

Beyond Operational Emissions: Assessing Ship Recycling as a Decarbonization Pillar for the Global Merchant Fleet

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Abstract

Maritime transport contributes 2.9% of global greenhouse gas emissions, traditionally evaluated through operational fuel cycles while neglecting lifecycle impacts. This study redefines merchant ship recycling as a strategic front-end pillar for global decarbonization by assessing Embodied Carbon Trade-offs. Utilizing a mixed PRISMA systematic and semi-systematic methodology of literature from 2019–2025, we analyzed bulk carriers, container ships, and tankers across six thematic clusters. Our findings demonstrate that scenarios involving the potential decommissioning of up to 22.2% of the global merchant fleet exceeding 20 years of age could significantly mitigate lifecycle emissions by displacing primary iron-ore smelting with circular electric arc furnace marine-steel recovery. Crucially, this environmental dividend is non-linear and bound by regional energy matrices; under deeply decarbonized grids, this technological displacement can theoretically yield an upper-bound 72% emissions reduction, whereas fossil-heavy power supplies significantly diminish net mitigation margins. Practically, this research provides an operational roadmap for shipowners and regulators navigating the Hong Kong Convention and carbon border mechanisms. This work concludes that sustainable shipbreaking has the potential to function as an economically viable, strategic reservoir of low-carbon raw materials essential for achieving international net-zero targets throughout the entire shipping structural lifecycle.

Keywords: circular economy; decarbonization; ship recycling; ship scrapping



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1. Introduction

Maritime transport accounts for approximately 80% of global trade, consolidating its position as one of the fundamental pillars of the global economy [1]. However, this activity also contributes approximately 2.9% of greenhouse gas (GHG) emissions worldwide, an estimate based exclusively on international marine fuel consumption [2]. In response, the International Maritime Organization (IMO) has directed its decarbonization strategies toward reducing operational emissions, initially through the tank-to-wake approach and, more recently, through well-to-wake assessments, which consider emissions associated with the entire fuel life cycle [3]. Although these approaches represent a significant advancement in mitigating emissions during ship operation, they continue to exclude those

generated during construction and end-of-life stages; consequently, the carbon footprint of the maritime sector remains underestimated [4].

Shipbuilding constitutes one of the industrial activities with the highest intensity in terms of material and energy consumption. Marine-grade steel represents the primary structural component of merchant ships and must comply with stringent mechanical, corrosion resistance, fatigue, and dynamic loading requirements established by international classification societies [5]. Hull manufacturing involves highly specialized industrial processes, including hot rolling, plasma cutting, and structural welding, which operate at elevated temperatures and require extremely strict dimensional tolerances to ensure structural integrity and operational safety [6–12]. These processes demand substantial amounts of energy and generate significant emissions associated with both steel production and subsequent industrial transformation [8].

These impacts are particularly relevant for bulk carriers, container ships, and oil and chemical tankers, which constitute the predominant segments of the global merchant fleet and experienced cumulative growth of 35.4% between 2015 and 2024 [13]. Projections from the United Nations Conference on Trade and Development (UNCTAD) and the Organization for Economic Co-operation and Development (OECD) indicate that these ship categories will continue to lead maritime transport growth over the next decade due to sustained increases in demand for raw materials, manufactured cargo, fuels, and chemical products [4,14].

The magnitude of this challenge is demonstrated by the analysis conducted by the International Council on Clean Transportation (ICCT), according to which 677 ships constructed between 2021 and 2022 accounted for 27% of the gross tonnage of new builds arriving at USA ports during 2022 and consumed approximately 25.5% of the marine-steel used during that period [15]. Furthermore, the report indicates that bulk carriers, container ships, and tankers accounted for approximately 67% of total marine-steel consumption and that the construction of these ships generated approximately 18.5 Mt of CO_{2eq}, of which around 16.5 Mt were associated with steel produced in China, Republic of Korea, and Japan [15]. These findings highlight that a considerable share of maritime transport emissions originates before ships have even begun their operational life, making these specific segments the ones with the greatest potential for emissions reductions through circular economy strategies.

The sustained growth of the global fleet has also been accompanied by progressive ship ageing. By 2023, more than 22.2% of the global merchant fleet had exceeded twenty years of service, a situation particularly evident in the tanker segment, where more than 20% of operational units had surpassed this age threshold [13]. While emissions during the operational phase depend on variable factors, such as the type of fuel used [16,17], technological efficiency, and maintenance practices [18], emissions associated with manufacturing and recycling are primarily determined by energy- and material-intensive industrial processes. Consequently, fleet renewal represents an opportunity to recover large quantities of marine-steel, reduce the demand for primary production, and advance toward circular economy models capable of decreasing GHG emissions from the maritime sector [19,20].

Ship recycling constitutes the mechanism through which recovered materials, primarily steel, are returned to the production chain. This activity is carried out in specialized ship recycling yards located mainly in Bangladesh, India, Türkiye, China, and several European Union (EU) Member States, where infrastructure exists for the dismantling of large metallic structures and the treatment of hazardous waste [15]. Unlike shipbuilding yards, whose objective is to manufacture vessels under stringent technological standards, recycling yards must maximize material recovery while simultaneously ensuring environmental protection and occupational safety. Therefore, this activity is regulated by international instruments

such as the Basel Convention [21] and the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships [22], which entered into force in June 2025, and the European Ship Recycling Regulation (Regulation 1257/2013) [23]. These frameworks establish requirements related to hazardous materials inventories, certification of authorized facilities, and environmentally sound management of the dismantling process [24].

Nevertheless, despite the growing interest in maritime transport decarbonization, available research continues to focus primarily on operational emissions, alternative fuels, the economic aspects of ship dismantling, and regulatory challenges associated with ship recycling [12,25–32]. Several studies have highlighted the need to understand how future IMO regulations will influence recycling demand, the technological capacity of recycling yards, and fleet renewal costs, as well as to develop frameworks that integrate environmental sustainability, economic competitiveness, and regulatory compliance [25,26]. Similarly, recent research emphasizes that the environmental benefits derived from marine-steel recovery, particularly in terms of GHG emission reductions, remain insufficiently quantified [33,34], while future research agendas continue to prioritize alternative fuels and more inclusive decarbonization policies [12,35,36]. Collectively, these findings reveal a critical knowledge gap concerning the contribution of ship recycling in reducing the embodied carbon of the merchant fleet life cycle, an aspect that has not yet been comprehensively assessed.

To contribute to closing this knowledge gap, the present study examines merchant ship recycling as a strategic component of maritime transport decarbonization by evaluating the emission mitigation potential associated with the recovery and reuse of marine-steel within the bulk carrier, container ship, and tanker segments.

