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Review

Decarbonizing Seaport Maritime Traffic: Finding Hope

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Abstract: The maritime transport industry contributes around 3% to worldwide CO_2 emissions, with 2023 emissions projected to be approximately 58 billion tons. Consequently, to attain decarbonization objectives, the implementation of effective reduction measures in maritime operations, especially at seaports as significant contributors, is essential. On the other hand, seaport operations are categorized into two main areas: land logistics, encompassing cargo handling, storage, customs processing, and inland transportation, and maritime logistics, which includes vessel traffic management, berth allocation, cargo loading and unloading, and fuel and maintenance services. While land logistics' decarbonization has been extensively studied, maritime logistics operations, accounting for about 60% of port CO_2 emissions, remain underexplored. Their progress relies on regulations, cleaner fuels, and digital solutions; yet high costs and slow adoption pose significant challenges. As a result, this study employed PRISMA-ScR methodology to select relevant research resources and validate global reports from international organizations, enhancing transparency and providing practitioners and experts with a comprehensive analysis of seaport maritime emissions, as well as decarbonization initiatives. This study analyzes the future trajectory of the initiative based on current data, evaluating its potential benefits and systematically reviewing recent literature. It explores decarbonization strategies in maritime operations, emphasizing regulations, cleaner fuels, and digital solutions while highlighting challenges such as high costs and slow adoption. Key issues examined include maritime border delineation, infrastructure constraints, technological advancements, regulatory barriers, and the opportunities that decarbonized seaports offer to ports and their surrounding regions.

Keywords: maritime; ports; decarbonization; logistics; sustainability; shipping

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1. Introduction

Approximately 80% of all international products are transported by sea. However, this vital economic activity has a significant environmental cost, particularly greenhouse gas (GHG) emissions. Conversely, the maritime sector, which transports the mentioned volume of international transport, emits 3% of world GHGs, or over one billion metric tons of carbon dioxide (CO_2) [1].

Big maritime vessels utilize high-sulfur fuels, generating large amounts of sulfur dioxide (SO_x) and nitrogen dioxide (NO_x), worsening acid rain and coastal air quality. As a result, ports are impacted by high emissions from ship movement, cargo loading, and unloading, and seaport regions, the heart of maritime logistics and transport operations, are under immediate threat from these emissions, necessitating urgent action [2].

On the other hand, the need to decarbonize maritime operations has lately emerged as a critical objective in the worldwide fight against climate change, in which politicians, environmental groups, and maritime sector experts play a vital and decisive role [3]. This is due to global duties and coastal ecosystem and community protection. According to the International Maritime Organization (IMO), international shipping GHG emissions must be reduced by at least 50% by 2050 compared to 2008, underlining the need for global cooperation on this problem [4,5].

On the other hand, the mentioned emissions have serious environmental and health effects. Climate warming threatens seaport infrastructure and nearby residents by raising sea levels and causing extreme weather. Maritime activities pollute the air, causing respiratory illnesses, cardiovascular diseases, and higher mortality rates around ports. These locations' poor air quality increases healthcare costs and lowers millions of people's quality of life [6,7].

Furthermore, these emissions have socioeconomic effects that require port area decarbonization. Many coastal economies rely on tourism, fishing, and agriculture, which are sensitive to environmental degradation, and marine pollution threatens them. Poor air quality may deter tourists from coastal cities, while pollution and ocean acidification harm marine ecosystems and fisheries. Environmental neglect may reduce productivity, raise healthcare costs, and burden local governments and businesses with long-term consequences [8,9].

As a result, by using the PRISMA-ScR literature review method, the authors of this study investigate the decarbonization of seaports, explicitly focusing on marine traffic and associated concerns within port limits. This analysis study's "*primary objective*" is to evaluate the current state of maritime traffic decarbonization within seaport boundaries, identify the challenges and solutions presented in the existing literature, and analyze the process using available evidence and statistics, alongside briefly numerating opportunities provided by these decarbonizations for the seaports, and finally present a resealable and logical answer for the main question of the research based on worldwide evidence.

The "*research gap*" refers to the shortage of prior studies on maritime logistics activities in the seaport operations that consider the state of the literature while ignoring fresh contributions. It also refers to a broad and general classification of maritime decarbonization challenges inside port boundaries rather than particular case studies and delimitation issues. It also pays particular attention to maritime traffic and specific seaports' maritime delimitation. The "*target audience*" comprises academics, stakeholders, and professionals within the logistics and maritime sectors. The "*novelty of issue*" refers to delineating maritime borders under international standards, using contemporary literature to categorize information and interpret it to figure out the current status and present explicit answers to the main research question.

This section examines the theoretical basis of seaport and maritime emissions within seaport boundaries. Section 3 outlines the research methodology, while Section 4 presents the literature's findings and categorizes the associated challenges. Section 5 analyses and interprets these findings, highlighting opportunities for decarbonization. The final section concludes with the primary outcomes, limitations of the study, and recommendations for future research in the same or related fields.

2. Literature Review

This section addresses general information regarding maritime operations and current ship–port interface measures aimed at seaport decarbonization. Ship–port interaction is essential for maritime transport logistics and operations. Shipping encompasses berthing, unberthing, loading, unloading, fueling, and maintenance at this interface. This inter-

action has notable environmental implications, especially concerning emissions, energy consumption, and overall efficiency. The IMO and the EU have observed that transitioning to more sustainable ship–port interfaces contributes to global climate change mitigation and promotes greener economic objectives [10,11].

On the other hand, a substantial portion of the CO_2 emissions produced by the transportation business are attributed to seaports, as stated by Statista. Maritime transportation is responsible for 12% of the total CO_2 emissions that the transportation industry produces. According to the sub-sector, the distribution of carbon dioxide emissions produced by the transportation industry worldwide in 2022 is depicted in Figure 1 [12].

