. The systematic literature review shows that research in this area is limited. In terms of geographic coverage, all papers reviewed focused on effects in Europe or Asia. Notably, none of the papers reviewed addressed impacts in North America, Africa, Australia, or South America. The identified research gap highlights the importance of conducting comprehensive studies in these regions to enhance the global understanding of inland waterway transport's environmental impact. Therefore, future research should aim to broaden the geographical scope of investigations on GHG emissions from inland vessels.

The literature review showed that for GHG emission measurements, portable emission test systems are in use, which consist of a SEMTECH-DS gas analyzer and use an NDIR (non-dispersive infrared detector) to detect CO_2. Since these methods involve significant investments, future research should also explore whether there are more efficient and calibrated approaches to provide real-time insights into the CO_2 performance of inland vessels.

In the section on calculating GHG emissions, there are several papers that attempt to adapt the EEDI or EEXI to inland navigation. By implementing EEDI and EEXI in inland navigation, the industry can not only align itself with global efforts to reduce GHG emissions, but also promote sustainable practices that optimize fuel consumption and minimize environmental impact. The literature review also shows that the core topics of papers focusing on reduction measures for GHG emissions are alternative fuels, like LNG, methanol, hydrogen, ammonia, and biodiesel or fuel cells.

By providing insights into these aspects, the paper not only serves to inform but actively contributes to the progression of knowledge, filling critical gaps, and offering practical solutions. It empowers stakeholders to make informed decisions, guides further research endeavors, and ultimately supports the ongoing efforts towards sustainable practices in inland navigation. Nevertheless, in our systematic literature review, we acknowledge several limitations that present avenues for further research. Despite our efforts to ensure transparency in the search, selection, and validation processes, an inherent level of subjectivity remains. The scope of our findings is confined to the specific search strings used and the limited number of relevant journal publications identified. We think it is important to include the terms CO_2, greenhouse gases, GHG, or carbon dioxide in the search strings, because many studies just deal with NOx and Sox emissions. The literature review from Bouman et al. [37], which provides a comprehensive overview of the potential and measures to reduce CO_2 emissions from shipping, concludes that studies that consider stricter regulations on NOx and SOx emissions in ECAs rarely focus on the impact on CO_2 emissions or the overall GHG effect. Moreover, they found several authors who reported an increase in CO_2 equivalent emissions as a function of stricter NOx and SOx regulations.

A further step should be to include projects and studies in the literature search. Their reports could provide valuable input, especially in topics that are very practical. An example of such a report is "Decarbonization of the inland waterway sector in the United States" from Dundon et al. [38].

Given the unique challenges and complexities associated with inland navigation, scientific papers addressing GHG emissions in this context can provide valuable insights and solutions. By delving into the intricacies of GHG measurement, calculation methodologies, and reduction strategies tailored to inland navigation, researchers can contribute to the development of effective and targeted solutions. Comprehensive studies can help to bridge existing knowledge gaps, inform policymakers, and guide industry stakeholders toward implementing practical measures that align with global environmental objectives. Prioritizing this topic in academic discourse is not only essential for advancing our understanding but also imperative for shaping a resilient and environmentally conscious future for inland navigation.

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