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Sustainability Performance of FPSO Recycling

Júlia Fernandes Sant' Ana [1,*], Lino Guimarães Marujo [1] and Carlos Eduardo Durange de Carvalho Infante [2]

[1] Production Engineering Program, Alberto Luiz Coimbra Institute for Graduate Studies and Research in Engineering, Federal University of Rio de Janeiro, Cidade Universitária Campus, Rio de Janeiro 21941-598, Rio de Janeiro, Brazil; lino@pep.ufrj.br
[2] Business Administration Department, Federal University of São João del Rei, São João del Rei 36307-351, Minas Gerais, Brazil; prof.eduinfante@ufsj.edu.br
* Correspondence: julia.fernandes@pep.ufrj.br

Abstract

The recycling of Floating Production Storage and Offloading (FPSO) units has become an important economic and environmental challenge as a growing number of offshore assets reach end-of-life. This study evaluates the comparative economic, environmental, and social performance of alternative FPSO recycling scenarios evaluated using a stochastic Monte Carlo simulation, focusing on five FPSOs that operated in Brazil and were scheduled for recycling either domestically or in Denmark. Twelve performance indicators were aggregated into sustainability indices using a Monte Carlo simulation with 100,000 iterations, enabling analysis of robustness and variability across ten recycling scenarios. The results indicate that Brazilian recycling scenarios (P-32 and P-33) outperform the Danish scenarios in terms of global performance, with Global Sustainability Index values predominantly ranging from 0.59 to 0.75, compared to 0.37 to 0.61 for the Danish cases. Differences in performance are mainly associated with towing distance, cost structure, and emissions. Social indicators show limited variability and act as a stabilizing component across scenarios. Plasma cutting presents slightly better environmental and economic results than LPG cutting, although it does not alter the overall ranking of scenarios. These findings support decision-making on FPSO recycling scenarios by highlighting the role of uncertainty and contextual factors, particularly in emerging recycling markets.

Keywords: ship recycling; offshore platforms; sustainability performance; Monte Carlo simulation

1. Introduction

The recycling of Floating Production Storage and Offloading (FPSO) units has become a central topic in discussions about corporate sustainability and the oil and gas industry, given the increasing number of units approaching the end of their useful life [1]. It is estimated that more than a thousand ships and floating units reach the end of their useful life per year worldwide, representing an environmental, economic, and social challenge [2].

In the international context, the recent ratification of the Hong Kong Convention (HKC) and the consolidation of regulatory frameworks such as the European Ship Recycling Regulation demonstrate a global trend toward strengthening the environmental and labor standards applied to ship recycling. According to Article No 2 of the HKC, the term "ship" refers to a vessel of any type operating or having operated in the marine environment and includes floating platforms, Floating Storage Units (FSUs), and Floating Production Storage and Offloading units (FPSOs), including units being towed or stripped of equipment.

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Although FPSOs are classified as ships for regulatory purposes, their recycling differs from that of conventional merchant vessels. FPSOs combine ship-type hulls with offshore production systems and may present contaminants associated with oil and gas operations, such as naturally occurring radioactive material (NORM), mercury, and process residues [3]. These factors affect planning, handling, and risk management during recycling activities and must be considered when assessing alternative recycling scenarios for offshore production units.

In this framework, prior knowledge of material flows is essential for ship recycling planning. It enables ship recycling facilities to size resources, estimate economic returns, and anticipate waste generation across process stages, supporting cost control and the management of environmental and occupational risks [4]. At a global scale, study [5] demonstrates that the primary environmental benefit associated with ship recycling derives from the avoidance of primary steel production. This occurs because steel represents approximately 85% of the total weight of a typical ship and can be recovered and reintegrated into industrial supply chains, illustrating the role of ship recycling as a circular economy pathway for retaining material value and reducing the demand for virgin raw materials. The authors also emphasize that socioeconomic aspects, such as employment generation and fluctuations in light displacement tonnage (LDT) prices, play a relevant role in the selection of ship recycling destinations. Ship recycling is therefore characterized by multiple operational stages, high labor demand, and the involvement of diverse stakeholders [6].

The ship recycling process typically begins with preparation and cleaning activities (pre-cutting), during which hazardous substances such as asbestos, PCBs, toxic paints, and oils are identified and removed. The process includes the drainage of tanks, removal of sludge and operational residues, and cleaning of holds, aiming to reduce the risks of fire, explosion, and pollution during subsequent cutting operations [7]. Following the initial cleaning, the ship is segmented into sections using oxy-fuel (LPG) torches or plasma cutting. These technologies differ in terms of efficiency, occupational safety, and generated emissions. Plasma cutting is generally more precise and cleaner, whereas LPG offers a lower cost but generates higher pollutant emissions [2]. Each cut section is subsequently transferred from the primary cutting zone to the secondary zone, where the final downsizing into transportable pieces occurs [7]. Simultaneously, reusable items (including equipment, furniture, and electronic components) are salvaged and traded in the second-hand market [7]. The entire process is concluded with the sorting and segregation of recyclable materials and hazardous waste, ensuring the environmentally sound disposal of each material type.

For offshore production units, particularly FPSOs, the preparation and cleaning stage may also involve decontamination procedures associated with hazardous materials and naturally occurring radioactive material (NORM), resulting from oil and gas operations. Case-based evidence indicates that regulatory constraints on waste handling and disposal, as well as logistical requirements for offshore and onshore decontamination, can affect project timelines and overall costs, even when such costs are not explicitly quantified [8].

Within this context, circular economy principles have been increasingly referenced in the literature as a conceptual framework for ship recycling activities [9]. The approach proposed by the Ellen MacArthur Foundation distinguishes technical and biological cycles and emphasizes the extension of material use through reuse and recycling strategies. Applied to ship recycling, these principles support the organization of material flows that prioritize recovery and reintegration into production chains rather than disposal. Previous studies have discussed the application of circular economy concepts to ship and offshore structure recycling in different regional contexts, highlighting their relevance for material recovery and waste management strategies [10,11].

However, recent contributions emphasize that high material recovery rates alone do not guarantee circularity when environmental and social externalities persist. In this context, the concept of a "True and Ethical Circular Economy" highlights the importance of traceability, upstream design choices, transparency, and coordination across the value chain [9,12]. At the implementation level, circular ship recycling depends on coordination across a broader maritime industrial ecosystem involving shipyards, classification societies, ports, scrap and waste companies, recyclers, brokers, equipment suppliers, and regulatory authorities [12]. Nevertheless, the transition toward safer and more circular recycling practices remains constrained by limited transaction transparency, regulatory burdens, and narrow operational margins that restrict investments in improved technologies, while recycling processes still involve hazardous material streams requiring specialized treatment even when representing a relatively small mass fraction [12,13]. Innovation has therefore been framed as an enabling pathway, particularly through upstream design strategies and lifecycle documentation. Recent guidance encourages the integration of end-of-life considerations into ship design [14], including design-for-recycling measures aimed at minimizing hazardous substances and facilitating ship recycling operations [12]. These approaches are also linked to documentation and material passport mechanisms designed to reduce information gaps and support reuse and remanufacturing strategies. Examples include lifecycle documentation systems proposed for ships and corporate applications such as the Cradle-to-Cradle Passport developed by Maersk, as well as initiatives proposing Ship Lifecycle Passports aligned with emerging disclosure requirements [9,12].

Recycling practices vary according to the method adopted and the regulatory and infrastructural context. Beaching, commonly used in parts of South Asia, is associated with limited environmental containment and higher occupational risks [15]. The landing method, applied for example in Turkey, involves transferring ship sections onto inclined ramps, combining operational efficiency with improved containment [16]. The alongside method, which is common in Europe, enables controlled operations utilizing cranes, thereby reducing the risk of leaks compared to beaching [6]. The dry-docking method is considered the safest and most environmentally sound approach, as it allows for the complete containment of pollutants, though it involves high costs [17].

Of the 210 FPSO units currently operational worldwide, 64 are located in Brazil, followed by the United Kingdom (17), Nigeria (16), and China (14) [1]. Despite hosting the largest number of FPSO units, the recycling of offshore production units in Brazil remains limited [18]. According to the International Association of Oil & Gas Producers (IOGP), the country presents a high potential for activity cessation in the coming years but still faces structural challenges in establishing a national ship recycling chain. As a result, Brazilian FPSO units are sent to foreign ship recycling facilities, mainly in Europe, which results in a loss of economic value, technological dependence, and the absence of local benefits [18].

Although Brazil has shipyards with adequate infrastructure, experience with large-scale FPSO recycling in Brazil is still developing, with the first dry-dock operations involving the FPSOs P-32 and P-33 expected between 2024 and 2025 [1]. In parallel, the absence of a consolidated regulatory framework and economic incentives restricts the feasibility of implementing this activity on a national scale. Within this context, Bill No. 1.584/2021 represents an initial effort to establish normative foundations for the sector, drawing on international regulatory practices.

Methodological gaps persist in the measurement of the sustainable performance in ship recycling, particularly for FPSOs. While regulations address hazardous material management, quantitative instruments for assessing environmental impacts and carbon balances in ship recycling remain limited [19]. In addition, the scarcity of reliable empirical data and historical time series, together with restricted public data availability, constrains

the development of emissions inventories, cost estimations, and social indicators [5,20]. These limitations highlight the need for methodological approaches capable of supporting the evaluation of sustainability performance across different ship recycling scenarios and contexts, thereby offering technical support for strategic and regulatory decisions.

Given this scenario, the present study focuses on the comparative performance of FPSO recycling. The analysis is applied to real-world scenarios, integrating economic, environmental, and social indicators. The objective is to provide a comparative, scenario-based assessment consistent with data availability.

The remainder of this article is structured as follows. Section 2 presents ship recycling performance indicators identified through a systematic literature review conducted in accordance with the PRISMA protocol. Section 3 describes the methodological approach and scenario construction, including the characterization of the five FPSO case studies, and the Monte Carlo simulation procedure. Section 4 presents and discusses the results obtained for the sustainability indices (global, environmental, social, and economic) across the ten ship recycling scenarios. Finally, Section 5 summarizes the main conclusions, discusses the limitations of this study, and offers recommendations for future research.