To provide an analytical basis for this assessment, this study proposes three conceptual frameworks developed by the authors to interpret these complex interactions:

- The Embodied Carbon Trade-offs (ECT) Framework: Grounded in life-cycle assessment (LCA) methodologies applied to heavy industries and recent maritime decarbonization approaches [15], this framework interprets the balance between greenhouse gas emissions generated during raw material extraction and ship manufacturing (cradle-to-gate, C2G) and the emissions avoided through the circular recovery of steel at the end of the vessel's service life (end-of-life, EoL). It analyzes how initial embodied carbon over a service life of 25–30 years [13] may be partially offset by substituting primary steel with recycled steel produced in electric arc furnaces (EAFs) [8,31,32].
- The Front-End Decarbonization Perspective: Adapted from industrial project management methodologies, including Front-End Loading (FEL) and Front-End Engineering Design (FEED), this analytical lens examines how early-stage decisions adopted during ship design dictate life-cycle emissions. It evaluates how the early integration of low-carbon materials, hull hydrodynamic optimization, and assisted propulsion technologies can minimize environmental impacts before the operational phase begins [15].
- The Circular Toxicity Framework: Built upon existing knowledge regarding hazardous substances management in ship recycling and circular economy challenges [22,24–30], this framework interprets the interaction between inherited toxic substances—such as lead, asbestos, PCB, and other heavy metals [24–30]—and circular material flows. It addresses the risk that legacy materials from vessels constructed during the twentieth century [22] may contaminate secondary steel flows during recycling, reduce metallurgical quality through down cycling, increase occupational exposure, and release persistent pollutants into marine ecosystems.

Methodologically, this research combines a systematic literature review conducted according to the Systematic Reviews and Meta-Analyses (PRISMA) guidelines [37,38] published between 2019 and 2025. The analysis integrates evidence related to ship recycling technologies, international regulations, merchant fleet trends, circular economy principles, and decarbonization strategies to identify areas of convergence, existing knowledge gaps, and future research opportunities.

The main contribution of this study is the development of an integrative conceptual framework that connects naval engineering, life-cycle assessment, and circular economy principles to evaluate the role of ship recycling in reducing the embodied carbon of maritime infrastructure. The findings aim to demonstrate that ship recycling should be considered not only an end-of-life waste management activity but also a structural mechanism for reducing the embodied emissions associated with shipbuilding and supporting the transition toward a net-zero merchant fleet.

2. Materials and Methods

The methodological framework adopted in this study combines a systematic literature review following the PRISMA [37,38] with a complementary semi-systematic review approach. This mixed methodology provides both methodological rigor and conceptual breadth, enabling the identification of high-quality empirical evidence while incorporating emerging interdisciplinary perspectives related to circular economy principles, ship recycling, and maritime decarbonization.

The systematic review allows for a rigorous and reproducible selection of empirical data, whereas the semi-systematic review is particularly appropriate for sustainability-related topics characterized by conceptual diversity and evolving research streams [37,38]. The combination of both methods allows for a broader and more contextualized exploration, integrating both empirical evidence and emerging perspectives.

2.1. Systematic Review Design

This systematic review was designed, conducted, and reported in strict accordance with the Preferred Reporting Items for PRISMA [37,38]. A formal review protocol was not prospectively registered in PROSPERO or any other systematic review registry prior to conducting this synthesis.

The systematic search strategy was conducted exclusively using the Web of Science (WoS) Core Collection [37,38], which is widely recognized as the most comprehensive and prestigious multidisciplinary database for high-impact environmental and maritime research. The literature search was performed in January 2026 and focused on peer-reviewed articles published between 2019 and 2025. This temporal boundary was established to capture the most recent scientific developments concerning ship recycling, lifecycle assessment, and circular economy strategies.

To ensure the highest scientific quality and methodological robustness, the eligibility criteria strictly restricted the selection to articles published in Q1 journals indexed in WoS [39]. This rigorous quality filter is justified to prioritize studies characterized by the most stringent peer-review processes, highest scientific impact, and strongest methodological standards, thereby mitigating potential biases associated with lower-ranked publications and strengthening the credibility of the review's evidence base.

2.2. Inclusion and Exclusion Criteria

To establish a transparent selection process and address potential ambiguity, specific and formalized eligibility criteria were defined. Studies were included in the systematic review when they met all the following inclusion criteria:

- Published as a peer-reviewed article between 2019 and 2025.
- Published in a Q1 journal indexed in WoS.
- Written in English.
- Focused specifically on merchant ships, including bulk carriers, container ships, and oil/chemical tankers. This focus is justified as these segments dominate the fleet's composition, have experienced significant global growth, and represent a critical potential for marine-steel recovery and GHG mitigation.

Studies were excluded when they met any of the following criteria:

- Document types such as conference proceedings, editorials, book chapters, reports, theses, or other non-peer-reviewed literature.
- Studies addressing maritime transport or logistics without a direct connection to ship recycling, dismantling, or end-of-life vessel management.
- Studies presenting insufficient methodological information.
- Duplicate records or overlapping datasets within the database.

2.3. Search Strategy

To operationalize the systematic review, the search string was rigorously engineered into two distinct thematic clusters combined via Boolean operators. The first cluster captures environmental, lifecycle, and carbon metrics, while the second isolates the maritime, industrial, and asset-specific dimensions of vessel dismantling.

To ensure exact reproducibility, maximize thematic alignment with the study's core keywords, and eliminate syntax-driven algorithmic exclusions, the finalized search equation applied to the WoS Core Collection was structured as follows:

TS = ("carbon footprint" OR "carbon emission*" OR "greenhouse gas emission*" OR "GHG emission*" OR "CO₂ emission*" OR "carbon impact*" OR "carbon assessment*")

AND

TS = ("merchant ship recycling" OR "merchant vessel recycling" OR "ship recycling" OR "vessel recycling" OR "ship dismantling" OR "shipbreaking" OR "ship breaking" OR "ship scrapping" OR "end-of-life vessel*" OR "end of life vessel*")

2.4. Study Selection Process

The study selection process followed the four-stage flow diagram proposed by the PRISMA framework: identification, screening, eligibility assessment, and inclusion.

Initially, records were retrieved from the WoS Core Collection [37,38] using the predefined search string. Following data extraction, preliminary screening of titles and abstracts was performed according to the predefined inclusion and exclusion criteria. Studies considered potentially relevant were then subjected to a full-text assessment to verify their strict adherence to the Q1 WoS indexing and thematic relevance. After the screening and eligibility assessment stages, a final sample of 35 articles was retained for the systematic review. The complete study selection procedure is presented in Figure 1.

2.5. Semi-Systematic Review

In addition, a semi-systematic review is incorporated, which is suitable for addressing interdisciplinary topics such as the circular economy, where concepts and approaches vary. This second approach is justified on the basis of studies that employ this technique to analyze sustainability tools in maritime transport [37,38]. The combination of both methods allows for a broader and more contextualized exploration of the study, integrating both empirical evidence and emerging perspectives.