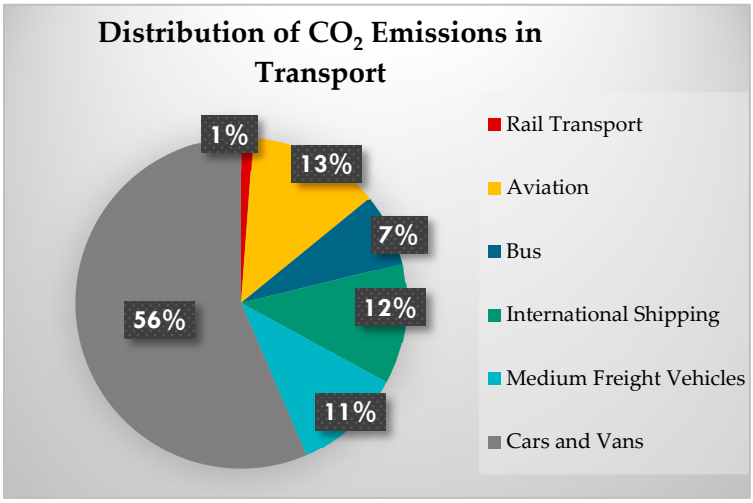


Figure 1. Distribution of CO_2 emissions produced by the transportation sector worldwide in 2022. Source: [12].

This study addresses maritime emissions within seaport boundaries. However, before discussing pollution from maritime traffic in seaports, it is essential to outline two categories of maritime traffic within port limits. The initial category of maritime traffic emissions relates to Scope One emissions, as outlined by ISO 14064 [13]. This category includes emissions from vessels such as pilot boats, tugboats, and service boats managed by the port authority. Research indicates that this segment accounts for less than 1.5%, thus falling outside the focus of this study [14].

The second portion belongs to Scope Three emissions (as defined by ISO 14064), which arise from maritime traffic not directly managed by the port authority but indirectly supervised by it [13]. Moreover, this portion is divided into two subsections: the first addresses emissions from vessels like tugboats, service boats, and other vessels utilized for service purposes by concessionary companies within seaport maritime boundaries, while the second pertains to vessels in commercial cargo transportation. The second group is the subject of this study, and evidence indicates that they contribute to almost 60% of entire seaport emissions [14].

For example, Valencia Port, an EcoPort member and European benchmark port, provides a good framework for assessing port emissions. Recent data from this port authority reveal that Scope 3 emissions constituted over 97% of the port's total emissions in prior years, escalating to 99% in 2021 and 2022 [15,16]. Additionally, the authors of this study undertook a distinct study in 2023 that focused on this port as a case study. The study revealed that marine traffic (which belongs to the second group of Scope 3) accounted for about 56% of the total Scope 3 emissions [14]. Considering Valencia Port's position in the EcoPort network, these data provide a significant reference that may be utilized by other ports in Europe, facilitating broader generalizations on port emissions.

This example shows the significance of maritime traffic emissions inside port boundaries and the importance of mitigating them. Figure 2 shows the share of maritime traffic and emission scopes calculated based on ISO 14067 in the port of study mentioned [14].

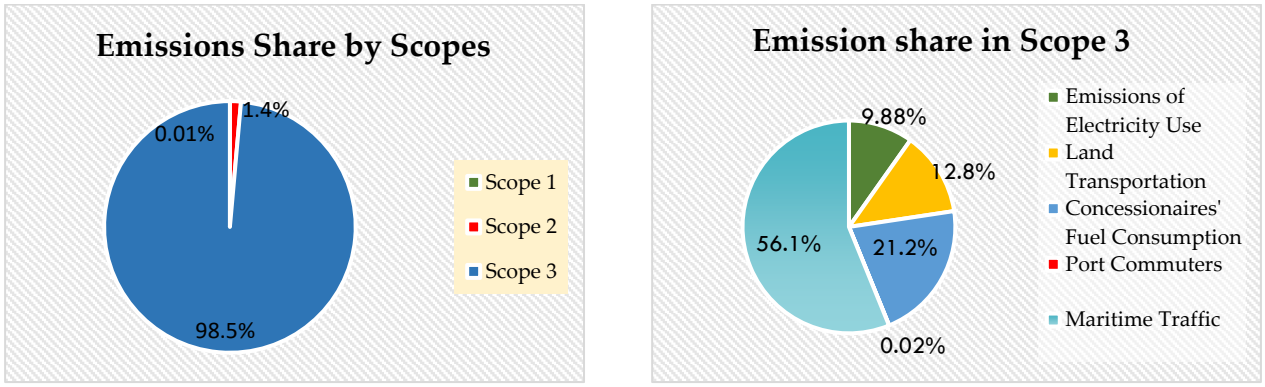


Figure 2. Emission share and maritime traffic share in the port of Valencia. Source: [14].

Moreover, according to a study by the International Transportation Forum, shipping emissions inside ports are drastically increasing and must be cut down. Figure 3 shows the trend anticipating the emission share of shipping inside seaport areas up to 2050 [17]. In this figure, the anticipated emissions are shown for each gas separately: CH_4 is Methane, CO is Carbon Monoxide, CO_2 is Carbon Dioxide, NO_x is Nitrogen Oxides (generic term for nitrogen monoxide (NO) and nitrogen dioxide (NO_2)), PM_{10} is Particulate Matter (particles with diameters of 10 µm or less), $PM_{2.5}$ is Particulate Matter (particles with diameters of 2.5 µm or less), and SO_x is Sulfur Oxides (generic term for sulfur dioxide (SO_2) and sulfur trioxide (SO_3)).

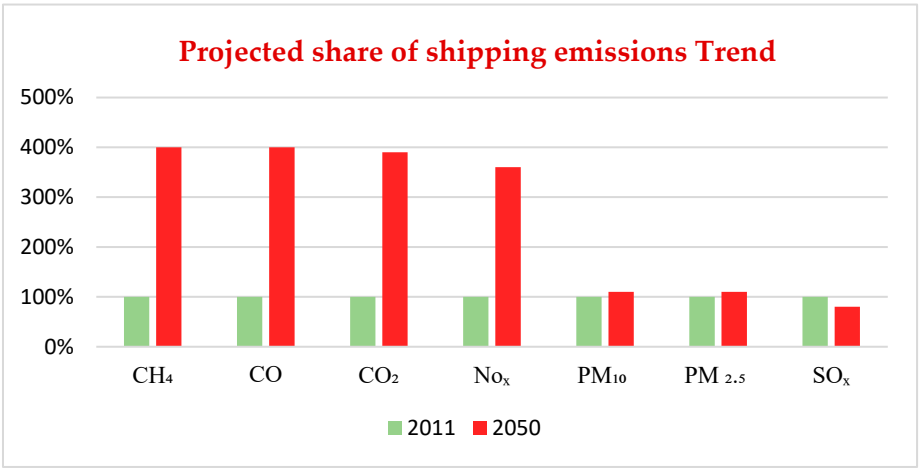


Figure 3. Projected share of shipping emissions in seaports from 2011 to 2050. Source: [17].