2. Ship Recycling Performance

The literature suggests several metrics that allow for the evaluation of recycling performance, covering the three dimensions of sustainability: social, economic, and environmental. Within the social dimension, the literature addresses topics such as employment generation and working conditions concerning the health and safety of laborers.

For conventional ship recycling activities at the national level, in Alang, India, study [7] estimates that 160 ship recycling facilities recycle approximately 350 ships annually, yielding around 2.7 million tons of recovered steel. Approximately 70% of the workforce is concentrated in the cutting stage. The authors of [4] report that a 10,000-ton vessel can be recycled in just two days, while the facility dimensions vary from 50 to 240 m in length and 30 to 120 m in width. These figures illustrate the magnitude of the employed labor force and the critical importance of physical planning to ensuring minimum working conditions. Similarly, the work in [21] observes that in Bangladesh, the ship recycling activity employs approximately 25,000 direct and 200,000 indirect workers, supplying 80–90% of the country's domestic steel consumption, but simultaneously recording high accident rates.

In contrast, for offshore production units such as FPSOs, social and operational conditions are strongly influenced by additional technical constraints. The study by [3], based on a global assessment of ship recycling facilities equipped to handle NORM-contaminated FPSOs, highlights the limited capacity for recycling large-scale units, showing that only seven out of the 19 assessed facilities can receive FPSOs exceeding 300 m in length.

Risks to worker health and safety are a recurrent theme in the literature. The authors of [22,23] indicate that the lack of formal management systems and the non-compliance with clauses of the HKC contribute to a hazardous scenario (accidents involving falls, fires, and explosions), necessitating improved training and safety culture. In [7], the authors identify the cutting stage as the most critical in terms of accidents. Studies such as those by [20,24] quantify carcinogenic risks due to soil contamination by toxic elements and estimate that 15% of the workforce exposed between 1994 and 2002 may develop mesothelioma [20]. Furthermore, studies [21,25] draw attention to the socioeconomic condition of these laborers, who receive between 1 and 6 USD per day, often without adequate training, which results in high rates of accidents and occupational diseases.

Within the economic dimension, the findings in [26] demonstrated that in India the recycling of a 10,000-ton ship yields an average profit of US$67 per ton, whereas the

same operation in the United States results in a loss of US$24 per ton. This difference is attributed to the lack of a market for used components in the U.S., stringent safety requirements, and high labor costs, which implicitly reflect occupational health-related costs, including expenses associated with workplace safety, accident prevention, and long-term health impacts arising from exposure to hazardous substances [26]. The authors of [5] further reinforce that the price paid per ton of light displacement tonnage (LDT) ranges from US$130/LDT in Europe to US$420/LDT in Asia, thus incentivizing ship owners to send ships to destinations with fewer regulatory restrictions. Although the beaching method appears profitable in the short term, the study in [17] showed that it generates a profit of only US$62 per LDT, compared to US$96/LDT for standard recycling practices. Additionally, fluctuations in scrap steel prices have been identified as a source of financial instability for the beaching method, reinforcing its economic vulnerability and environmental unsustainability [5].

This overview confirms that profitability is strongly conditioned by the regulatory environment. Applying the Weighted Aggregated Sum Product Assessment (WASPAS) method, the authors of [27] observed that in Turkey the number of recycled ships decreased following the adoption of the HKC and the European Ship Recycling Regulation, reflecting a consequent increase in compliance costs. For offshore platforms, the financial challenges are even more specific. The authors of [3] estimate mooring costs of approximately US$ 18,000 per day for FPSOs contaminated with NORM. Meanwhile, [18] proposes a model that aggregates the costs of material removal, storage, handling, and unit acquisition, considering optimistic and pessimistic scenarios for scrap revenue.

In addition to direct cutting costs, productivity, shaped by technological choices and process management, is a critical component of profitability. The author of [19] demonstrated that waterjet cutting reduces environmental impacts but increases cutting time, whereas [2] showed that plasma cutting can be up to 60% faster than oxy-LPG cutting, boosting daily revenues despite higher initial investment costs.

Beyond the choice of cutting technology, productivity also depends on how material flows are planned and managed. In [6], using Material Flow Analysis (MFA), the authors demonstrated that over 96% of a ship's mass can be reused when its composition is well-documented and segregation processes are carefully planned. This integrated management approach is also reflected in the studies of [3,18], who linked productivity to calculations of man-hours required for FPSO recycling, enabling more precise estimations of the time and costs involved for complex, large-scale units.

From an environmental standpoint, key concerns in the recycling of ships and FPSOs include greenhouse gas (GHG) emissions and energy consumption, as well as the generation and management of hazardous waste, which may affect soil, water, and air compartments. Several studies quantify the climatic impacts associated with various cutting technologies [2,19].

There is a clear consensus on the climate benefits of steel recycling. The authors of [28] calculated that producing rebar from scrap saves 16.5 GJ of energy and avoids 1965 kg CO_2-eq per ton compared to production from primary ore. In [5], the authors estimated that converting 1 kg of cast iron accounts for 81% of the total recovered material, thereby reducing environmental impacts. In a cradle-to-grave analysis of a Panamax oil tanker, results in [29] confirmed that the operational phase dominates the environmental impacts, but the end-of-life phase offers an opportunity to reduce emissions through steel recovery. However, the recycling method adopted plays a critical role. The authors of [17] estimated that standard recycling methods (landing, alongside, or dry docking) avoid emitting 809 kg CO_2-eq per LDT, while beaching increases emissions due to the inadequate handling of hazardous waste.

The complexity is heightened in specific cases, such as the recycling of FPSOs. The authors of [30] demonstrated that GHG emissions must consider not only the recycling process itself but also stages like disconnection and towing, where the diesel consumed by the unit and support vessels constitutes a relevant source of impacts that is still poorly incorporated into traditional models. To integrate economic value and environmental impact, the work in [31] developed an adjusted eco-efficiency index, demonstrating that a significant portion of the added value remains in Europe, while the environmental impacts are concentrated in Asia. This reinforces the need for instruments that incentivize a fairer distribution of environmental costs throughout the lifecycle.

It is important to note that the quantitative values reported in the literature reflect specific regulatory, technological, temporal, and socioeconomic contexts. As such, they should be interpreted as context-dependent benchmarks that illustrate orders of magnitude, dominant drivers, and structural patterns, rather than as directly comparable or transferable performance measures across regions or time periods.

Based on the review of these studies, it was possible to identify seven indicator groups and their corresponding example metrics for evaluating ship recycling performance, as presented in Table 1.

Table 1. Performance Indicators.

Sustainability Dimension	Performance Indicators	Metrics Examples	Source
Social	Employment Generation	Number of workers	[5,7,18,21,22,31,32]
	Occupational health	Exposure time to waste and/or noise	[20,22–24,32–34]
	Occupational Safety	Number of accidents, days away from work	[4,7,21,22,25,28,33]
Economical	Cost	Cost of Activities (cutting, administrative, operational, labor, handling, and storage)	[2,3,17,18,20,26]
	Revenue	Selling price of ferrous and non-ferrous scrap	[3,5,6,18,26,27]
Environmental	Emissions	CO_2eq emissions	[5,19,29,35]
	Hazardous Waste	Soil contamination factor, concentration of hazardous waste, and quantity of pollutants	[21,23–25,29,30,34,36]

3. Materials and Methods

Initially, we conducted a comprehensive literature review covering studies on ship recycling in order to identify potential performance indicators, which constituted the first stage of this research, as illustrated in Figure 1.

Using the PRISMA protocol [37], we retrieved articles related to the topic of this study from the Web of Science (primary database) and Scopus. The following search strategy was applied: ("FPSO" OR "Floating Production Storage and Offloading" OR "ship") AND ("decommission*" OR "dismantle*" OR "end-of-life" OR "recycle*" OR "scrap*" OR "circular economy") AND ("performance" OR "assessment" OR "indicator*" OR "metric*" OR "impact*"). The search returned 650 articles, from which, after evaluating the titles and abstracts, 26 documents were selected, as shown in Figure 2. These articles were used to consolidate the set of indicators presented in the systematic review chapter, as shown in Table 1. Although the resulting indicator set covers environmental, economic, and social dimensions, some aspects discussed in the literature were not operationalized in the

simulation model due to limitations in the availability and consistency of the required data. In particular, impacts on water resources were not explicitly included in the model, despite evidence that ship recycling activities may pose risks to coastal environments through the release of hazardous materials and contaminants [4,25]. Similarly, the broader sustainability literature increasingly highlights the transition toward climate neutrality and the reduction of greenhouse gas emissions as central objectives of contemporary environmental policy and sustainability research [38]. These aspects may therefore represent relevant variables to be incorporated into future assessments of ship recycling system.

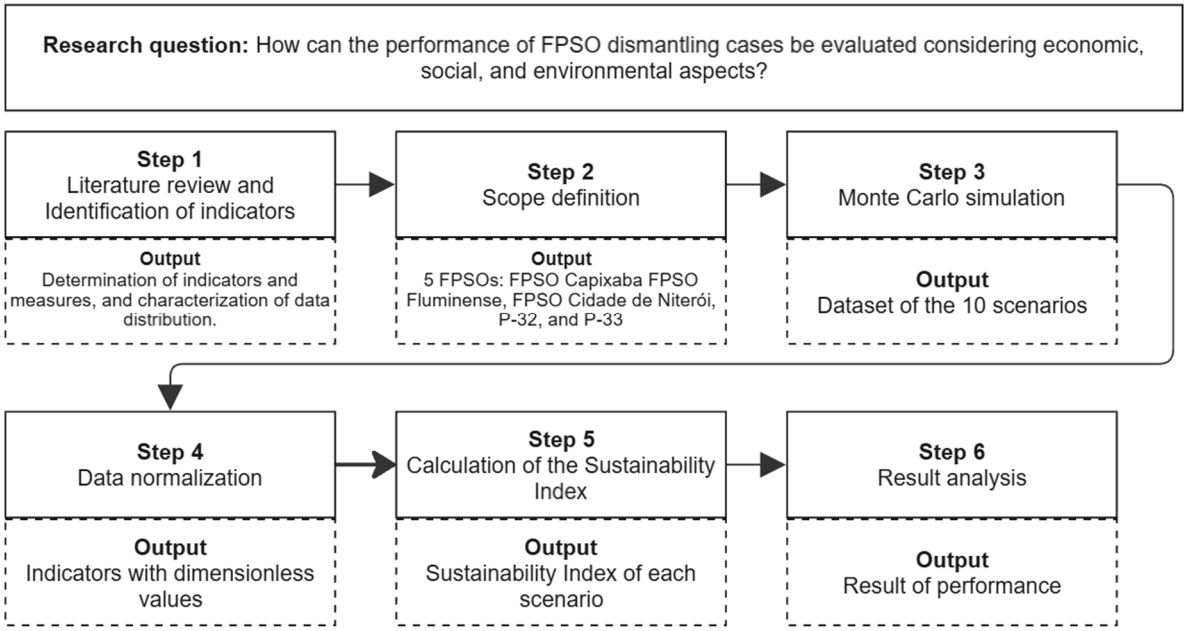


Figure 1. Structure of the research. Note: Solid-line boxes represent process steps, while dashed-line boxes represent outputs.