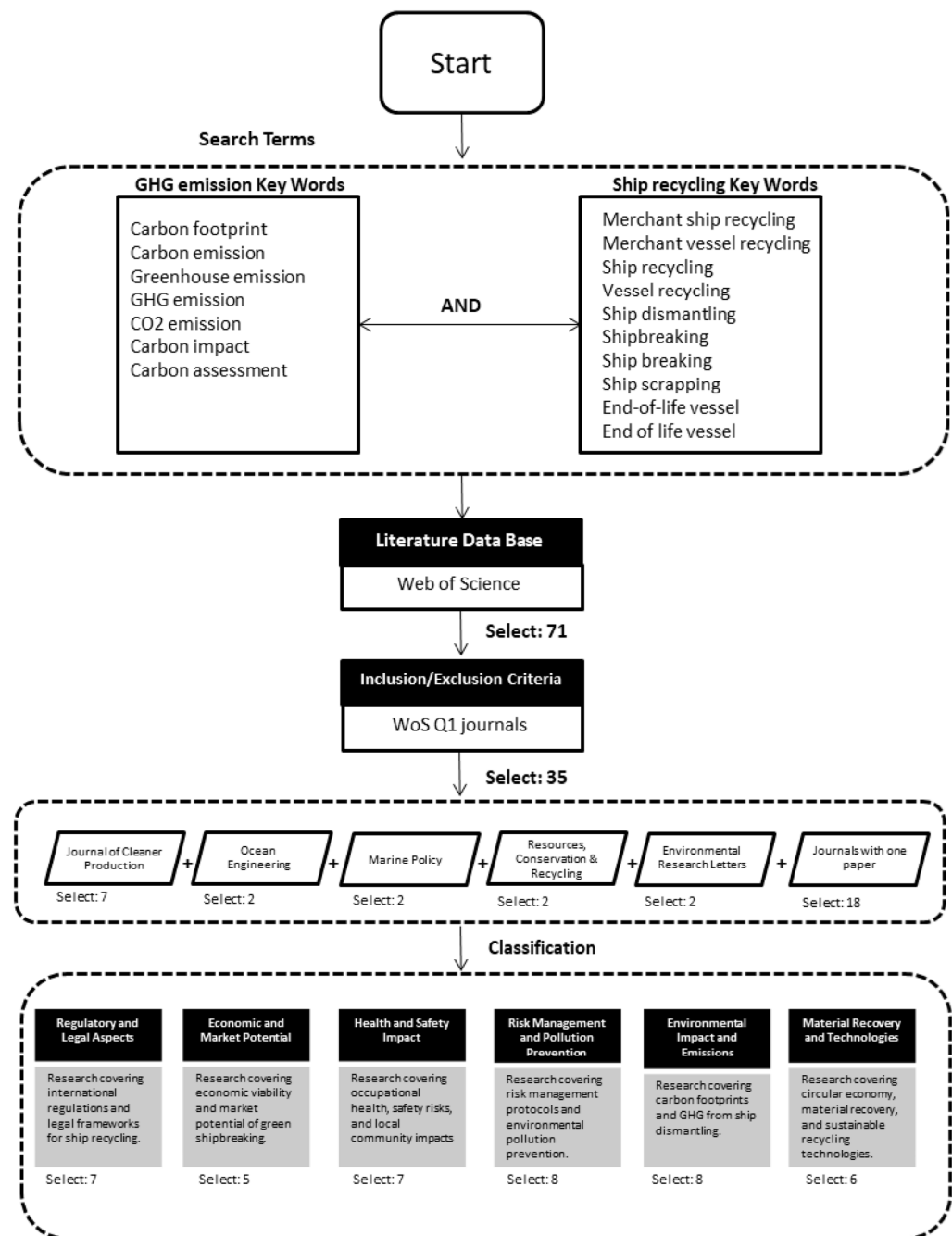


Figure 1. Diagram of the PRISMA selection of studies.

2.6. Reproducibility and Data Reliability

To enhance transparency and enable future replication, the database source, search string, temporal boundaries, and quality eligibility criteria adopted in this review are explicitly reported. The use of standardized PRISMA procedures combined with fully detailed keyword groupings ensures that future researchers can replicate the search strategy, apply the same selection criteria, and update the evidence base as new studies become available. Furthermore, restricting the systematic analysis strictly to peer-reviewed Q1 journals within WoS contributes to minimizing potential biases associated with publication quality, thereby strengthening the reliability and scientific credibility of the findings derived from this review.

Artificial intelligence (AI) integration was utilized during the development of this study. Specifically, Gemini 1.5 Pro was employed to assist in drafting and refining the

manuscript text, as well as translating specific sections into English. All AI-generated outputs were thoroughly reviewed, verified, and edited by the authors to ensure scientific accuracy and technical integrity.

3. Systematic Review Results and Discussion

The systematic review identified 35 published scientific articles that directly address current trends in the recycling of merchant ships. These reveal a growing interest among the scientific community in integrating circular economy strategies, GHG emission reduction, and energy optimization in the maritime sector within ship recycling approaches. These studies provide a state-of-the-art overview of the topic. Table 1 shows how these articles have been grouped into six thematic areas.

Table 1. Articles by thematic area.

Areas	2019	2020	2021	2022	2023	2024	2025
Regulatory and Legal Aspects	--	Devaux and Nicolai [40]; Hsuan and Parisi [41]	Solakivi, et.al [42]	Lin, et al. [43]	Fernandes, da Silva and Pereira [44]	Pozdnakova [45]; Mathew [46]	--
Economic and Market Potential	Gunbeyaz, Kurt and Baumler [47]; Ocampo and Pereira [48]	Benjamin and Figueiredo [49]; Mitra, et al. [50]	--	--	--	Tola, Mosconi and Gianvincenzi [51]	--
Health and Safety Impact	Alam et.al [52]; Gunbeyaz, Kurt and Baumler [47]	Mitra, et al. [50]; Rahman, Kim and Laratte [53]	Zhou, et al. [54]; Tanha, et al. [55]	--	Mentes [56]; Zhou, Li and Lou [57]	--	--
Risk Management and Pollution Prevention	Ozturkoglu, Kazancoglu and Ozkan-Ozen [58]	Singh, et al. [59]; Rizvi, et al. [60]	--	Glinski [61]	Zhou, Li and Lou [57]	Sezer, et al. [62]; Islam, et.al [63]; Celik, Akyar and Ceylan [64]	--
Environmental Impact and Emissions	Eronat, Bengil and Neser [65]; Ocampo and Pereira [48]	Rahman and Kim and Laratte [53]; Mitra, et al. [50]	Soner, Celik and Akyuz [66]; Steuer, Staudner and Ramusch [67]; Sunaryo, et al. [68]; Zhou, et al. [69]	--	--	--	--
Material Recovery and Technologies	--	--	--	Glinski [61]; Gunbeyaz, Kurt and Turan [70];	Bleischwitz, Holler and Kriegl [71]; Önal [72];	Tola, Mosconi and Gianvincenzi [51]	Schulz, et al. [73]

India and Bangladesh are among the most analyzed countries, reflecting their dominant role in the dismantling industry. It is also revealed that there is a significant presence of studies focusing on Europe and Turkey, especially in relation to regulatory, technological and environmental aspects.

3.1. Regulatory and Legal Aspects

The regulatory and legal landscape constitutes a critical pillar in the discourse of ship recycling, shifting from fragmented voluntary standards to stringent, binding frameworks. The Hong Kong Convention [22] and Regulation 1257/2013 [23] are central to this evolution, which aim to institutionalize safe [54] and environmentally sound practices. Scientific literature in this domain [40,45] rigorously examines the legal architecture governing a ship's end-of-life stage, focusing on jurisdictional complexities in international waters, flag-state accountability, and the controversial legality of "beaching" versus certified shore-based facilities.

However, a significant scholarly imbalance persists. While the macro-legal structures are well-documented, micro-level operational impacts receive disproportionately less attention. This research gap is particularly acute in the Global South [44,46], where the disconnect between international mandates and precarious local working conditions remains a barrier to achieving true sustainability [41]. Consequently, there is a pressing exigency for interdisciplinary research that bridges the divide between high-level regulatory compliance and the socio-technical protection of labor and ecosystems at the frontline of dismantling operations [42–44].