In addition, the maritime industry is pursuing innovative strategies to mitigate environmental impact. An established method involves utilizing alternative and cleaner marine fuels such as liquid natural gas (LNG), hydrogen, or ammonia in place of conventional heavy fuel oil (HFO) to reduce emissions [18–20]. Enhancing energy efficiency is a primary focus, with advancements such as hybrid propulsion systems, air lubrication, and optimized hull designs contributing to reduced fuel consumption and emissions. Shore-to-ship electricity, known as cold ironing (CI), enables vessels to connect to the power grid during docking, decreasing the dependence on onboard power generators. Moreover, the automation and digitalization of operations present considerable opportunities for reducing

fuel consumption [18]. On the other hand, many studies underscore the assessment of alternative fuels' economic, environmental, and regulatory impacts, emphasizing the need for stronger international collaboration [21].

Decarbonization at the ship–port interface involves improving operating processes and embracing new technologies. Onshore power supply (OPS), or CI, is a significant interaction metric [22,23]. This technology lets vessels link to the port's electrical grid instead of using fuel oil for lighting, refrigeration, and communication. Shore-to-ship electricity from renewable energy may eliminate moored vessel emissions [24].

This is particularly significant given that vessels are often moored for prolonged durations, and inactive engines may significantly increase emissions inside port boundaries. In addition, studies suggest that shore-to-ship electricity may reduce GHG emissions by up to 98% in ports using renewable energy for their electrical requirements [25]. For example, for ships docking at the Port of Los Angeles, which launched CI technology, vessel emissions have dropped by 95% [26].

Improving port operations and logistics is another key to ship–port decarbonization. Digitalization and automation improve maritime operations, cargo management, and other port activities, reducing emissions due to shorter hoteling duration, etc., [27,28]. Digital technologies that enhance ship arrival timings and port scheduling may decrease waiting periods, too. This would enable vessels to navigate at reduced speeds (a method referred to as slow steaming) and lower their emissions both at sea and in port [29].

In addition to scheduling optimization, port facilities automation may reduce emissions and can operate instead of vessel cargo handling facilities. Diesel engines power port cranes, trucks, and container handlers, causing GHG emissions and air pollution. If vessels at the dock can use CI, ports may reduce fossil fuel use and improve operational efficiency by powering and automating this equipment [30,31].

For instance, the Port of Rotterdam and Singapore have invested in automated electric cranes and trucks to decarbonize. This has reduced emissions and increased port throughput, showing that decarbonization may support economic objectives [32,33].

Additionally, decarbonization relies on ship–port fueling too. LNG, hydrogen, and ammonia replace HFO, requiring new bunkering infrastructure and fuel logistics. The maritime industry is transitioning to LNG, which emits less GHG than HFO [34]. However, various ports with LNG bunkering facilities facilitate this shift. LNG is greener than traditional marine fuels, but widespread use may lock the shipping industry into decades of fossil fuel use [35]. Thus, ports must establish hydrogen and ammonia infrastructure, becoming zero-carbon fuels. Both fuels can be decarbonized long-term since they release no GHGs. Hydrogen and ammonia infrastructure is new and requires significant investment to build production and delivery networks [36].

On the other hand, carbon capture and storage (CCS) systems might reduce ship–port emissions from petroleum-powered vessels in the short to medium term. CCS involves sequestering CO_2 emissions at the combustion source, compressing the gas, and then storing it underground or reusing it in industrial applications. CCS has mainly been studied for terrestrial power plants, but current research suggests it may be used on maritime ships [37].

Several ports are exploring the use of CCS to decarbonize by changing ships to capture or collect emissions while moored. However, CCS technology is unlikely to be widely used due to the high cost and logistical challenges of storing and moving carbon. As technology develops and costs fall, CCS may cut shipping and port carbon emissions [38,39].

The ship–port interaction is also critical for energy efficiency in the maritime transport chain. Retrofitting vessels with more efficient engines and propellers, improving hull design to minimize drag, and using waste heat recovery systems may enhance energy

efficiency [40]. Ports may encourage these practices by rewarding shipping firms that use energy-efficient systems. Some ports have green port fees that discount ships that satisfy environmental criteria or utilize low-emission fuels. These programs reward sustainable shipping practices and encourage corporations to invest in cleaner technology and decarbonize the sector [41]. The methodology for collecting and filtering relevant literature is briefly presented in the following section.

3. Methods

This research was performed as a scoping evaluation review of mitigating maritime traffic emissions in seaports. It included a study and analysis of the background and contemporary literature about the primary topic of this work, formulated following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses in Scoping Reviews (PRISMA-ScR). It aims to assist readers in comprehending the pertinent language, fundamental principles, and essential elements to report for scoping reviews. The stages and methods include "Identification", "Screening", "eligibility", and "inclusion", as seen in Figure 4. The stages included the following tasks:

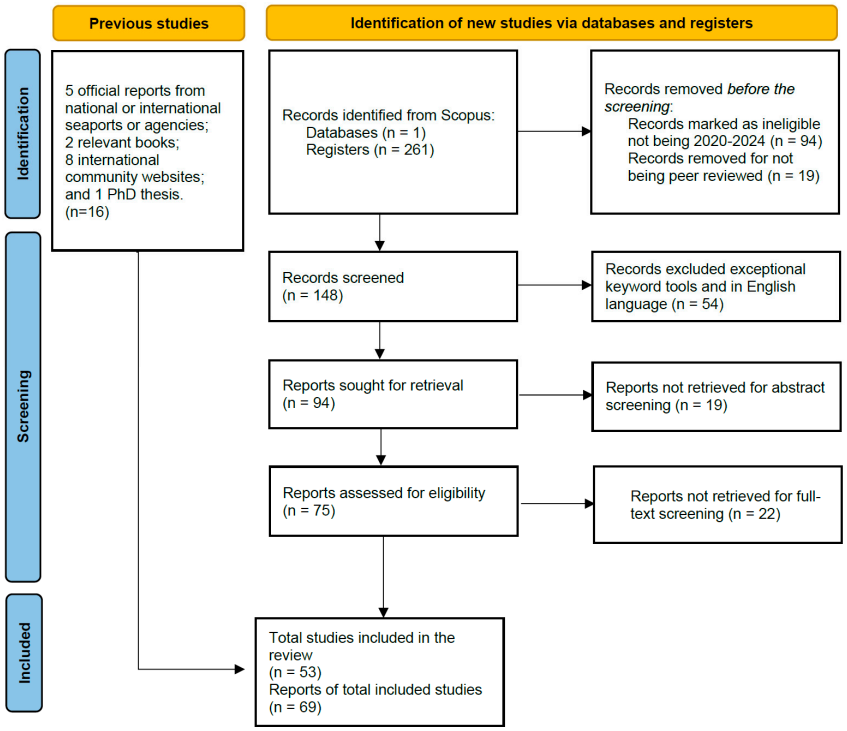


Figure 4. PRISMA framework for the systematic literature review.