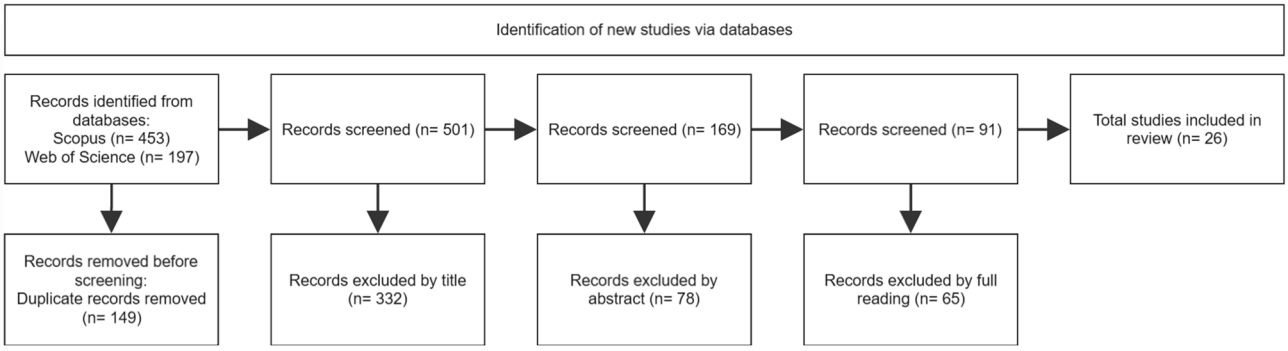


Figure 2. Systematic review diagram.

Subsequently, in Step 2, we defined the scope of the study to include five FPSOs currently undergoing recycling and which operated in Brazil: FPSO Capixaba, FPSO Fluminense, FPSO Cidade de Niterói, P-32, and P-33. FPSO Capixaba and FPSO Cidade de Niterói were ships contracted by Petrobras for oil field development, with FPSO Capixaba owned by SBM and FPSO Cidade de Niterói owned by MODEC. FPSO Fluminense was owned by Shell. SBM, Shell, and MODECopted to recycle their platforms at the Modern American Recycling Services (M.A.R.S.) facility in Frederikshavn, Denmark. For P-32 and P-33, the steel producer Gerdau won the auction for recycling [18]. Currently, P-32 is being recycled at the Ecovix shipyard in Rio Grande do Sul, Brazil. P-33 is currently moored at the Port of Açu, awaiting recycling, which is also planned to take place at the Ecovix

shipyard. These cases define the recycling scenarios analyzed in this study. The Danish scenarios represent established European recycling facilities with longer towing distances, while the Brazilian scenarios reflect emerging domestic recycling capacity with significantly shorter transport routes [1]. In addition, two cutting technologies were evaluated at each location: LPG cutting and plasma cutting. These technologies differ in productivity, energy consumption, emissions, and operational costs, allowing for the assessment of trade-offs between environmental and economic performance [2].

The technical information for each FPSO was collected from documents published by public agencies, such as the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) and the National Agency of Petroleum, Natural Gas, and Biofuels (ANP) [39–43], and is presented in Table 2. Additionally, at this stage, some indicators were adapted to the context of the scenarios involving the five platforms under study, as will be presented in the next section.

Table 2. Characteristics of the FPSO under study.

Characteristics	FPSO Capixaba	FPSO Fluminense	FPSO Cidade de Niterói	P-32	P-33
Sedimentary basin	Jubarte field, Campos basin	Bijupirá and Salema field, Campos basin	Marlim Leste field, Campos basin	Marlim e Voador field, Campos basin	Marlim field, Campos basin
Year of construction	1974 (oil tanker)	1974 (cargo)	1974 (tanker)	1974	1978
Year of conversion	2005	2003	2008	1977	1998
Water depth (m)	between 1400 and 1500	between 400 and 950	between 820 and 2081	between 140 and 185	between 710 and 854
Start of operation	2010	2003	2009	1998	1998
Production interruption	May 2022	December 2021	between January and June 2023	December 2020	July 2019
Lenght (m)	320.8	390	315	337.1	337
Breadth (m)	54.5	60	60	54.5	54.5
Draft (m)	27	16	20.3	21.67	21.62
Lightweight (ton)	52,020	53,227	55,026	44,532	48,921

The companies responsible for the recycling of the FPSOs in Denmark highlight that the selection of the M.A.R.S. facility resulted from an international screening process that evaluated ship recycling facilities worldwide. This evaluation was based on technical and regulatory criteria related to environmental requirements, including NORM, hazardous waste disposal, and sun coral control. MARS was chosen due to its existing environmental licensing and international certification, which ensures full compliance with the standards of the Hong Kong Convention and the requirements of the European Ship Recycling List, thereby guaranteeing traceability, occupational safety, and adequate hazardous material management. This institutional and technological difference underscores the contrast between the current conditions of the European industry, already consolidated in sustainable recycling, and the Brazilian context, which is still in the structuring phase. This reinforces the urgency for a national regulatory framework in Brazil that is aligned with international best practices for recycling.

Based on the data collected for each of these FPSOs, a Monte Carlo simulation (MCS) was executed using Python, implemented in the Spyder (version 5.4.3), with 100,000 repetitions, resulting in a robust database, which constituted Stage 3. MCS is a well-established stochastic technique for risk and uncertainty management, uncertainty propagation, and probabilistic risk analysis [44]. By representing uncertain input parameters through probability distributions rather than single-point estimates, MCS enables sustainability outcomes to be interpreted probabilistically, supporting comparisons across scenarios under uncertainty rather than relying solely on mean values [45,46].

Recent studies have demonstrated the suitability of Monte Carlo approaches for systems characterized by heterogeneous data sources, operational uncertainty, and limited historical datasets, including applications to ship recycling and end-of-life infrastructure contexts, such as assessments of economic feasibility [18], environmental impacts [47], and health risks [24].

During each simulation run, input values associated with economic, environmental, and social dimensions were randomly sampled from predefined probability distributions, defined a priori based on literature and secondary data sources and explicitly reported in Table A1 (Indicators of the assessment), and the resulting sustainability indices were recorded. The selection of probability distributions followed the nature of the available data and established practices in uncertainty modeling. When parameters were characterized by bounded ranges defined by minimum, most likely, and maximum values, triangular distributions were adopted due to their transparency, bounded nature, and frequent use in Monte Carlo simulations under data scarcity [48]. In addition, bimodal distributions were applied exclusively to specific plasma cutting parameters for which the reference literature reports discrete operational alternatives rather than continuous variability [2]. In the economic dimension, the parameter "plasma_cost" was modeled using a bimodal distribution to represent two documented cost–productivity configurations (USD 272.45 and USD 318.82 per shift), which are inversely associated with plasma cutting productivity (23 and 15 min/ton, respectively). Similarly, in the environmental dimension, bimodal distributions were applied to the plasma cutting parameters "cutting_length" (3500 mm and 4150 mm) and "cutting_speed" (300 mm/min and 600 mm/min). As the reference data do not indicate a functional relationship between these parameters [2], they were treated as independent discrete alternatives, with equal probability (50%) assigned to each value to reflect documented technological options rather than artificial continuity.

Subsequently, in Stage 4, the 100,000 samples generated by the Monte Carlo simulation were exported and normalized on a 0 to 1 scale to compute the Global Sustainability Index (GloSI), the Environmental Sustainability Index (EnvSI), the Social Sustainability Index (SocSI), and the Economic Sustainability Index (EcoSI). This normalization respected the objective of maximizing indicators with a positive impact ("workers" and "revenue"), and minimizing those with a negative impact ("days_away", "acquisition_cost", "labor_cost", "handling_storage_cost", "plasma_cutting_cost", "lpg_cutting_cost", "towing_emission", "plasma_cutting_emission", "lpg_cutting_emission", and "crane_emission").

For situations in which higher indicator values produced better results, we applied Equation (1).

$$x'_i(j,k) = \frac{x_i(j,k) - min_{j,k}\{x_i(j,k)\}}{max_{j,k}\{x_i(j,k)\} - min_{j,k}\{x_i(j,k)\}} for\ i:1\ldots m, k:1\ldots n, j:1\ldots p \quad (1)$$

where $x_i(j,k)$ is the original value of indicator i for scenario j in Monte Carlo repetition k, and $x'_i(j,k)$ is the corresponding normalized value.

For situations in which lower indicator values produced better results, we applied Equation (2).

$$x'_i(j,k) = \frac{max_{j,k}\{x_i(j,k)\} - x_i(j,k)}{max_{j,k}\{x_i(j,k)\} - min_{j,k}\{x_i(j,k)\}} for\ i : 1 \dots m, k : 1 \dots n, j : 1 \dots p \quad (2)$$

This type of normalization was necessary because, due to the absence of comparable scenarios in the surveyed literature that shared similar characteristics with the object of study, we opted to utilize an internal benchmark. In this approach, the best value observed among the analyzed scenarios for each measure was selected and assigned as the reference point.

Thus, in Stage 5, the Sustainability Index was calculated, which was obtained by taking the average of the normalized indicators used in each studied scenario. Finally, in Stage 6, the results are analyzed.