3.2. Economic and Market Potential

This thematic area examines ship recycling as a highly dynamic industrial sector where profitability is increasingly intersected by environmental performance. The research being conducted highlights the inherent volatility of the shipbreaking market, which is traditionally governed by the cyclical nature of the shipping industry and the price fluctuations of the global ferrous scrap market [47]. However, modern economic analysis has evolved beyond simple scrap-value assessments to include the impact of freight rate volatility on scrapping decisions; when freight markets are depressed [49], shipowners accelerate disposal to mitigate operational losses, creating a surge in recycling supply.

A critical frontier in this area is the assessment of the economic viability of Green Shipyards [48]. Unlike traditional yards, sustainable facilities internalize the costs of waste management and worker safety, necessitating new financial models in order to remain competitive against lower-standard competitors. The literature suggests that this gap is being bridged by the decarbonization premium of the circular economy [50]. Specifically, the expansion of carbon markets (such as the EU Emissions Trading System [74]) and the implementation of carbon border adjustment mechanisms are imposing higher costs on primary marine-steel production [75].

As primary marine-steel becomes more expensive due to carbon taxes, the intrinsic value of end-of-life ships increases significantly [51]. This shift transforms a decommissioned ship from a mere waste liability into a strategic reservoir of low-carbon raw material. Furthermore, the integration of ship recycling into the financial environmental, social, and governance criteria of major banks—often referred to as the Poseidon Principles for Recycling—is redirecting capital toward certified facilities, effectively making sustainable dismantling an economic imperative rather than a voluntary choice [75].

Consequently, evaluating the financial feasibility of sustainable shipyards requires a profound understanding of ECT. While the internalization of waste management and strict containment protocols elevate the upfront operational costs of Green Shipyards, these expenditures are financially offset by the premium value of the recovered low-carbon marine-steel. By shifting from primary iron-ore smelting to scrap-fed electric arc furnaces (EAF), the market transitions from an extractive model to a closed-loop system where the financial value of the asset is directly tied to its carbon mitigation potential.

3.3. Health and Safety Impact

This thematic area prioritizes the human dimension of the maritime circular economy, focusing on the systemic occupational risks inherent in shipbreaking yards, particularly in South Asian hubs [52]. Research by authors such as Rahman (2021) [53] and Zhou (2020) [54] utilizes advanced quantitative methodologies—including longitudinal health studies and probabilistic risk assessments—to evaluate worker exposure to a complex cocktail of hazardous substances, such as heavy metals (lead, mercury), asbestos fibers, and PCB [47,50,52]. These studies reveal that without stringent containment protocols, the physical act of dismantling a ship becomes a significant vector for chronic respiratory diseases and long-term dermatological and neurological impairments among the workforce.

The scientific objective in this domain has evolved from a purely descriptive account of accidents toward a predictive correlation between technological upgrading and injury mitigation. Investigation focuses on how transitioning from manual labor-intensive beaching to mechanized, yard-based dismantling—supported by semi-automated cutting technologies and standardized personal protective equipment (PPE)—directly reduces the frequency of fatal accidents and acute industrial poisonings. Furthermore, this area explores the socio-technical gap in the Global South [47,50,52,55], where the informal nature of the labor force often complicates the implementation of standardized safety management systems.

Ultimately, the literature underscores that a truly sustainable maritime sector cannot be achieved solely through carbon reduction; it must ensure social sustainability [56]. Authors in this field argue for a Just Transition in ship recycling, where international certifications are not merely bureaucratic requirements but essential tools to decouple industrial material recovery from the degradation of human health [57]. This reinforces the necessity for global maritime policies to integrate human rights and occupational safety as non-negotiable components of the circular economy.

This human dimension underscores the structural boundaries of resource recovery, where the pursuit of material circularity directly clashes with Circular Toxicity. The physical act of cutting and dismantling structural components without institutionalized containment protocols transforms the shipyard into a localized vector for heavy metal and chemical accumulation. Therefore, managing Circular Toxicity becomes a non-negotiable prerequisite within the maritime circular economy, proving that high material recovery rates are unsustainable if they trigger the systemic degradation of human health and local labor ecosystems.

3.4. Risk Management and Pollution Prevention

Beyond general environmental assessments, this research cluster—exemplified by the work of Sezer et al. (2024) [62], Islam et al. (2024) [63], and Celik et al. (2024) [64]—focuses on the technical and operational mitigation of localized ecological disasters. The primary scientific challenge in this domain is the management of the pollution legacy contained within a ship's structure. Research focuses on developing predictive risk assessment models designed to prevent the accidental release of hydrocarbons, oily sludge, and bilge water during the primary cutting stages, particularly in the intertidal zones where traditional containment is technically complex and often insufficient [58,60].

A critical sub-sector of this area is the geochemical management of contaminated sediments. Studies investigate the leaching kinetics of heavy metals—such as lead, cadmium, and mercury—and legacy anti-fouling biocides like tributyltin (TBT) into the benthic environment. The literature emphasizes that once these pollutants migrate into the seabed, they alter the local geochemical profile and trigger long-term bioaccumulation processes in marine biota, posing a direct threat to coastal biodiversity and food security. Consequently, this field is deeply rooted in process engineering, focusing on the design of impermeable

secondary containment, specialized drainage systems, and industrial-grade spill-response protocols that can withstand the extreme operational demands of dismantling large-scale maritime structures.

A critical sub-sector of this area is the operational management of Circular Toxicity through the geochemical tracking of contaminated sediments. Studies have investigated the leaching kinetics of heavy metals and legacy anti-fouling biocides into the benthic environment. Mechanistically, this risk is quantified via the quality and purity index of the recycled secondary material, where a value of 1 denotes perfect purity. As this index deviates from 1 due to the presence of specific structural and coating contaminants—such as $j = 1$ for lead and $j = 2$ for copper from anti-fouling paints—the threat of long-term bioaccumulation in marine biota increases. Managing these variables (j up to m contaminants) through impermeable secondary containment is essential to prevent secondary material supply chains from reintroducing hazardous compounds into the industrial loop.

Furthermore, this area addresses the management of hazardous waste streams, including asbestos and ozone-depleting substances (ODS), through the lens of disaster prevention. Authors argue that pollution prevention in ship recycling must be treated as a high-stakes industrial safety operation rather than a mere waste disposal task. By integrating computational fluid dynamics and geographic information systems (GIS), current research aims to map the dispersion of pollutants in the event of containment failure, providing a technical baseline for the Carbon Neutral Port and Green Yard certifications [49].

3.5. Environmental Impact and Emissions

The environmental footprint of ship recycling is a multifaceted challenge that spans from local ecosystem degradation to global carbon emissions. A critical concern in maritime regions is oil and chemical pollution. Eronat et al. (2019) [65] demonstrated the gravity of this issue in Çandarlı Bay (Turkey), using satellite monitoring to detect significant oil pollution directly linked to ship recycling activities. This physical impact on marine environments is further compounded by the release of hazardous materials during dismantling, a process that requires rigorous assessment. In this respect, Soner et al. (2022) [66] utilized the Fuzzy Best–Worst Method (BWM) to provide a structured evaluation of potential environmental impacts, highlighting that the complexity of ship structures often leads to unforeseen ecological risks if not managed through precise methodological frameworks.