- **Identification**: Conducting a search inside the "Scopus" database with a combination of keywords, namely "carbon footprint" OR "decarbonization" OR "GHG emission" OR "CO_2 emission" AND "port" OR "seaport" OR "maritime" OR "marine", yielded a total of 261 results.
- **Screening**: These processes are interconnected, as a singular or combination of eligibility issues arise at each screening phase. This refinement was predicated on publication from 2020 to the conclusion of 2024 and involved removing records that were not peer-reviewed or were in preprint (to get superior input only from contemporary and recent research). It included only peer-reviewed studies, resulting in 148 study kinds.
- **Eligibility**: This process involved establishing exclusion criteria, specifically limiting studies to those on seaport decarbonization. Only English language studies were included. A second-round keyword screening of abstracts initially reduced the number

of studies to 54. Following this, an abstract screening filtered it down to 19 studies, which were then subjected to full-text evaluation, further narrowing the selection to 22 studies. Ultimately, the remaining research could address the study questions and demonstrate sufficient scientific rigor. As a result of this filtering process, 53 research articles were identified.

- **Inclusion**: This section comprises five official reports from national or international seaports or entities, two pertinent books related to the subject, eight websites belonging to various international communities utilized for their statistics and data, and one PhD thesis with related data, which contributed 16 sources. In addition, the last stage of research culminates in 69 references. The whole filtering technique is shown in Figure 4.

4. Findings

This section examines the challenges associated with mitigation efforts to decarbonize maritime and shipping activities at seaport borders. It draws on the existing literature and analyzes pertinent data regarding the ship–port interface in these locations, which are based on classifications from the filtered literature. On the other hand, the high density of maritime operations inside seaport borders exacerbates this environmental issue, especially in densely populated coastal regions where air pollution and GHG emissions significantly impact public health, biodiversity, and climate change. Given the increasing global demand to diminish emissions and fulfill the objectives established by the international unions, the author tried to classify challenges in the decarbonization of maritime traffic in seaports based on the 69 references, which can be seen in Figure 5:



Figure 5. Maritime decarbonization challenges inside port boundaries.

Before addressing the physical challenges of the seaport's decarbonization process, the authors recognized the need to thoroughly examine a key theoretical challenge: the geographical delimitation of the area deemed relevant for decarbonization efforts. The exploration of this topic unfolds in the following subsection.

A. Delimitation of seaport maritime boundary for emission assessment

As a vessel approaches a port, it may either utilize anchorage or intend to enter the port for specific operations. Depending on the mission, entering and exiting the port can be divided into various activities. Figure 6 illustrates a simplified flowchart to facilitate the understanding of emissions associated with each segment. Because all emissions in this process are due to the existence of the seaport, l emissions from the "START" point to the "SAILING" point are considered as ports' maritime traffic emissions (Scope 3).

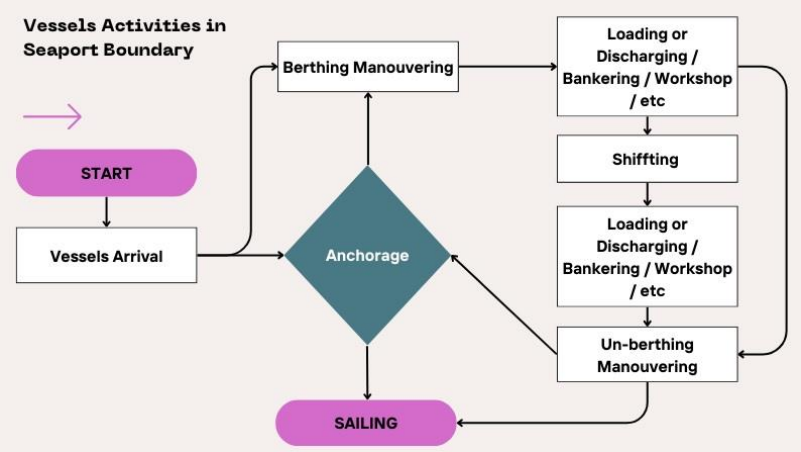


Figure 6. Vessel activity in the seaport boundary (own authorship).

As decarbonization and GHG reduction become more important, the ship–port interaction is a crucial area for intervention. Decarbonization at this stage of the maritime logistics chain may have significant environmental advantages by lowering vessel emissions. This study identifies emissions from all three steps of anchorage: maneuvering, berthing, unberthing, etc. In each part, vessels can potentially have significant emissions, so emission mitigations must be applied.

One of the challenges of decarbonizing maritime traffic inside seaport areas is determining seaport maritime boundaries to evaluate emissions inside this boundary, comparing the current situation with other ports or the same port in different timeframes, and assessing decarbonization initiatives. Conversely, it has been determined that current publications address emissions from maritime traffic in ports; moreover, they need to clearly delineate the borders of the port within which activities will be studied [42].

According to Article 11 of the United Nations Convention on the Law of the Sea (UNCLOS), as established by the Division for Ocean Affairs and the Law of the Sea (DOALOS) in 1983 [43], "the port boundary is defined as the outermost permanent harbor works that constitute an integral component of the harbor system, which are considered part of the coast to delineate the seaport sea. Offshore installations and artificial islands must not be considered permanent harbor structures", which determines the land-based boundary of a seaport [43].