4. Results and Discussion

4.1. Initial Definitions

Based on the indicators identified in the literature, data collection for the five FPSO case studies was conducted through bibliographic and documentary research. Table 1 summarizes the performance indicators identified in the systematic literature review as potential candidates for assessing ship recycling activities. The selection of indicators for the quantitative assessment considered the availability of current and comparable data, as well as their suitability for probabilistic modeling across all scenarios. As a result, Table A1 (Appendix B) reports the subset of 12 indicators and their corresponding metrics that could be operationalized to assess the sustainability performance of ship recycling activities in the five FPSO case studies. Because ship recycling operations are still ongoing and documentation is not consistently available across all units, some relevant issues identified in Table 1, such as NORM aspects, could not be included in the quantitative model. These issues are therefore treated as data-driven limitations rather than excluded concerns.

There are two indicators related to the social dimension, as reported in Table A1: "workers", which evaluates the potential for employment generation, and "days_away", which represents the number of workdays lost due to absenteeism resulting from occupational accidents and health-related incidents during ship recycling operations.

The economic dimension comprises six indicators: "acquisition_cost", which represents the cost of acquiring the unit for ship recycling; "labor_cost", which accounts exclusively for workforce-related expenses; "handling_storage_cost" associated with material handling and temporary storage operations during ship recycling facility; "plasma_cutting_cost" and "lpg_cutting_cost", which represent technology-specific cutting operational costs and are applied in a mutually exclusive manner depending on the cutting method adopted; and "revenue", which reflects the economic return from the sale of steel recovered through ship recycling activities.

Finally, the environmental dimension includes four indicators: "towing_emission", which captures greenhouse gas emissions associated with towing the FPSO from original location to ship recycling facility; "plasma_cutting_emission" and "lpg_cutting_emission", which quantify emissions generated during cutting operations according to the selected technology; and "crane_emission", representing emissions associated with crane-assisted lifting and handling activities during ship recycling operations.

It is important to note that, although 12 indicators were selected, not all indicators are simultaneously applied in every scenario. Some indicators are technology-specific and therefore mutually exclusive, depending on the cutting method adopted. In particular, "lpg_cutting_cost" and "plasma_cutting_cost", as well as "lpg_cutting_emission" and

"plasma_cutting_emission", are alternately used according to the cutting technology considered in each scenario, thereby avoiding overlap between cost and emission components.

Based on the combination of FPSO unit, ship recycling facility location, and cutting technology, ten scenarios were analyzed: (1) FPSO Capixaba sent to M.A.R.S. with LPG cutting; (2) FPSO Fluminense to M.A.R.S. with LPG cutting; (3) FPSO Cidade de Niterói to M.A.R.S. with LPG cutting; (4) FPSO P-32 to Ecovix with LPG cutting; (5) FPSO P-33 to Ecovix with LPG cutting; (6) FPSO Capixaba to M.A.R.S. with plasma cutting; (7) FPSO Fluminense to M.A.R.S. with plasma cutting; (8) FPSO Cidade de Niterói to M.A.R.S. with plasma cutting; (9) FPSO P-32 to Ecovix with plasma cutting; (10) FPSO P-33 to Ecovix with plasma cutting. For clarity, scenario labels used in the figures follow a standardized naming convention in which "Bra" and "Den" indicate the country where the ship recycling facility is located (Brazil or Denmark, respectively). The relationship between indicators, scenarios, and cutting technologies, as well as the differentiating variables among scenarios, is summarized in Table A2 (Appendix B).

In the baseline assessment, all indicators are assigned equal weights. Consequently, the contribution of each sustainability dimension to the GloSI is determined by the number of indicators grouped under each dimension, without assuming any explicit normative prioritization among economic, social, and environmental aspects.

The analysis for all indicators was focused on steel, as it represents the material with the greatest reuse potential and economic relevance within the context of ship recycling [49]. Regarding the environmental dimension, because the recycling of these FPSOs is still ongoing, information on the final destination of the recovered steel is not yet available. Although the steel recycling process itself is not included in this analysis, the steel scrap generated during ship recycling can be utilized as a secondary raw material for steel production, in conformity with the PCR *Basic Iron or Steel* [50,51]. This system boundary delimitation is consistent with previous studies that assess ship recycling performance by focusing on operations within the ship recycling facility, while treating steel remelting and secondary steel production as downstream industrial processes belonging to a different system [6,29]. Emissions associated with steel remelting are influenced by region-specific factors, such as energy mix and steelmaking configurations, rather than by ship recycling practices themselves [28,35]. Including this stage would therefore introduce variability unrelated to the recycling scenarios under comparison. For this reason, the system boundary includes towing to the ship recycling facility, cutting process (performed by LPG or plasma), and the crane operation used to handle the cut pieces within the ship recycling facility, ensuring methodological coherence and comparability across all scenarios.

It is worth emphasizing that to adjust monetary values over time, we use price indices, such as the Consumer Price Index (CPI). This rationale can be applied either through calculation using Equation 3 or by consulting online calculators (CPI Inflation Calculator, 2025). Table A3 (Appendix B) presents the adjusted data as well as the distribution.

$$\text{Adjusted Value} = \text{Original Value} \cdot \frac{\text{Index in the future year}}{\text{Index in the base year}} \quad (3)$$

4.2. Results

Based on the normalization of the indicators and the calculation of the Sustainability Index, it was possible to determine the sustainability ranking of the scenarios, as shown in Figure 3. For interpretative purposes, three categories were defined: (i) superior sustainability, for global performance indices greater than or equal to 0.8; (ii) intermediate sustainability, for indices between 0.5 and 0.8; and (iii) lower sustainability, for indices less than or equal to 0.5. These categories are applied as internal interpretative classes derived from the 0–1 normalization and are not intended to represent absolute or normative sustain-

ability thresholds, but rather to facilitate the qualitative discussion of relative performance levels across scenarios.

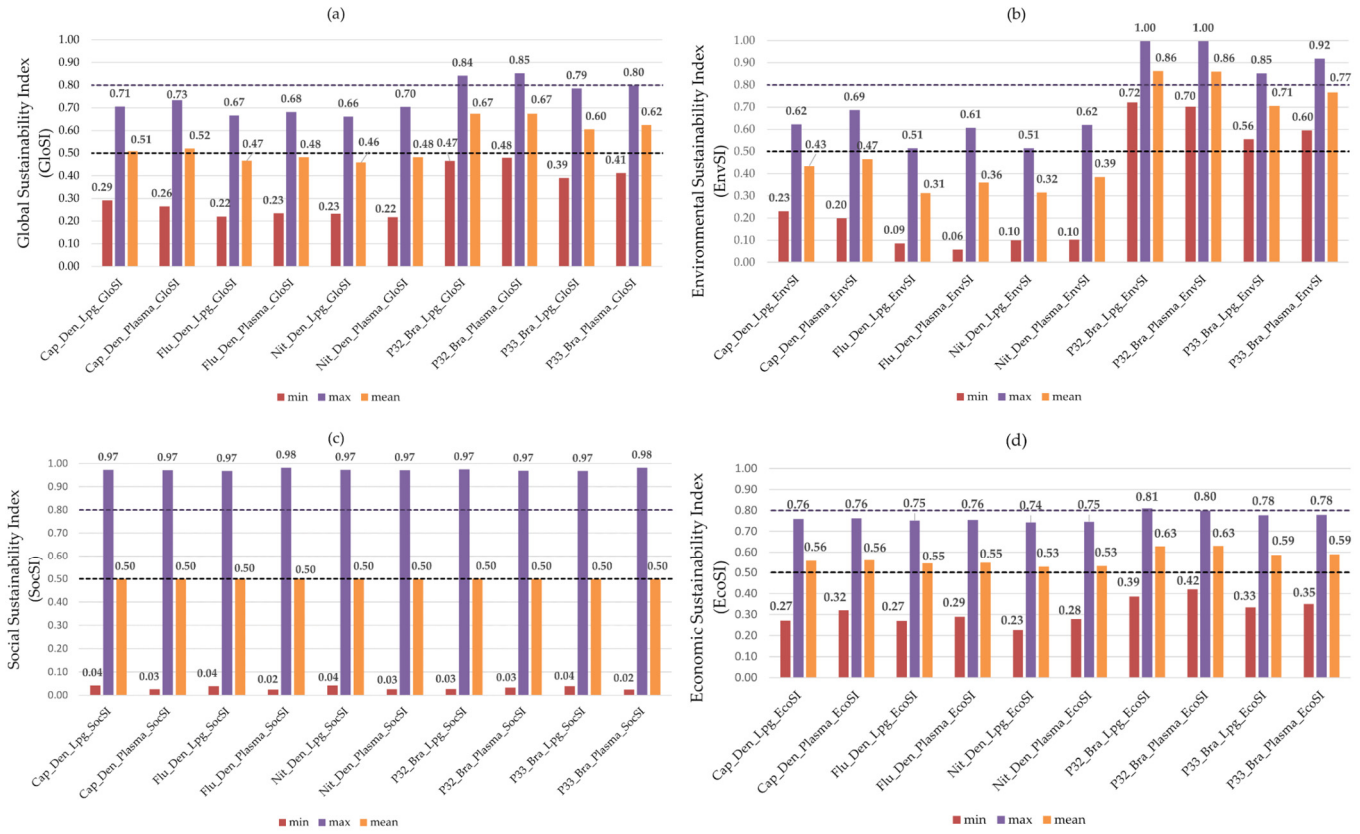


Figure 3. Comparison of the simulated results: (**a**) Global Sustainability Index (GloSI); (**b**) Environmental Sustainability Index (EnvSI); (**c**) Social Sustainability Index (SocSI); (**d**) Economic Sustainability Index (EcoSI). Note: Dashed horizontal lines indicate reference thresholds at 0.5 and 0.8.

Figure 3a presents the aggregated performance of the ten simulated scenarios based on the GloSI, which synthesizes environmental, economic, and social aspects in a weighted manner. It is observed that scenarios P-32 and P-33 achieve the highest average and maximum values, consistently positioning themselves within the intermediate and superior sustainability ranges. Following this, the scenarios of the FPSO Capixaba present average GloSI values within the intermediate sustainability range, indicating that these scenarios maintain a balance among the evaluated dimensions, although they do not reach the efficiency levels observed in P-32 and P-33. In contrast, the scenarios of FPSO Fluminense and FPSO Niterói record average values below 0.50, placing them in the lower sustainability range.