Beyond local pollution, the energy intensity of the industry contributes substantially to global emissions. Mitra et al. (2020) [50] assessed energy-based CO₂ emissions in Bangladesh, revealing a high correlation between traditional shipbreaking methods, carbon output, and severe health risks for workers. This underscores the necessity of transitioning towards Green Ship Recycling. Zhou et al. (2021) [69] proposed a conceptual framework to identify the factors influencing this transition, emphasizing that modeling and policy alignment are essential to mitigate the industry's carbon footprint.

The feasibility of sustainable practices often depends on regional contexts and global disruptions. While Steuer et al. (2021) [67] highlighted the potential of the circular economy in China to manage end-of-life ships effectively, other regions face significant hurdles. For instance, Ocampo and Pereira (2019) [48] questioned the sustainability of these activities in Brazil, while Sunaryo et al. (2021) [68] conducted a gap analysis in Indonesia, revealing a disconnect between current practices and international environmental standards. Furthermore, the resilience of these environmental management systems was tested during the global pandemic by Rahman et al. (2021) [53].

3.6. Material Recovery and Technologies

This is the most technical and forward-looking area (e.g., Önal 2023 [72], Bleischwitz et al., 2023 [71], and the recent Schulz et al., 2025 [73]). It focuses on metallurgical efficiency and innovation in dismantling. It addresses advanced cutting techniques (plasma, waterjet), automation in alloy separation, and, fundamentally, improving scrap quality for use in EAF. It represents the transition toward a 100% circular shipbuilding steel industry.

Most recent studies present a methodological evolution, which tends to integrate multidimensional approaches such as life cycle analysis, risk assessment, and circular economy. This trend reflects the move towards a more holistic understanding of recycling, not only as a technical practice, but as part of a structural transformation in global maritime sustainability.

In terms of the benefits identified, environmental impact and emissions are the recurring themes. This confirms that ship recycling is considered a key strategy for the reduction of GHG and the mitigation of the ecological footprint of shipping, despite the problems it brings to people's health, as it is a highly labor-intensive industry, and the effects on land and marine ecosystems. Nevertheless, the recovery of materials (mainly marine-steel) stands out as a technological and economic advantage, with several studies analyzing recovery processes and energy efficiency.

Based on the semi-systematic review, several complementary sources were identified, including international standards, sectoral statistics, and technical documents, which allowed for a more in-depth analysis of the emission reductions associated with the recycling of merchant ships. Thanks to this integration, it was possible to contextualize the environmental benefits of ship recycling compared to new manufacturing, especially in terms of GHG abatement and resource savings.

China, Republic of Korea, and Japan are the main manufacturers of merchant ships, standing out for their technological capacity and production volume. In contrast, Bangladesh, Turkey, and India lead the ship recycling sector, accounting for more than 70% of the tonnage scrapped worldwide, thanks to their shipyards dedicated to this activity and the demand for recovered marine-steel. Turkey and some European countries are also active participants, especially under environmental regulatory frameworks—Regulation 1257/2013 [23].

This contrast between shipbuilding and recycling countries reveals a disconnect with the principles of EPR, since according to international regulations, such as the Hong Kong Convention [22] and Regulation 1257/2013 [23], manufacturers should facilitate the safe and environmentally responsible recycling of end-of-life ships. However, in practice, a significant percentage of ships are sold to third parties—often brokers or companies under a different flag—before being dismantled. This sale process removes the original manufacturer from direct responsibility for the final destination of the ships, allowing them to be transferred to shipyards in countries with weaker environmental and labor standards.

4. Semi-Systematic Review Results and Discussion

While maritime decarbonization policies heavily prioritize operational fuels, the environmental debt of a ship begins with the primary, carbon-intensive manufacturing of its structural marine-steel. This section explores the ECT inherent to the global fleet, demonstrating how strategic ship recycling acts as an upstream, Front-end Decarbonization Strategy capable of mitigating the initial environmental liability incurred during the shipyard construction phase.

Although there are no existing pressures on energy consumption and emissions in the ship manufacturing processes, the ICCT report [15] states that marine-steel accounts for approximately 75–85% of a ship's total structural weight. By applying these percentages

to DWT ranges, approximate values of the amount of this steel used are obtained, which allows for a comparison of different ship types on an indicative basis, as shown in Table 2.

Table 2. Structural ship marine-steel of merchant ships.

Ship Type	Typical DWT	Estimated Structural Weight (t)	Estimated Marine-Steel (75–85%) (t)	Predominant Type of Marine-Steel	Main Manufacturer Countries	Reference
Bulk Carrier	80,000–100,000	12,000–15,000	9000–12,750	ASTM A131 Grado A/AH36	China, Japan, Republic of Korea	[76]
Container Ship	100,000–130,000	14,000–18,000	10,500–15,300	ASTM A131 EH36/DH36	China, Germany, Republic of Korea	[15]
Oil/chemical Tanker	120,000–160,000	16,000–22,000	12,000–18,700	ASTM A131 DH36/EH36 + stainless marine-steel	Republic of Korea, Japan, China	[34]

The emission factor associated with marine-steel production varies significantly depending on the type of technology employed and the raw material used. Although the EAF process is generally considered less emission intensive, its impact depends on the type of input, such as pig iron, direct reduced iron (DRI) or scrap, and the carbon intensity of the energy source used [77]. In China, for example, the use of pig iron as the main input in EAF, together with an energy matrix with a significant share of non-renewable sources (550–600 gCO_{2eq}/kWh) [78], results in an average intensity of 1.4 tCO_{2eq}/t of marine-steel. This shows that a higher share of EAF does not guarantee lower emissions if it is not accompanied by improvements in energy efficiency, recycled inputs, and low carbon footprint electricity [15].

In addition to marine-steel, which forms the structural basis of ships, other materials are used in much smaller proportions. Aluminum is the only secondary material that can reach a 2–5% share, especially in superstructures and light ships. The remaining materials—such as fiberglass composites, copper, zinc, titanium, plastics, rubber, glass, wood, and concrete—each account for less than 1% of the total weight. They are mainly used in specific systems, interior finishes, corrosion protection and functional or decorative elements [7].

In the construction of bulk carriers, container ships, and oil/chemical tankers, several hazardous materials are used which, although essential for specific technical functions, represent environmental and human health risks if not properly managed. Among the most relevant are paints with biocides such as copper oxide and volatile organic solvents (including xylene, trimethylbenzene, and 4-methyl-2-pentanone) for anti-corrosion and antifouling coatings [7].

Bulk carriers, container ships, and oil/chemical tankers have an estimated useful life of between 25 and 30 years [13,79], depending on factors such as maintenance [18], operating conditions [16,17], and current environmental regulations—Regulation 1257/2013 [23]. Once they have reached the end of their operational cycle, their recycling becomes a strategic action within the framework of the circular economy, as it allows the recovery of valuable materials (mainly marine-steel) and significantly reduces the environmental impact associated with informal abandonment or dismantling.

Although in theory more than 90% of a ship's mass can be recycled (Table 3), marine-steel accounts for almost all of this percentage, while other materials (such as aluminum,

copper, plastics, and composites) are recovered in much lower proportions [33]. Thus, promoting their recycling under international standards not only contributes to the sustainability of the maritime sector [20] but also promotes resource efficiency, emission reductions, and employment generation in specialized shipyards.