On the other hand, the control and jurisdiction system in the anchorage area is delineated in UNCLOS Article 12, "Roadsteads", while the access channel is examined in Article 22, "Sea lanes and traffic separation schemes in the territorial sea", and Article 25, "Rights of protection of the coastal State". These articles assert that both port anchorage areas and access channels are subject to the control and jurisdiction of the coastal state, which may be regarded as a port authority. Furthermore, according to Article 212 of UNCLOS, entitled "Pollution from or through the atmosphere", the coastal state has the authority to implement and oversee air pollution regulations within its jurisdiction and control [43].

According to these definitions and regulations, a vessel's entire stay (from START to SAILING step in Figure 6), including using anchorage areas and access channels, is considered part of the seaport area for emission concerns and relevant issue considerations; hence, emissions generated by maritime traffic within these regions should also be regarded as part of seaport emissions.

The logical use of an anchoring area, access channel, and any adjacent river to the port is contingent upon the presence of the port, and this interpretation, including the implications of these emissions, is entirely accurate. In this regard, delineating a seaport's maritime boundary is crucial, as it significantly influences the outcomes of emission calculations.

This, in turn, affects the attention, policies, strategies, priorities, and financial allocations that port authorities and other relevant entities dedicated to the specified port.

B. Infrastructure Upgrades

The transition to decarbonizing maritime traffic within port borders requires significant infrastructural changes. Shore power facilities CI are crucial to this change. Retrofitting older ports to handle shore power takes tremendous cost and electrical capacity, especially in unsuitable ports [44,45].

Port electrification includes shore power and infrastructure upgrades for electric and hybrid vessels. This involves installing charging stations and energy storage devices to meet demand. Research suggests that entirely powered ports might strain local systems, particularly if renewable energy is favored to avoid negating emissions savings by using fossil fuels. To accommodate electric ships and port gear, ports must consider grid stability and capacity development [46].

Ports must modernize their infrastructure to handle hydrogen, ammonia, LNG, and electricity. Most ports need more specific storage and bunkering facilities for these fuels. Retrofitting ports to allow these fuels requires substantial capital and continuous maintenance, which may be costly for smaller port authorities.

C. High Costs of Alternative Fuels

Hydrogen, ammonia, and biofuels cost far more than HFO or marine diesel. Hydrogen, primarily renewable hydrogen, needs a substantial amount of energy to manufacture. Ammonia, a viable alternative, has comparable issues because of its energy-intensive Haber-Bosch manufacturing process. These manufacturing expenses increase the cost of marine fuel adoption [47].

In addition, adopting alternative fuels demands significant port infrastructure investment. Since their fueling systems are intended for traditional fuels, ports must develop new facilities to accept hydrogen and LNG. This comprises fueling stations, storage tanks, and hazardous material safety systems. To accommodate various shipping needs, ports must retrofit or create new fueling hubs for numerous fuel types, which requires significant capital investment [48].

Alternative fuels need to be adapted or constructed in new ships. To mitigate dangers, ships fueled by hydrogen or ammonia require specific engines, fuel tanks, and safety measures. Retrofitting older vessels may be too costly or impractical. Also, alternative fuels have lower energy density than traditional fuels. Therefore, more ships are required to go the same distance. This reduces cargo space and threatens shipping companies' profitability [49].

D. Shore Power Availability

CI, or shore power, enables ships to connect to the port's electrical grid and switch off their auxiliary engines when docked, lowering pollution. Shore electricity is scarce at many ports, especially in developing countries. High infrastructure expenses, particularly for renovating older ports, hamper it. To meet decarbonization targets, ports need stable and ideally renewable power [50]. Furthermore, electricity supply and demand variability make shore power availability difficult. Large ships require a lot of electricity when docked. However, many locations' power grids are inadequate [50].

Shore power adoption regulations differ by area. The EU requires shore power for bigger vessels at important ports by 2030, but many countries need more legislation or incentives. Without consistent worldwide rules and financial incentives, ports may not prioritize the large expenditure required to modernize their electrical infrastructure, prolonging the shift to universal shore power [51].

E. Regulatory Gaps

The fragmented local, national, and worldwide regulatory framework hinders port decarbonization. The IMO has set high decarbonization objectives, including a 50% decrease in GHG emissions by 2050, but ports lack a clear and globally applicable framework to accomplish them. Ports' regulatory frameworks vary by region and government, making decarbonization strategies inconsistent [52].

Moreover, port decarbonization policies differ by country, with some imposing strict emissions limitations and others having fewer. The EU Emissions Trading Scheme (ETS) for shipping reduces carbon emissions. However, it does not extend internationally, and countries outside the EU may not have matching frameworks. Cross-border regulation is essential to closing these disparities [53].

The maritime industry's delayed adoption of low-emission technology limits the worldwide fleet of decarbonized vessels. Most ships use fossil fuels like HFO, which increases port emissions. Despite the IMO goal of reducing GHG emissions by 50% by 2050, retrofitting ships is expensive, and alternative propulsion systems like hydrogen fuel cells and battery-powered vessels are slow to develop. Thus, the scarcity of decarbonized vessels hinders maritime emission reductions, particularly in port regions [53].

F. Limited Decarbonized Vessels

Retrofitting or replacing ships is expensive and complicated, which hinders decarbonization. Retrofitting older vessels to operate on ammonia or biofuels may be prohibitively costly, so shipowners are hesitant to spend until they know which technologies will become industry standards. The need for experimental technology also limits the implementation of zero-emission ship and machinery buildings. The sluggish fleet transformation makes it difficult for ports to fulfill decarbonization objectives [54].

In addition, decarbonized vessels need to adapt faster due to port infrastructure gaps for alternative fuels. Shipowners are cautious about investing in green technology without enough infrastructure since running such vessels is unpredictable. The worldwide fleet of decarbonized ships is too tiny to meaningfully reduce port emissions, delaying the transition to sustainable maritime commerce [55].

G. Coordination Challenges

Decarbonizing maritime transportation inside port borders requires several players with different interests and skills, making coordination tricky. This procedure relies on port authorities, shipping businesses, logistics providers, fuel suppliers, and government organizations. However, their different agendas and budgetary limits sometimes prevent cooperation. Shipping corporations may not invest in greener technology if ports lack infrastructure. However, ports are reticent to improve without industry demand. The "chicken-and-egg" dilemma makes decarbonization coordination challenging [56]. Furthermore, the fragmented regulatory environment adds complexity. Ports must follow local, national, and international emission and environmental rules. Due to inconsistent decarbonization regulations, ports tackle green projects differently [57].