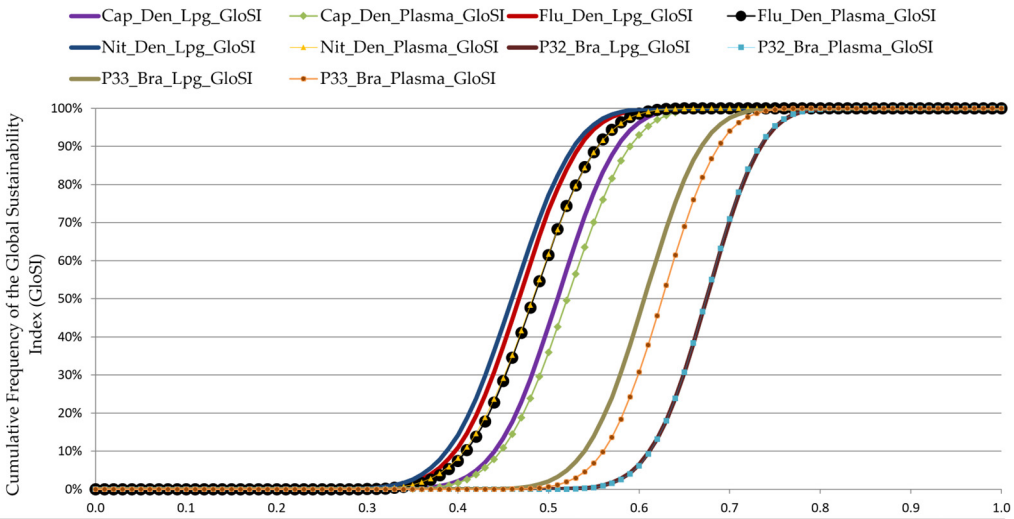
The superior performance observed in the Brazilian scenarios is primarily driven by logistical and cost-related factors rather than by technological differences alone. The substantially shorter towing distances for P-32 and P-33 reduce fuel consumption and associated emissions, which has a dominant effect on the environmental performance. In addition, lower acquisition and handling-related costs contribute to improved economic outcomes, resulting in higher and more stable global sustainability scores. In contrast, the Danish scenarios are penalized by long-distance towing requirements, which increase both emissions and costs, limiting overall performance despite the presence of well-established recycling infrastructure.

Figure 3b presents the performance of the Environmental Sustainability Index (EnvSI). Similar to the GloSI results, the P-32 and P-33 scenarios show the highest averages, remaining within the upper sustainability range, while the other scenarios remain within

the intermediate range. Although the overall ranking of the scenarios is similar to that of the GloSI, a greater spread among the mean values is observed, indicating higher environmental variability across the evaluated alternatives.

Figure 3c demonstrates that the results for the Social Sustainability Index (SocSI) exhibit little variation among the ten scenarios. All scenarios are concentrated within the intermediate and superior ranges, demonstrating homogeneity in social performance. Thus, the social component acts as a stabilizing factor, without significantly altering the sustainability hierarchy observed in the other dimensions. Figure 3d presents the results of the Economic Sustainability Index (EcoSI), in which the P-32 and P-33 scenarios once again stand out with the best performances, falling within the upper sustainability range. Similar to what is observed in Figure 3c, there is less dispersion among the mean values, suggesting greater economic stability across these scenarios.

To facilitate comparative analysis, the sustainability index values were grouped into performance classes, as shown in Figure 4. The cumulative distribution function (CDF) curves illustrate the differences in sustainability levels among the 10 recycling scenarios evaluated. For the GloSI, all P-32 and P-33 scenarios show a 100% probability of scoring above IS $\geq$ 0.4, and approximately 54.5% (P33_Bra_Lpg_GloSI) to 93.84% (P32_Bra_Plasma_GloSI) achieving scores equal to or greater than 0.6, indicating predominantly intermediate and superior performance ranges. Meanwhile, the FPSO Capixaba scenarios exhibit a more dispersed distribution, with approximately 94.16% (Cap_Den_Lpg_GloSI) of the results falling within [0.4, 0.6), suggesting classification within the intermediate range. On the other hand, the FPSO Fluminense and FPSO Niterói scenarios display higher density below 0.5, with probabilities ranging from 61.47% (Flu_Den_Plasma_GloSI) to 73.14% (Flu_Den_Lpg_GloSI) of being positioned in the lower sustainability range.



	[0–0.1)	[0.1–0.2)	[0.2–0.3)	[0.3–0.4)	[0.4–0.5)	[0.5–0.6)	[0.6–0.7)	[0.7–0.8)	[0.8–0.9)	[0.9–1]
Cap_Den_Lpg_GloSI	0.00%	0.00%	0.00%	2.13%	40.57%	53.59%	3.70%	0.00%	0.00%	0.00%
Cap_Den_Plasma_GloSI	0.00%	0.00%	0.00%	1.67%	34.25%	57.08%	6.99%	0.01%	0.00%	0.00%
Flu_Den_Lpg_GloSI	0.00%	0.00%	0.11%	10.89%	62.14%	26.49%	0.38%	0.00%	0.00%	0.00%
Flu_Den_Plasma_GloSI	0.00%	0.00%	0.06%	7.36%	54.05%	37.13%	1.40%	0.00%	0.00%	0.00%
Nit_Den_Lpg_GloSI	0.00%	0.00%	0.21%	14.02%	62.93%	22.59%	0.26%	0.00%	0.00%	0.00%
Nit_Den_Plasma_GloSI	0.00%	0.00%	0.09%	8.12%	53.55%	36.73%	1.52%	0.00%	0.00%	0.00%
P32_Bra_Lpg_GloSI	0.00%	0.00%	0.00%	0.00%	0.01%	6.49%	63.97%	29.32%	0.22%	0.00%
P32_Bra_Plasma_GloSI	0.00%	0.00%	0.00%	0.00%	0.01%	6.15%	64.84%	28.83%	0.18%	0.00%
P33_Bra_Lpg_GloSI	0.00%	0.00%	0.00%	0.00%	2.08%	43.42%	51.96%	2.55%	0.00%	0.00%
P33_Bra_Plasma_GloSI	0.00%	0.00%	0.00%	0.00%	0.64%	30.14%	63.23%	5.99%	0.00%	0.00%

Figure 4. Cumulative frequency of the Global Sustainability Index (GloSI).

The Monte Carlo simulation highlights that uncertainty affects the evaluated scenarios in different ways, depending on their cost and emission structures. Brazilian scenarios exhibit narrower performance distributions, indicating greater robustness and predictability across simulations, whereas Danish scenarios show wider dispersion, reflecting higher sensitivity to towing distance, fuel consumption, and handling-related cost assumptions. Although plasma cutting presents slightly lower environmental and economic impacts than LPG cutting, its effect is mainly observed in the dispersion of results rather than in shifts in average performance, reinforcing the role of uncertainty analysis in distinguishing robust from more volatile recycling options.

For the EnvSI (Figure A1 in Appendix A), a similar behavior is observed, but with greater dispersion and sensitivity to cutting and transportation emissions. The probabilities indicate that all P-32 and P-33 scenarios exceed an EnvSI value of 0.6 in more than 95% of the simulations. Meanwhile, the Capixaba, Fluminense, and Niterói scenarios exhibit values below 0.5 in 56.27% (Cap_Den_Plasma_EnvSI) to 99.97% (Nit_Den_Lpg_EnvSI) of their results, confirming more limited environmental performance.

For the SocSI (Figure A2 in Appendix A), the curves of the ten alternatives nearly overlap, with over 48% of occurrences falling within the intermediate sustainability range [0.5, 0.8), highlighting uniformity and stability in the social parameters. Finally, the EcoSI (Figure A3 in Appendix A) mirrors the hierarchy observed in the GlobSI, where all P-32 and P-33 scenarios achieve a probability greater than 90% of EcoSI $\geq$ 0.5, compared to the other scenarios. The highest concentration of results is observed in the "P32_Bra_Lpg_EcoSI" and "P32_Bra_Plasma_EcoSI" cases, which stand out by predominantly falling within the [0.6, 0.7) range, whereas the remaining scenarios are concentrated in the range [0.5, 0.6).

We also analyzed the performance of the scenarios in a disaggregated manner with respect to the GloSI. Comparatively, the scenarios related to recycling in Denmark, as shown in Figure 5, exhibit distributions concentrated between 0.37 and 0.61, characterizing the threshold range between intermediate sustainability levels. Furthermore, there is a low probability of achieving GloSI values higher than 0.7. This configuration indicates stable yet limited performance, with a restricted margin for advancement toward superior sustainability levels. It is also observed that the use of plasma cutting slightly shifts the distributions toward higher values, though the gain remains marginal.

The Brazilian scenarios, as illustrated in Figure 6, demonstrate a consistently superior global performance compared to all other cases evaluated. The distributions of the GloSI indicate that 90% of the simulations are concentrated between 0.59 and 0.75 for the P-32 and between 0.52 and 0.70 for the P-33, predominantly encompassing the intermediate sustainability range. Similarly to the Danish scenarios, the plasma cutting method maintains a slight advantage over the LPG method, reflecting a minor gain in efficiency without significantly altering the statistical behavior of the distributions. The overall distribution of performance clearly highlights that the Brazilian scenarios surpass the values achieved by the Danish cases. This configuration suggests that the national operations combine the most sustainable and consistent conditions among all evaluated scenarios.