Table 3. Structural ship marine-steel of merchant ships [7].

Type of Ship	Percentage of Recovered Marine-Steel (%)	Commentary
Bulk Carrier	95–97	Simple structure, high proportion of marine-steel in hull and decks.
Container Ship	93–96	Includes more technical components but remains highly salvageable.
Oil/chemical Tanker	90–94	Presence of stainless marine-steel, specialized tanks, and more composite materials.

Marine-steel recycling can reduce up to 72% of the energy required or emissions to produce the same material from virgin raw materials [7,15] (Table 4). Although the percentages may vary slightly depending on the type of steel and the process, the claim that it requires only one third of the energy is a valid synthesis and is supported by recent industry data.

Table 4. Benefits of merchant ship recycling.

Author	Year	Estimated Reduction
Broadbent [11]	2016	Recycling marine-steel reduces CO ₂ emissions by approximately 58–72%, compared to primary steel production, depending on the energy mix and process efficiency.
Önal, Neser, and Gursel [72]	2023	Recycling of materials reduces the impact from raw materials significantly, approximately by 80%.
ICCT [15]	2024	Using recycled marine-steel in shipbuilding can reduce lifecycle emissions by up to 70%, compared to primary steel production.
Narci and Can Dogan [7]	2025	The use of alternative, best-available shipbuilding technologies leads to notable reductions in environmental impacts. [...] Improvements ranged from 32 to 99% in categories such as global warming, ecotoxicity, and human toxicity.

Mechanistically, the reported maximum carbon abatement potential of up to 72%—equivalent to avoiding approximately 1.5 tCO₂eq per ton of recycled marine-steel [11]—is strictly contingent upon a complete technological displacement model. Specifically, this assumes that secondary scrap processed via EAF entirely replaces primary iron-ore smelting via the traditional blast furnace–basic oxygen furnace (BF–BOF) route. Crucially, this environmental dividend is inherently non-linear and exhibits high elasticity toward regional energy matrices; the 72% emission reduction represents an upper-bound efficiency frontier that is only achievable when the EAF infrastructure is powered by a deeply decarbonized electricity grid. Under fossil-heavy energy profiles, such as those characterizing major South Asian shipbreaking hubs, the localized carbon intensity of the power supply significantly diminishes the net carbon mitigation margins. Furthermore, the structural impact of decommissioning 22.2% of the global fleet is specifically modeled around large merchant ships (bulk carriers, tankers, and container ships) exceeding 20 years of age, establishing a clear asset boundary that prevents the overgeneralization of circular carbon offsets across smaller or non-steel-intensive ship classes.

The recycled marine-steel can be used in the following processes:

1. Construction of new ships: Recycled marine-steel can be reincorporated in the manufacture of hulls, decks, and internal structures of new ships, promoting circularity. This steel recycling has been presented as a simple and cheap option due to its physical characteristics, which allow steel to be 100% reusable, maintaining its main properties during the recycling process. Techniques such as the EAF (which transforms scrap metal into high quality steel through an electric steel furnace) are able to recycle steel infinitely, without losing the material's properties. Therefore, reprocessing is a viable option to steel waste, especially considering the waste generated at the discontinuation of an end-of-life ship. At present, 37% of the steel in the world is manufactured from steel scrap. It is estimated that each ton of recycled steel saves the following [80]:
 - 1400 kg of iron ore
 - 454 kg of mineral coal
 - 18 kg of lime
 - In addition to reducing CO₂ emissions by 1.5 t—cooperating to a lower carbon footprint.
2. Green marine-steel production for the maritime sector: Recycled steel is used as raw material in EAF processes, reducing emissions and energy in production.
 - Recycling 1 kg of marine-steel avoids approximately 1.5 kgCO₂eq, 13.4 MJ of primary energy, and 1.4 kg of iron ore, representing savings of 73% in emissions, 64% in energy, and 90% in raw material versus primary production [11].
 - Use of recycled marine-steel in EAF contributes to a material efficiency of 97.6%, reduces the use of virgin raw materials, and reduces environmental impact [8].
 - The EAF process using scrap as raw material can consume up to 75% less energy than the traditional BF–BOF process. In addition, EAF uses 50% electricity, which facilitates the integration of renewable energy [81].
3. Manufacture of industrial components: It is transformed into profiles, sheets, and parts for machinery, port infrastructure, and maritime equipment.
 - Recycled marine-steel can be used in the following: quay walls, breakwaters and jetties, deep sea structures adapted to the growing size of ships and, finally, sheet piling systems such as AZ[®]-800 and HZ[®]-M, which have reduced their weight by up to 25–50% thanks to improvements in steel grades and rolling techniques [82].
 - Studies indicate that 70% of marine-steel in new construction should come from secondary (reused or recycled) sources [83].
 - Green marine-steel can be used in the construction of roads, pavements, and marine structures, as well as a replacement for high quality aggregates in concrete for harbor works [84].
4. Export as foundry scrap: In many cases, naval marine-steel is exported to countries with smelting capacity, where it is converted into various metal products. In addition to South Asia, as already mentioned, ship recycling is picking up in many regions, such as East Asia and the Mediterranean, driven by the demand for recycled marine-steel. Tariffs on virgin steel in the United States and the EU have increased the value of scrap, encouraging its export. Finally, India, Bangladesh, and Pakistan handle more than 70% of the world's recycled tonnage, converting steel into various industrial products [85].
5. Direct reuse in civil infrastructure: Some structural parts are reused without casting in civil works, such as piles, reinforcements, or temporary structures. There are initiatives and projects that have achieved carbon reduction or carbon capture certifications

linked to the use of recycled marine-steel, especially in the context of low-emission production through processes such as the EAF. Among these are the following:

- ArcelorMittal's XCarb™ is an initiative that certifies the reduction of carbon emissions through the production of marine-steel from recycled scrap in EAF powered by renewable energy. Through XCarb™ marine-steel certificates, customers receive verifiable documentation that enables them to report reductions in their Scope 3 emissions under the GHG Protocol, with carbon footprints as low as 300 kg CO₂/t of steel produced [86].
- High-performance construction projects have demonstrated that using 100% recycled marine-steel through EAF routes can reduce the embodied carbon of a building's structure by up to 60%. For instance, the integration of circular economy principles and Leadership in Energy and Environmental Design (LEED) v4 requirements in marine-steel-framed structures allows for significant credits in material transparency and life-cycle impact reduction, as evidenced by the environmental performance of sustainable urban developments in North America [87].
- The Onlyplastic project of the Feralpi group (Italy) has developed a technology that replaces coal injected into EAF furnaces with recycled polymers from non-recoverable plastic waste. This substitution significantly reduces CO₂ emissions during smelting, and the project has been validated by LCA audits under European industrial decarbonization standards, contributing to the production of reinforcing marine-steel with a low carbon footprint [88].

Presently, there are limited documented experiences that have managed to certify the removal or reduction of carbon emissions specifically linked to the use of recycled marine-steel in industrial processes. However, there are pioneering initiatives that have made progress in this field, combining material traceability, life cycle audits, and internationally recognized standards. Some representative projects that have obtained certifications or validations in this field are described below.