Energy suppliers, shipping corporations, and port managers must work together to embrace alternative fuels and new technology, yet they frequently have opposing goals. Green energy options like hydrogen or ammonia-fueling stations must be safe and cost-effective. Shipping corporations may also emphasize operational efficiency above environmental concerns. Coordinating such systems involves significant investment and industry standards, which have been challenging to develop [57].

H. Technological risk

Lack of maturity in crucial technologies is a significant challenge in decarbonizing maritime traffic within port borders. Despite their potential, hydrogen fuel cells, ammonia engines, and electric propulsion systems are currently being developed. These technologies have performance, scalability, and safety issues. Early adoption risks investing in technologies that may not become industry standard or be replaced by more efficient options [58].

Moreover, due to rapid technological innovation, ports may use outmoded technology. Global decarbonization ambitions drive fast technical innovation in the shipping and maritime sectors. Early LNG infrastructure expenditures are being reviewed as ammonia and hydrogen technologies gain success. Rapid technological change needs port authorities to be adaptable, but it also makes long-term investments questionable [59].

I. Safety concern

A significant safety issue with decarbonizing maritime traffic inside ports is the flammability and explosiveness of alternative fuels like hydrogen and ammonia. Hydrogen has a broad flammability range and little ignition energy, but ammonia is poisonous and corrosive, complicating handling and storage [60]. In addition, the storage and transportation of alternative fuels, especially in substantial quantities for maritime applications, present considerable safety difficulties.

As a result, managing such fuels in congested port settings necessitates stringent safety protocols and exceptionally trained staff to avoid mishaps [60]. To mitigate safety issues related to alternative fuels, ports must establish stringent procedures and monitoring systems. At the same time, specialized storage facilities should revise their regulatory frameworks and engage in comprehensive staff training programs [61].

J. Economic Competitiveness

Ports that use decarbonization technology often encounter elevated operating expenses. These costs may elevate shipping businesses' charges, rendering decarbonized ports less competitive than conventional ports dependent on fossil fuels. As a result, ports may forfeit market share to others that have not yet implemented sustainable procedures, particularly if shipping businesses emphasize immediate financial gains above environmental concerns [62].

On the other hand, the economic competitiveness of decarbonized ports is contingent upon regional and national legislation. Ports in nations with stringent environmental standards may get financial assistance or subsidies to mitigate the expenses associated with green infrastructure. Conversely, ports in areas with less rigorous environmental regulations may have less pressure to decarbonize, resulting in an inequitable competitive landscape. The competitiveness of decarbonized ports is significantly influenced by the legislative framework and the global shipping industry's transition toward sustainability [62].

5. Discussion

This research acknowledges issues such as inadequate and opaque statistics, discrepancies in marine macroeconomic data, and low transparency from authorities, while also noting that most studies focus on land logistics inside seaports, rendering maritime data less accessible. The lack of a uniform approach for delineating seaport borders hampers GHG emissions predictions, resulting in contradictory conclusions. Notwithstanding these constraints, this study has compiled and classified pertinent data to facilitate a discourse on the prospects arising from the decarbonization of marine trade inside port limits. This part will present a concentrated examination of the prospects of decarbonization in seaport maritime traffic, utilizing information from current projects and worldwide records.

5.1. Opportunities

Decarbonizing ports presents several obstacles, yet it offers various opportunities that significantly benefit ports and their adjacent areas. Decarbonization should be seen not as a challenging transition but as an opportunity for innovation, development, and integration into sustainable maritime supply chains. On the other hand, opportunities stemming from maritime traffic emissions mitigations at seaports may be classified into four primary categories: Technological Innovation, Policy and Regulatory Frameworks, Economic Opportunities, and Environmental Sustainability. Each of these domains provides unique avenues for reducing emissions while improving the efficiency and sustainability of seaports. Figure 7 shows this classification:

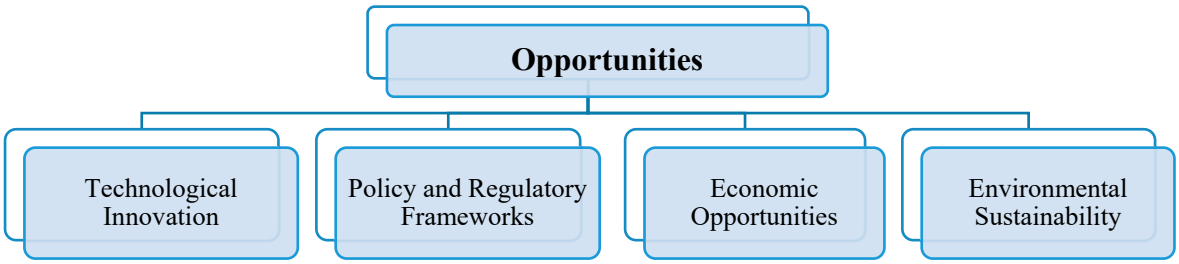


Figure 7. Maritime traffic emissions in seaport opportunities.

Technological innovation offers a significant pathway for reducing maritime and shipping transportation emissions and enhancing seaport efficiency. Innovations that mitigate emissions provide ecological advantages, enhance operational efficiency, and provide long-term cost savings. The electrification of port operations, CI, LNG, and hydrogen fuels, as well as automation and intelligent technologies, might be categorized as subcategories of this group.

Conversely, exemplary instances of Policy and Regulatory Frameworks include IMO regulations, Emission Control Areas (ECAs), national and regional policies, and public–private partnerships. Additionally, regarding economic opportunities, the subcategories include green ports as economic hubs, new markets for clean technologies, incentives for shipping companies, and efficiency gains and cost savings.

Ultimately, Environmental Sustainability may include subcategories such as air quality improvement, contributions to national and international climate goals, marine ecosystem protection, and circular economy and resource efficiency. The following is an overview of the main opportunities that decarbonization offers for seaports:

Improved Air Quality and Public Health: Decarbonization initiatives that diminish CO_2 emissions often result in the concomitant reduction of other deleterious GHG pollutants and volatile organic compounds. These enhancements enhance air quality and public health in adjacent areas, providing substantial socio-environmental advantages.

Access to Global Green Markets: As regulators and consumers increasingly evaluate ports, there is a rising preference for those dedicated to sustainability. By adopting decarbonization practices, ports can effectively address these demands, positioning themselves to profit from the increasing global green market. This transition can ensure ports maintain relevance in a changing industry landscape influenced by climate-conscious logistics.