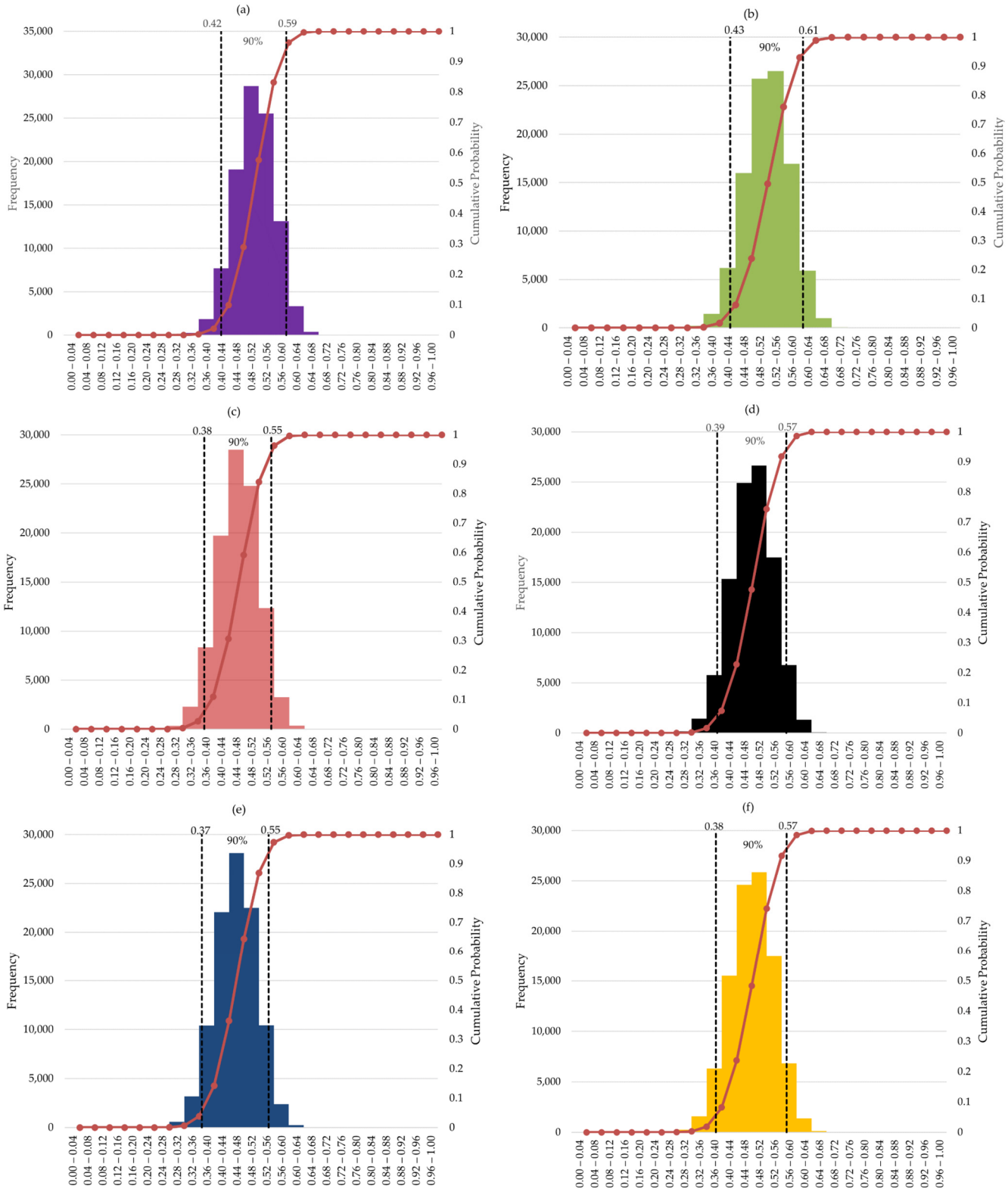


Figure 5. Distribution of performance of FPSOs recycled in Denmark: (**a**) Cap_Den_Lpg_GloSI; (**b**) Cap_Den_Plasma_GloSI; (**c**) Flu_Den_Lpg_GloSI; (**d**) Flu_Den_Plasma_GloSI; (**e**) Nit_Den_Lpg_GloSI; (**f**) Nit_Den_Plasma_GloSI. Note: The vertical dashed lines indicate the 5th and 95th percentiles (P5 and P95), and the red line represents the cumulative distribution.

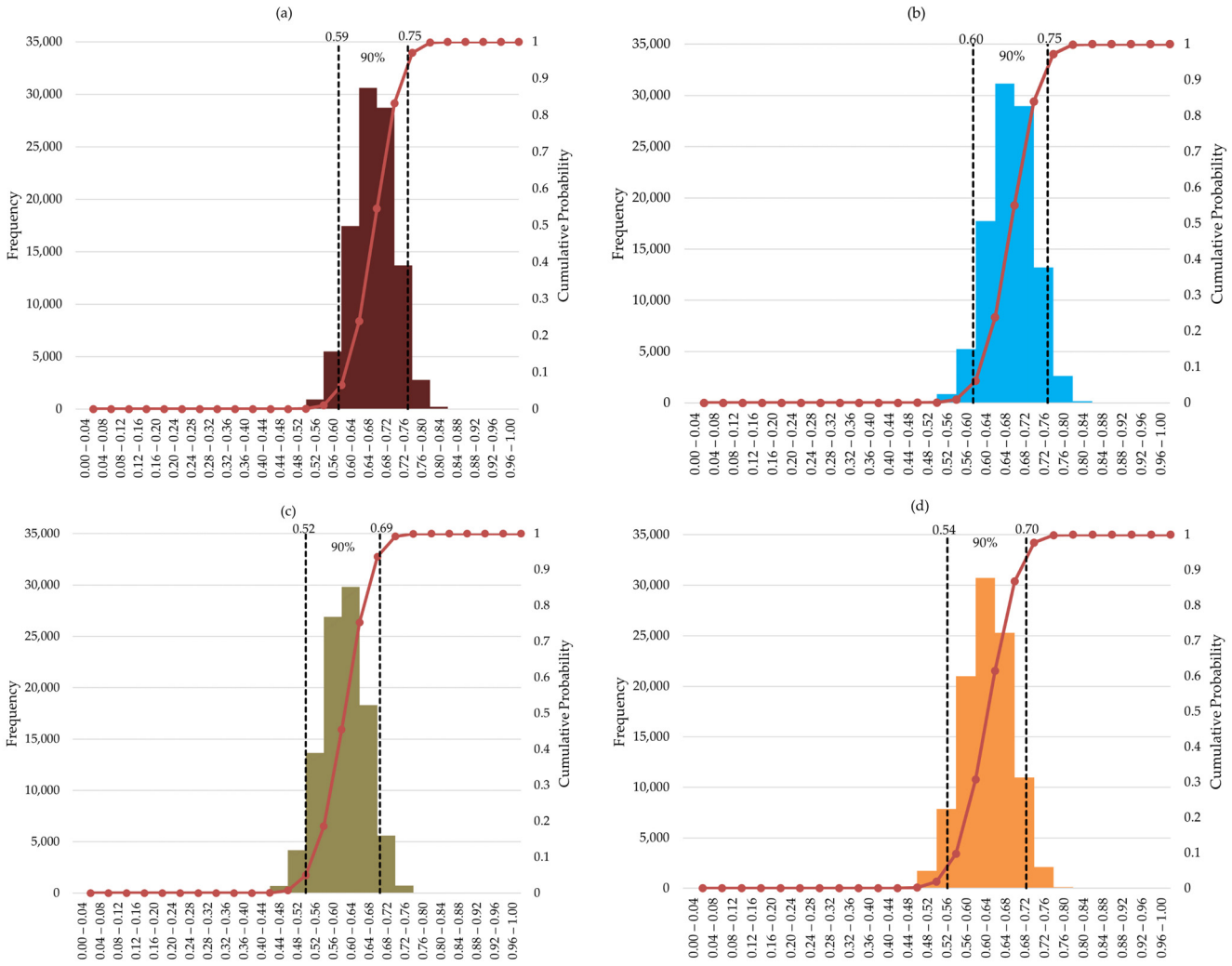


Figure 6. Distribution of performance of FPSOs recycled in Brazil: (**a**) P32_Bra_Lpg_GloSI; (**b**) P32_Bra_Plasma_GloSI; (**c**) P33_Bra_Lpg_GloSI; (**d**) P33_Bra_Plasma_GloSI. Note: The vertical dashed lines indicate the 5th and 95th percentiles (P5 and P95), and the red line represents the cumulative distribution.

From a decision-making perspective, the results presented in Figures 3–6 provide insights into how different recycling configurations the sustainability performance of the recycling scenarios analyzed. The observed differences between the Brazilian and Danish scenarios can also be interpreted within the broader context of circular economy systems in ship recycling. Denmark is frequently cited in the literature as an enabling context for circular economy development due to the presence of port-based industrial clusters and a well-established maritime ecosystem integrating shipyards, recycling companies, waste management firms, and logistics infrastructure [12]. However, the results obtained in this study indicate that, under the operational conditions analyzed, the Brazilian recycling scenarios achieve higher sustainability performance. This finding suggests that while mature circular economy structures may provide favorable institutional conditions, sustainability outcomes in ship recycling systems are also strongly influenced by specific operational configurations and logistical arrangements [6]. In this context, recent policy discussions emphasize that expanding recycling capacity and accelerating technological innovation are essential conditions for enabling ship recycling to deliver environmental, social, and economic value aligned with broader sustainability strategies, including the European Green Deal and the Circular Economy Action Plan [52].

At the operational level, the analysis of the most representative factors in each scenario highlights clear differences in indicator behavior according to the cutting technology employed. As shown in Figure 7, in scenarios utilizing LPG cutting, social indicators ("workers" and "days_away") have the greatest influence on the GloSI, followed by economic factors ("acquisition_cost" and "lpg_cutting_cost"). It is worth noting that, in the Brazilian cases, these indicators show a lower sensitivity range, reflecting greater operational stability and reduced vulnerability to cost fluctuations.