- The Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has developed a specific certification for port terminals seeking to reduce their carbon footprint. This certification assesses the use of sustainable materials, including recycled marine-steel, energy efficiency in port operations, and electrification of equipment. Ports that meet these criteria can be recognized as Carbon Neutral Ports (CNP), allowing them to demonstrate their commitment to the climate transition [89].
- The European Carbon Removals and Carbon Farming (CRCF) framework aims to establish clear criteria for certifying carbon removal in different sectors, including construction. In the port context, this framework can be applied to projects integrating recycled marine-steel as a structural material, provided that a significant reduction of emissions compared to conventional alternatives is demonstrated through LCA analysis. Although it is not an exclusive certification for ports, its focus on durable and traceable products opens the door to validate the positive climate impact of maritime infrastructure built with recycled steel [75].

4.1. Embodied Carbon

The results of this study highlight a significant blind spot in maritime environmental policy. While the Fourth IMO GHG Study 2020 [2] focuses on operational efficiency, our analysis of shipbuilding marine-steel (Tables 1 and 4) reveals that a ship environmental impact debt starts long before its entry into service. The manufacturing of a single 100,000 DWT container ship can emit approximately 20,000 to 25,000 tCO₂ just from steel production. By contrasting these with the potential 72% emission reduction through recycling

(Table 5), it is evident that ship recycling is not merely an end-of-life necessity but a front-end decarbonization strategy. This aligns with the findings of Meng et. al. (2024) [15] suggesting that the maritime industry must transition from a fuel-only perspective to a material-plus-fuel LCA.

Table 5. Methodological alignment matrix: empirical evidence vs. conceptual lifecycle formulations.

Variables/Dimensions	Systematic Review (Section 3)	Semi-Systematic Review (Section 4)	Similarities (Common Ground)	Divergences (Analytical Advances)
Fleet Boundaries	Global literature trends across broad regulatory and socio-economic themes [39,46].	Merchant ships (>20 years old) comprising 22.2% of the global fleet.	Both target the global merchant fleet under operational and market pressures.	Homogeneous regulatory view vs. precise structural and temporal asset boundaries.
Carbon Abatement	Localized, energy-based CO ₂ emissions during active dismantling phases [49,67].	Lifecycle carbon mitigation up to 72% via secondary EAF technological displacement [11,15].	Both identify ship recycling as a critical vector for maritime carbon reduction.	End-of-life output monitoring vs. an upstream front-end decarbonization strategy.
Energy Grid Mix	Spatial distribution and market dominance of South Asian hubs [51].	Non-linear carbon dividend elastic to regional electricity grid intensities.	Both acknowledge intense geographical asymmetry in the ship breaking sector.	Descriptive industry mapping vs. quantified local grid elasticity margins.
Circularity Efficiency	Static physical recovery metrics (90–97% steel mass) [7,33].	Dynamic downstream market reintegration routes (e.g., green ship steel).	Both positions recycled marine-steel from ships as a high-value strategic resource.	Bulk material volume focus vs. complex dynamic ECT.
Chemical Contaminants	Descriptive occupational hazards and localized benthic leaching [52,61,62].	Standardized ship material purity index tracking contaminants ($j = 1, j = 2$)	Both recognize hazardous substances as threats to industrial sustainability.	Localized health hazard monitoring vs. systemic Circular Toxicity risk tracking.

However, to avoid overgeneralization, these metrics must be contextualized within specific boundary conditions to ensure environmental accounting accuracy. Mechanistically, the reported maximum abatement potential of up to 72%—or approximately 1.5 CO₂ of recycled marine-steel—assumes a complete technological displacement where secondary scrap processed via EAF replaces primary iron-ore smelting via the BF–BOF route. Crucially, this environmental dividend is non-linear and highly sensitive to regional energy matrices; the 72% emission reduction is only achievable when the EAF infrastructure is powered by a low-carbon or deeply decarbonized electricity grid. Under fossil-heavy energy profiles, such as those characterizing major South Asian shipbreaking hubs, the net benefits diminish significantly due to the high carbon intensity of the terrestrial power supply. Furthermore, the structural impact of decommissioning 22.2% of the global fleet is specifically modeled around large merchant ships exceeding 20 years of age, establishing a clear asset boundary that prevents the overgeneralization of circular carbon offsets across smaller or non-steel-intensive ship classes.

4.2. Geographical Asymmetry and Energy Matrix Dependency

A critical finding in our discussion is the disparity between shipbuilding and recycling hubs. The concentration of manufacturing in East Asia (China, Japan, and Republic of Korea) and recycling in South Asia (Bangladesh and India) creates a geographical decoupling of environmental responsibility. Our data show that marine-steel in China production for the 677 ships analyzed is high-intensity due to its energy matrix (550–600 gCO₂eq/kWh) [78]. This implies that even if these ships are eventually recycled

in EAF plants, the net carbon benefit is diminished if the electricity grid is not decarbonized. This supports the argument of Hagedorn et al. (2022) [90] that circularity is only as green as the energy that powers it. Therefore, the Green Marine-steel initiative in the maritime sector must prioritize recycling in regions with low-carbon energy profiles or promote the integration of renewable energy in South Asian yards.

4.3. Material Purity and the Lead-Safe Circular Economy

The integration of Regulation 2024/367 [24] into our analysis introduces a vital sanitary dimension to industrial recycling. The discussion must emphasize that “circularity” is not just about quantity (90–95% of marine-steel recovered) but about quality. The presence of hazardous substances like lead, PCB, and asbestos in older ships (over 20 years old), as noted in the UNCTAD 2024 data [13], acts as a contaminant in the circular loop.

If these substances are not removed during the dismantling phase [22], the resulting marine-steel scrap may fail to meet the purity standards required for high-grade industrial components (Table 5). As noted by Singh and Kumar (2024) [59], the irreversible alteration of soil geochemistry in beaching yards is a direct consequence of failing to manage these “sanitary–industrial” interfaces. Thus, the transition to the EU List of Authorized Shipyards [91] is a prerequisite for a legitimate green steel market.

4.4. Extended Producer Responsibility and Economic Barriers

Finally, the disconnect identified between manufacturers and recyclers suggests a failure in the current EPR framework. At present, the sale to brokers serves as a loophole to bypass the Basel Convention [21] and Hong Kong Conventions [22]. For the maritime industry to achieve a true circular economy, shipbuilding contracts should include End-of-Life clauses or Digital Ship Passports [92]. This would ensure that the high-tensile marine-steel identified in Tables 1 and 4 is tracked and returned to certified EAF facilities, preventing the down-cycling of valuable alloys into low-grade construction materials.

5. Synthesis and Methodological Alignment

The integration of the empirical findings from the systematic review (Section 3) and the theoretical formulations of the semi-systematic framework (Section 4) elucidates a clear methodological progression. To resolve the analytical disconnect between descriptive data and lifecycle theory, Table 5 maps the key variables crossing both sections, establishing the similarities and specific conceptual advances achieved in this study.