Enhancing Competitiveness: Implementing decarbonization strategies enables ports to enhance their competitive advantage by cultivating a sustainable, environmentally friendly reputation. Ports that proactively decrease emissions will appeal to shipping companies and clients who value environmental stewardship. This "sustainable profile" might serve as a significant advantage in a market increasingly influenced by regulatory constraints and customer aspirations for sustainability.

Job Creation and Economic Growth: Decarbonization initiatives, including investments in renewable energy (wind, solar, marine, etc.), research and development, and sustainable technologies, can generate new employment opportunities in the port region. This transition to green industries fosters economic growth and establishes ports as pivotal participants in sustainable business ecosystems.

Contributing to Zero-Emission Value Chains: Numerous ports, particularly those in developing countries, can facilitate the development and distribution of zero- and near-zero-emission technology, renewable fuels, and sustainable energy sources for the maritime sector. Through engagement in these value chains, seaports may reduce transportation expenses and enhance the frequency of vessel arrivals while contributing to the global decarbonization initiative [63].

International Support and Mitigating Barriers: Global efforts led by entities like the IMO and the EU provide technical and financial assistance to aid ports in addressing the challenges of decarbonization. This global support assists ports, particularly in developing areas, in overcoming obstacles such as substantial initial expenses.

Financial Incentives for Developing Countries: Ports in economically disadvantaged countries may benefit from international financial systems, including the IMO's Market-Based Measures (MBMs), the EU's Emissions Trading System (ETS), subsidies, and grants. These incentives may alleviate the financial strain of decarbonization while including emerging ports in the global green business network [64].

Energy Security: Ports undertaking energy decarbonization initiatives may simultaneously tackle energy supply security challenges. The ongoing energy crisis in Europe, intensified by world crises such as the Ukraine–Russia war and the COVID-19 epidemic, has underscored the need for energy independence. Ports incorporating renewable energy into their operations are more adept at navigating future energy crises and securing long-term energy resilience.

In the final analysis, decarbonization is essential for environmental sustainability and presents an opportunity for ports to improve their competitiveness, stimulate economic development, and integrate into global green supply chains. By conforming to global decarbonization initiatives and using available resources, ports may significantly contribute to the sustainable development of the maritime sector [65].

5.2. Is There Potential for Sustainable Progress of the Seaports' Maritime Traffic Decarbonization?

Maritime traffic emissions at seaports have become a significant worry regarding global climate change and environmental damage. The present difficulty arises from the significant dependence on fossil fuels such as HFO and marine diesel oil, which are heavily used in port operations and by vessels when docked. In heavily populated port cities, these emissions may significantly degrade air quality and public health, worsening respiratory conditions and contributing to climate change.

Many seaports use conventional fossil-fuel energy sources, and vessels consume fuel while anchored, maneuvering, or docked, resulting in considerable emissions. The port infrastructure in several regions globally is insufficient to facilitate more sustainable options. Moreover, the inefficiency of port operations, including prolonged idle periods for vessels awaiting docking, intensifies emissions. Notwithstanding increased awareness, regulatory frameworks addressing port emissions remain disjointed, exhibiting inconsistent enforcement standards across different countries.

The EU Green Deal (2021) set a target of 90% emissions reductions for EU port cities by 2050, and the revised IMO strategy (2023) aims to significantly curb GHG emissions from international shipping, which can also help decarbonize maritime traffic in port boundaries.

The new targets include a 20% reduction in emissions by 2030, a 70% reduction by 2040 (compared to 2008), and achieving net-zero emissions (NZE) by 2050 [66,67].

Conversely, the recent report from the International Energy Agency (IEA) indicates that attaining the specified objectives necessitates an approximate 15% reduction in emissions from 2022 to 2030, presenting a formidable challenge considering the global circumstances following recovery from the COVID pandemic and other recent crises. Furthermore, as seen in Figure 8, which depicts CO_2 emissions from shipping between 2001 and 2023 and includes scientific projections for 2030, the anticipated CO_2 output in 2030 is around 605 MT [68].

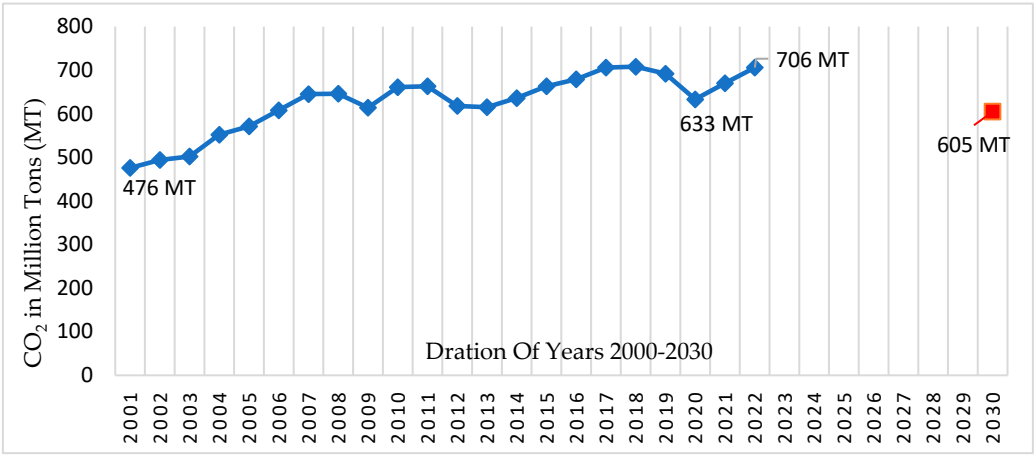


Figure 8. CO_2 emission from international shipping trend. Source: [68].

Moreover, based on the IEA's anticipation, the share of five main types of fuels in shipping, including fossil fuel, biofuel, hydrogen, ammonia, and methanol, will be as follows at the end of 2050, which is the next step of net zero emission scenario for international shipping [69]. The vertical axis unit in Figure 9 is the Exajoule, which is one EJ equivalent to 10^{18} joules.