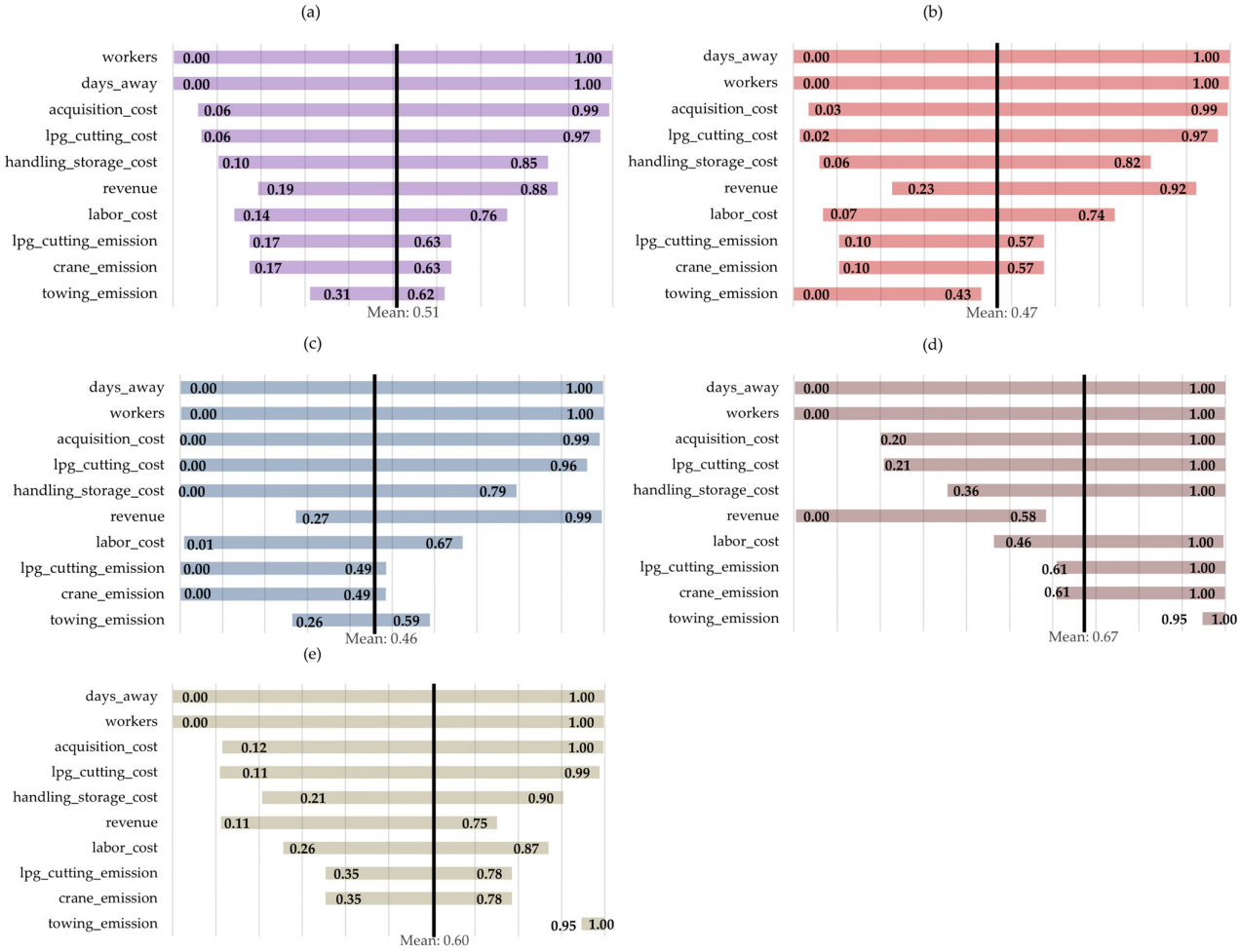


Figure 7. Indicators that impact scenarios utilizing LPG cutting: (**a**) Cap_Den_Lpg_GloSI; (**b**) Flu_Den_Lpg_GloSI; (**c**) Nit_Den_Lpg_GloSI; (**d**) P32_Bra_Lpg_GloSI; (**e**) P33_Bra_Lpg_GloSI.

In the scenarios involving plasma cutting, the hierarchy of factors follows a pattern similar to that observed in the LPG, as shown in Figure 8. This consistency is verified across all scenarios, in both Denmark and Brazil, demonstrating that the cutting technology does not alter the structure of the determinants but modulates their intensity. The Brazilian results exhibit smaller amplitudes, reflecting greater stability and robustness of performance.

Beyond the indicators evaluated in this study, the protection of water resources represents another important dimension in ship recycling activities. Previous studies have documented contamination of coastal environments, sediments, and surrounding ecosystems near ship recycling facilities, particularly due to inadequate management of hazardous materials and recycling residues [32,36], reinforcing the need to consider water resource protection within sustainability assessments of ship recycling activities. To mitigate these risks, the literature reports several environmental management strategies adopted in ship recycling facilities. These include the installation of impermeable surfaces and drainage systems designed to capture

contaminated runoff and direct it to water treatment facilities, the use of oil separators and sand traps, and the deployment of containment booms around vessels to prevent accidental spills during recycling operations. Additional measures include the controlled removal and storage of contaminated liquids, filtration systems for hazardous residues such as NORM or mercury, and the handling of hazardous waste in sealed areas equipped with drainage and containment systems [33]. Incorporating indicators associated with these practices in future assessments could contribute to more comprehensive decision-support frameworks, enabling the evaluation of how environmental management strategies influence sustainability performance in ship recycling scenarios.

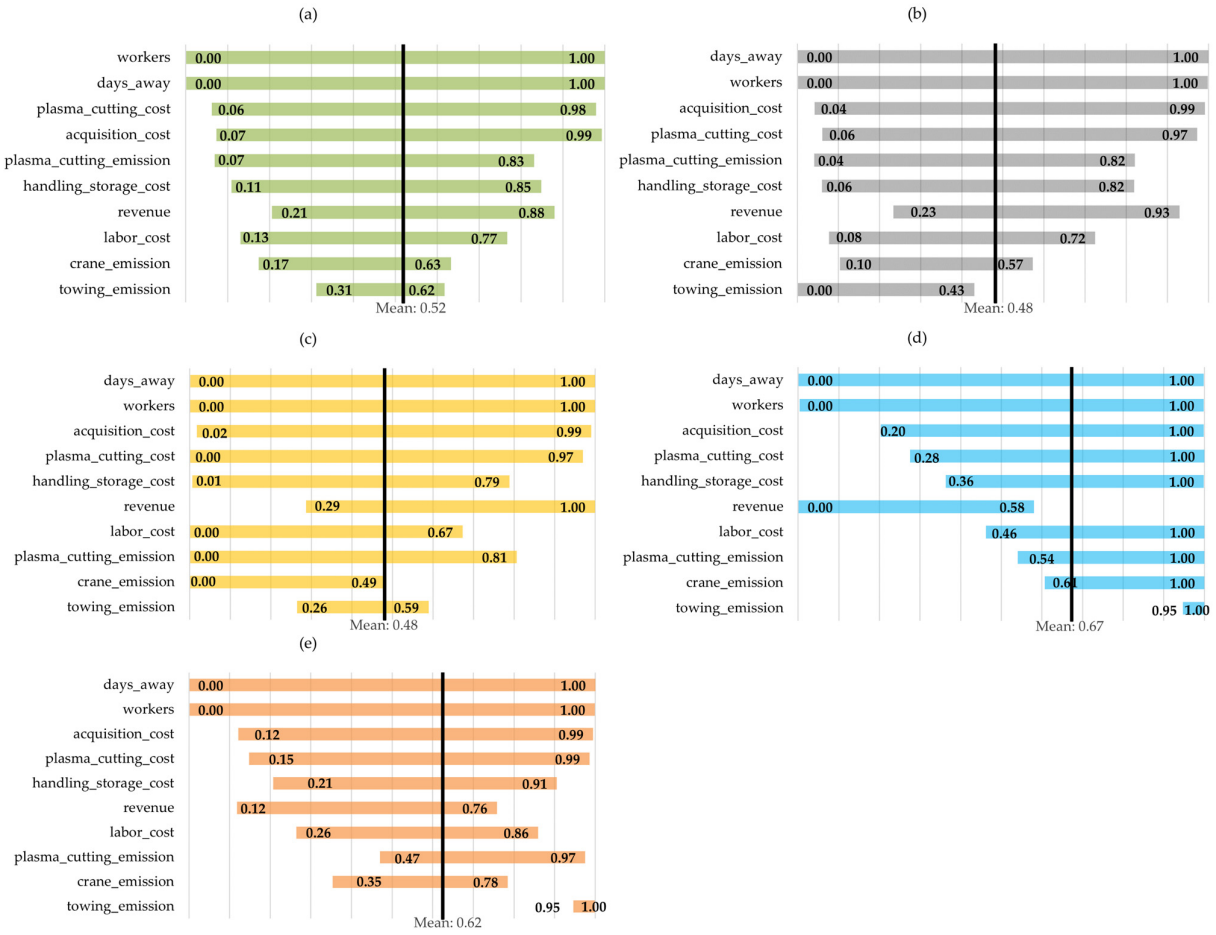


Figure 8. Indicators that impact scenarios utilizing plasma cutting: (**a**) Cap_Den_Plasma_GloSI; (**b**) Flu_Den_Plasma_GloSI; (**c**) Nit_Den_Plasma_GloSI; (**d**) P32_Bra_Plasma_GloSI; (**e**) P33_Bra_Plasma_GloSI.

Climate change mitigation also represents an important dimension in sustainability discussions related to ship recycling systems. Recent studies highlight that achieving climate neutrality requires coordinated technological, economic, and policy transformations aimed at reducing greenhouse gas emissions and supporting the transition toward low-carbon production systems. In the European context, differences in economic structures, energy systems, and policy commitments influence the pace and effectiveness of decarbonization strategies across countries [38]. In contrast, studies focusing on emerging economies emphasize the role of green energy and technological innovation in improving environmental quality and supporting sustainable development pathways. For example, ref. [53] examines BRICS countries and highlight the growing importance of green energy and technological innovation in addressing environmental degradation and climate challenges in rapidly developing economies. Complementarily, research on circular economy strategies shows

that improvements in material recovery, recycling, and resource efficiency can significantly contribute to greenhouse gas emission reductions and climate mitigation objectives [54]. From a governance perspective, the literature also highlights the importance of decision-support approaches capable of addressing complex sustainability challenges and supporting collective decision-making processes related to climate transitions [55].

Although climate-related indicators were not explicitly incorporated into the simulation model developed in this study, the scenario-based and probabilistic structure of the proposed approach provides insights that may support sustainability-oriented decision-making in ship recycling systems. In this sense, the results obtained can contribute to identifying operational configurations associated with lower environmental pressures and improved sustainability performance, providing analytical support for decision processes aligned with broader climate mitigation and sustainability transition objectives.

4.3. Sensitivity Analysis

To assess the robustness of the main conclusions with respect to indicator weighting assumptions, a formal sensitivity analysis was conducted using alternative hypothetical weighting schemes applied to the GloSI.