A critical analysis of the 35 reviewed studies reveals that the reported environmental and carbon mitigation efficiencies exhibit significant non-linear divergences, ranging from 32% up to 99% [7,11,15,71]. These differences do not stem from mathematical errors but from two fundamental variables: regional energy matrices and system boundaries. For instance, while Broadbent [11] and ICCT [15] establish an upper-bound carbon abatement boundary of 70–72% assuming low-carbon electricity grids for EAF reprocessing, studies in major South Asian hubs demonstrate that the high carbon intensity of local power grids (often exceeding 550–600 gCO₂eq/kWh [77]) severely diminishes net mitigation margins. Furthermore, a methodological cleavage is observed between descriptive regional gap analyses (such as Sunaryo [67] in Indonesia or Ocampo [47] in Brazil) and robust multicriteria decision-making frameworks. Regarding methodological robustness, approaches implementing quantitative LCA and the Fuzzy BWM [65] prove to be significantly more robust than static statistical compilations, as they actively account for the stochastic uncertainties of hazardous waste dispersion and complex ship structural toxicities.

Despite the proliferation of circular economy literature in the maritime sector, two major structural uncertainties remain unresolved. First, current literature fails to provide a

unified quantitative index to manage Circular Toxicity during primary intertidal cutting. While the recovery percentage of marine-steel is high (90–97% as mapped in Table 6), the chemical leaching kinetics of heavy metals ($j = 1$) and anti-fouling biocides ($j = 2$) into the benthic ecosystem are treated as qualitative external risks rather than parameterized variables within the circular loops. Second, a severe regulatory uncertainty persists regarding EPR. The reviewed literature acknowledges a systemic disconnect: major manufacturing nations (China, Republic of Korea, or Japan) transfer lifecycle liabilities to third-party brokers, effectively laundering the ship’s environmental debt before it reaches end-of-life shipyards in Bangladesh or India. None of the evaluated studies provide a mathematical or economic model to internalize this broker loophole, leaving a critical gap in international maritime policy enforcement.

Table 6. Critical assessment of selected literature: methodological robustness, divergences, and uncertainties.

Thematic Area	Most Robust Methodology Identified	Why Reported Data Differ	Remaining Uncertainties/Knowledge Gaps
Regulatory & Economic Aspects	Hybrid LCA & Carbon Market Modeling [49,50]	Differences depend on whether financial models internalize waste containment costs vs. traditional high-standard yard cost premiums.	Absence of legal/economic models to enforce EPR when ships are sold to third-party intermediate brokers.
Health, Safety & Risk Management	Fuzzy BWM [65] & Probabilistic Risk Assessment [52]	Divergences are rooted in geographic scope; localized labor informality in the Global South distorts accident tracking accuracy.	Lack of parameterization for Circular Toxicity; material recovery rates are clear, but chemical reintroduction into supply chains is unquantified.
Environmental Impact & Material Recovery	Quantitative LCA [11,15]	Carbon mitigation varies (32% to 99%) due to regional electricity grid factors (e.g., coal-heavy grids in EAF production).	Uncertainties in measuring the real carbon footprint reduction when secondary materials are exported as undefined foundry scrap [84].

The multi-dimensional analysis of the selected literature is structured in Table 6, which critically links the primary thematic areas with their methodological strengths, identified data discrepancies, and unresolved knowledge gaps.

6. Conclusions

- **Decarbonization Potential of Structural Marine-steel:** This research confirms that ship recycling is a primary decarbonization lever for the maritime industry. By recovering structural marine-steel from end-of-life ships, it is possible to achieve a reduction of up to 72% in GHG emissions compared to primary ore-based production, effectively abating approximately 1.5 tCO₂/t of recycled marine-steel.
- **Mitigation of Embodied Carbon:** Unlike operational decarbonization (tank-to-wake), which depends on fuel transition, the recovery of naval marine-steel directly addresses the embodied carbon of the global fleet. Integrating ship recycling into life cycle assessments allows for a more holistic and accurate accounting of the maritime sector’s total environmental footprint.
- **Sensitivity to Energy Matrices:** The environmental efficiency of the electric arc furnace route is highly dependent on regional energy profiles. In jurisdictions like China, a high-carbon intensity grid (550–600 gCO₂eq/kWh) [78] can diminish the net benefits of recycling, highlighting the urgent need for decarbonizing the terrestrial power grids to maximize the sustainability of the “green marine-steel” loop.

- **Regulatory Safeguards Against Circular Toxicity:** The enforcement of the Hong Kong Convention (2025) [22] and Regulation 1257/2013 [23] is critical to ensuring “clean circularity.” The systematic remediation of hazardous materials, such as PCB and lead, is not only an environmental necessity but a technical prerequisite to ensuring that the chemical purity of recovered scrap meets the standards for high-grade industrial applications.
- **Transition Toward Extended Producer Responsibility:** The identified disconnect between shipbuilding hubs and recycling regions necessitates a shift toward Extended Producer Responsibility. Implementing material traceability and design-for-recycling principles is essential to transform shipbreaking facilities into high-tech carbon-abatement hubs, fostering a truly sustainable maritime circular economy.
- **Future Research Directions:** To bridge the critical knowledge gaps identified in this study, future research must shift from qualitative systemic mappings toward robust, empirical predictive models. First and foremost, there is an urgent need to develop standardized methodological frameworks capable of precisely quantifying the net GHG emission reductions yielded by the ship recycling sector. While secondary steel production via EAF offers a proven lower carbon footprint, the maritime community lacks a global, verified accounting system to trace and allocate these Scope 3 emission offsets back to shipowners, shipbuilders, and port infrastructures. Future studies should focus on establishing localized LCA that account for variables such as geographical energy-matrix asymmetries, structural transport logistics, and the specific contamination degrees of marine-steel scrap.
- **Strategic Policy Pathways:** Furthermore, the decoupling of the maritime industry from its historic linear paradigm requires deep exploration into the techno-economic and political dimensions of the circular economy. Key future lines of inquiry should investigate the harmonization of international regulatory frameworks, such as integrating EPR with dynamic carbon taxation mechanisms (e.g., the EU Emissions Trading System). Research must also address the material–energy nexus by evaluating how technological innovations in clean energy grids can further decarbonize the heavy dismantling and melting processes themselves. Ultimately, transforming ship recycling into an indisputable pillar of maritime decarbonization depends on creating data-driven, traceable, and legally validated frameworks that turn end-of-life ships into measurable capital for global net-zero pathways.

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Abbreviations

The following abbreviations are used in this manuscript:

BF–BOF	Blast Furnace–Basic Oxygen Furnace
BWM	Best–Worst Method
CNP	Carbon Neutral Ports
CRCF	Carbon Removals and Carbon Farming
DRI	Direct reduced iron
DWT	Deadweight tonnage
EAF	Electric arc furnace
EU	European Union
GHG	Greenhouse gas
GIS	Geographic information systems
GT	Gross tonnage
ICCT	International Council on Clean Transportation
IMO	International Maritime Organization
<i>j</i>	Index of individual hazardous legacy materials
LEED	Leadership in Energy and Environmental Design
LCA	Life cycle assessments
<i>m</i>	Total number of analyzed structural and coating contaminants
MLIT	Ministry of Land, Infrastructure, Transport and Tourism
ODS	Ozone-depleting substances
OECD	Organization for Economic Cooperation and Development
PCB	Polychlorinated biphenyls
PPE	Personal protective equipment
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
TBT	Tributyltin
UNCTAD	United Nations Conference on Trade and Development
WoS	Web of Science

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