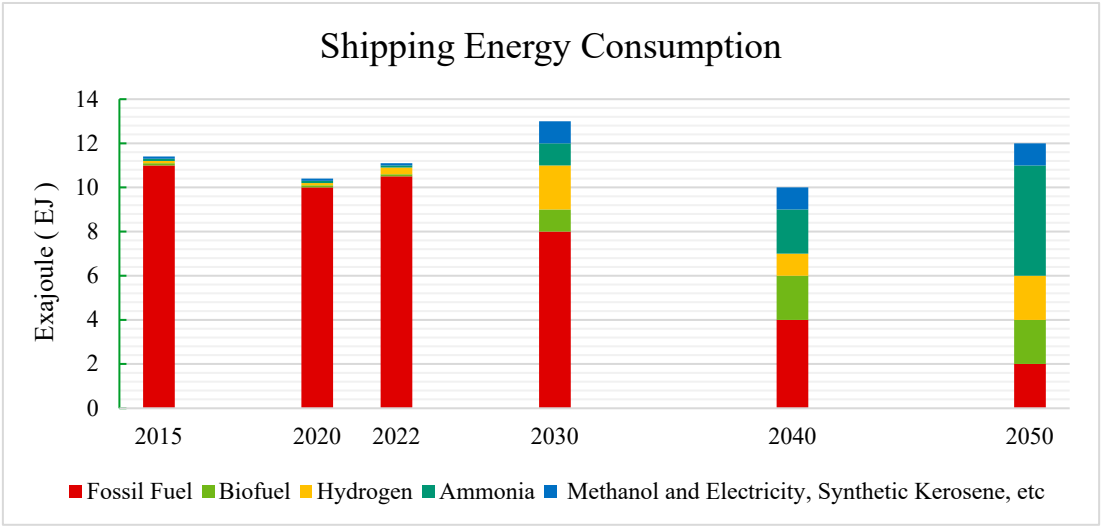


Figure 9. Shipping energy consumption from 2015 to 2050. Source: [69].

As shown, fossil fuel consumption in 2050, under the net-zero emission scenario, is projected to remain above 2 EJ. When applying the average carbon emission factor for marine fuels, approximately 77.4 kg CO_2 per GJ according to IPCC guidelines, this level of consumption could result in nearly 154.8 million tonnes of CO_2 emissions. Seaports, func-

tioning as critical nodes in maritime transport, also play a significant role in contributing to these emissions [69].

However, specific ports have initiated proactive measures, although these initiatives focus on affluent areas with access to modern technology and financial resources. Prominent ports, such as Rotterdam, Los Angeles, and Singapore, have invested in CI and alternative fuels; nonetheless, worldwide adoption rates are inconsistent. The electrification of port operations, including electric cranes and trucks, has shown potential but is still in the nascent phase of extensive deployment. Moreover, present decarbonization initiatives are obstructed by insufficient worldwide standards and the substantial expenses of upgrading existing vessels and port facilities.

Considering the trends in decarbonization, relevant data, and updates on plans and regulations from international organizations such as the IMO and the EU Commission, it is clear that the process is not progressing as expected. Nonetheless, the journey toward realizing these objectives is fraught with challenges. Recent worldwide economic tensions, conflicts in several regions, and unforeseen and substantial inflation have impeded the funding of green initiatives for numerous countries and regions. This highlights the essential significance of global economic stability in the efficacy of our decarbonization initiatives.

Indeed, we can comprehend the developments in maritime decarbonization and seaports, as maritime stakeholders may benefit from these initiatives. Nevertheless, the response to the question, "***Is there potential for sustainable progress of the seaport maritime traffic decarbonization?***" is ***DEFINITELY NEGATIVE*** unless the global economy advances and enables developing countries and disadvantaged areas to fund the shift to sustainable practices, while prioritizing an understanding of sustainability challenges over political, military, and strategic considerations by all governments worldwide.

6. Conclusions

This research review concentrated on decarbonizing maritime traffic within seaport boundaries by employing novel parameters for delineating seaports. Consequently, it aimed to ascertain the actual emissions within these areas. Governments, port authorities, and policymakers can enhance decision-making in this domain by comprehending the actual emissions and their corresponding environmental impact, which are directly linked to emission levels.

Conversely, due to the interconnectivity of seaports across countries and their role in facilitating trade between diverse regions and continents, policies must be formulated and endorsed on a large scale, necessitating collaboration among authorities.

In addition, the research faced limitations due to insufficient and transparent statistics, with vital data misalignments from shipping and maritime issues linked to macroeconomics. Additionally, some authorities are reluctant to provide comprehensive information, resulting in a lack of transparency in specific data segments. Moreover, most research concentrates on land logistics within seaports due to their accessibility and controllability. Consequently, obtaining pertinent information regarding maritime activities in seaports encounters specific barriers. Lastly, it is essential to note that there is currently no standardized framework for delineating seaport boundaries to estimate GHG emissions, resulting in varied outcomes in calculations and research studies and complicating investigations in this field.

Future strategies to reduce maritime transportation emissions must emphasize a comprehensive strategy that includes technical advancements, legislative changes, and international collaboration. A viable approach is the extensive use of shore power, allowing vessels to connect to the port's electrical grid instead of operating on diesel engines when docked. This approach could substantially decrease emissions at ports. This method may

be augmented by supplying the grid with renewable energy sources, such as wind and solar, converting ports into green energy hubs.

Furthermore, alternative fuels such as hydrogen, ammonia, and biofuels signify a crucial transition toward decarbonization. This necessitates significant investment in bunkering infrastructure and the global supply chain to guarantee availability and cost-effectiveness. Governments and industry stakeholders must cooperate to establish refueling networks that facilitate the use of these cleaner fuels.

Cutting-edge port technologies provide an alternative progressive approach. By enhancing port operations via digitization, including real-time traffic management systems, ports can minimize the duration that vessels spend idle or awaiting docking, thereby immediately reducing emissions. Adopting energy-efficient technologies, such as automation and AI-driven operations, will reduce the carbon footprint of ships and ports.

Ultimately, global cooperation and enhanced laws are essential for the future. The IMO must be pivotal in formulating more stringent worldwide emissions rules and incentives for sustainable shipping practices. Ports must collaborate, exchanging best practices and innovations that could be used worldwide. Sustainable finance methods and public–private partnerships will enable poor countries to access the resources necessary to decarbonize their ports. In the final analysis, while the present circumstances present considerable problems, the future provides several alternatives that, if executed efficiently and universally, could substantially reduce maritime traffic emissions in seaports. A collaborative initiative involving technology, policy, and industry is crucial for attaining a more sustainable shipping and maritime industry.

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