In the baseline assessment, all normalized indicators were assigned equal weights (0.10 each), and the GloSI was computed as the arithmetic mean of the ten indicators. To evaluate whether the results are sensitive to alternative sustainability prioritization perspectives, three additional weighting configurations were defined: social-heavy, economic-heavy, and environmental-heavy. In each configuration, a total weight of 0.5 was assigned to the prioritized sustainability dimension, while the remaining 0.5 was equally distributed between the other two dimensions.

The dimensional priorities were operationalized directly at the indicator level. Within each dimension, the assigned weight was evenly distributed across its corresponding indicators, as no explicit preference structure was assumed at the intra-dimensional level. This approach enables the assessment to isolate the effect of inter-dimensional prioritization without introducing additional subjective assumptions, while maintaining internal consistency. The complete set of indicator weights adopted in the baseline and alternative weighting schemes is reported in Table A4 (Appendix B).

The results of the sensitivity analysis are summarized in Table 3, which reports robust statistics of the GloSI distributions, including the median and the P5–P95 interval, for Brazilian and Danish ship recycling scenarios under each weighting scheme. Across all tested configurations, Brazilian scenarios consistently exhibit higher median GloSI values than Danish scenarios, with limited overlap between their respective P5–P95 intervals. Although absolute index values vary depending on the prioritization of social, economic, or environmental dimensions, the relative ranking between Brazilian and Danish scenarios remains unchanged.

Table 3. Global Sustainability Index (GloSI) results by scenario under different weighting structures.

Scenarios of GloSI	Baseline (Median [P5–P95])	Environmental-Heavy (Median [P5–P95])	Social-Heavy (Median [P5–P95])	Economic-Heavy (Median [P5–P95])
Cap_Den_Lpg_GloSI	0.510 [0.420–0.594]	0.482 [0.389–0.573]	0.498 [0.366–0.628]	0.513 [0.418–0.603]
Flu_Den_Lpg_GloSI	0.467 [0.376–0.553]	0.418 [0.322–0.511]	0.465 [0.331–0.595]	0.477 [0.380–0.567]
Nit_Den_Lpg_GloSI	0.460 [0.367–0.546]	0.415 [0.319–0.509]	0.461 [0.328–0.592]	0.469 [0.370–0.561]
P32_Bra_Lpg_GloSI	0.674 [0.594–0.750]	0.714 [0.629–0.797]	0.624 [0.494–0.751]	0.656 [0.568–0.739]
P33_Bra_Lpg_GloSI	0.606 [0.520–0.686]	0.625 [0.536–0.711]	0.573 [0.442–0.702]	0.596 [0.503–0.682]
Cap_Den_Plasma_GloSI	0.521 [0.427–0.608]	0.499 [0.388–0.603]	0.507 [0.371–0.639]	0.522 [0.425–0.614]
Flu_Den_Plasma_GloSI	0.483 [0.388–0.573]	0.443 [0.330–0.550]	0.477 [0.342–0.611]	0.490 [0.392–0.583]
Nit_Den_Plasma_GloSI	0.483 [0.385–0.574]	0.452 [0.336–0.560]	0.480 [0.343–0.613]	0.488 [0.387–0.583]

Table 3. *Cont.*

Scenarios of GloSI	Baseline (Median [P5–P95])	Environmental-Heavy (Median [P5–P95])	Social-Heavy (Median [P5–P95])	Economic-Heavy (Median [P5–P95])
P32_Bra_Plasma_GloSI	0.674 [0.595–0.749]	0.713 [0.626–0.797]	0.623 [0.493–0.751]	0.656 [0.570–0.738]
P33_Bra_Plasma_GloSI	0.626 [0.542–0.704]	0.656 [0.565–0.744]	0.589 [0.459–0.718]	0.612 [0.522–0.697]

5. Conclusions

The application of Monte Carlo simulation enabled the analysis of sustainability performance under uncertainty, allowing for indicator behavior to be observed across a wide range of variability and revealing patterns of stability and sensitivity among the evaluated scenarios. The results indicate that the Brazilian scenarios (P-32 and P-33) achieve a more balanced performance across the environmental, economic, and social dimensions, with relatively low dispersion in the simulated outcomes. This behavior suggests greater robustness and operational predictability when compared to the Danish scenarios (FPSO Capixaba, FPSO Fluminense, and FPSO Cidade de Niterói), which exhibited wider variability across several indicators.

The analysis also shows that social and economic aspects play a relevant role in shaping the GloSI. This configuration indicates that operational maturity and the local context are determining factors for sustainable performance, reinforcing the need for national policies that incentivize sustainable ship recycling, focusing on the generation of qualified employment and occupational safety. Such policies may also contribute to broader sustainability transitions by aligning ship recycling practices with emerging climate mitigation strategies and circular economy principles.

The study, however, presents some limitations and gaps that must be acknowledged. There is a scarcity of empirical data and reliable historical series concerning disaggregated costs, specific emissions per stage (such as cutting, lifting, and towing), and working conditions, which restricts the calibration of probabilistic parameters. In addition, limited public access to such information, often treated as strategic by companies and ship recycling facilities, required certain stages of the ship recycling process to be represented in a simplified manner. The Global Sustainability Index is intended as a comparative, internally normalized metric and does not represent an absolute measure of sustainability. Its interpretation is therefore subject to limitations related to indicator selection, weighting assumptions, and data availability. Similarly, the Social Sustainability Index relies on a limited set of proxies due to data constraints and does not capture all dimensions of social performance, such as long-term health outcomes or broader community-level impacts.

Despite these limitations, this research offers insights to the literature by applying a quantitative probabilistic approach to the comparative assessment of FPSO recycling scenarios evaluated under stochastic simulation. The results highlight Brazil's potential to participate more actively in this activity and underscore the importance of developing a national, sustainable offshore platform recycling chain supported by appropriate regulatory frameworks and industrial policies. From a circular economy perspective, these findings reinforce the relevance of FPSO recycling as a strategy for recovering materials with high industrial value, particularly steel, thereby reducing dependence on virgin resource extraction and contributing to more resource-efficient production systems.

As recycling operations are still ongoing, certain stages of the ship recycling process were necessarily represented in a simplified manner to ensure modeling feasibility. Future research should refine these representations through the incorporation of detailed field data and more granular operational descriptions. The proposed model is replicable to other ship recycling assessment scenarios involving different ship types and operational configurations, enabling comparative sustainability evaluations under uncertainty.

Future developments may also expand the analytical scope by incorporating additional performance variables related to climate change mitigation and water resource protection, including indicators associated with greenhouse gas emissions, energy efficiency, spill prevention systems, environmental monitoring programs, and hazardous waste traceability practices. Integrating these variables into future scenario-based assessments could strengthen decision-support frameworks by enabling a more comprehensive evaluation of environmental risks and sustainability trade-offs associated with alternative ship recycling configurations, while also aligning recycling strategies with broader climate change mitigation goals and water resource protection practices.

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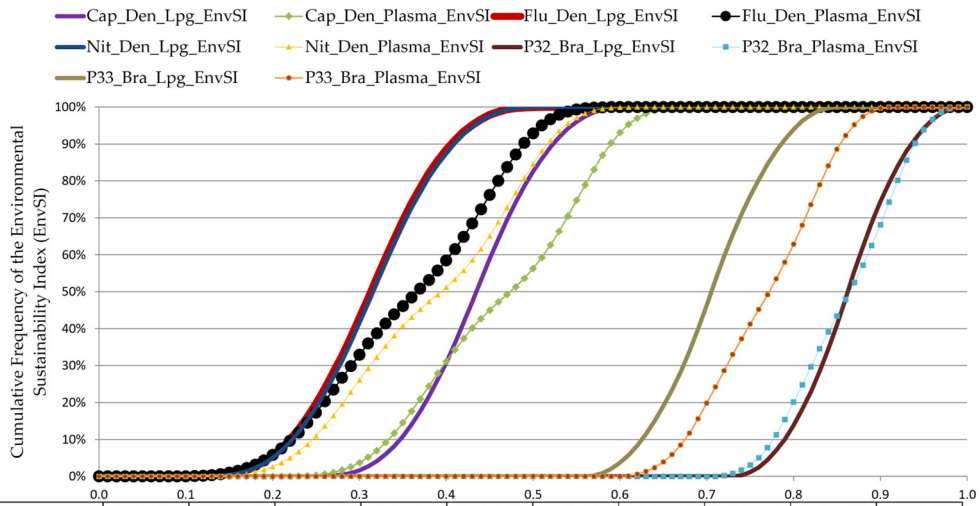
Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

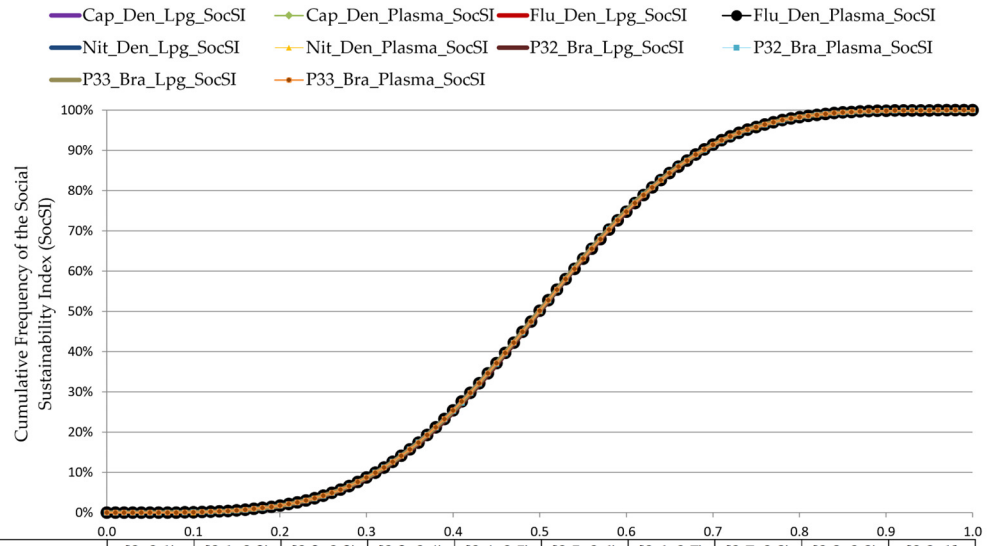
Conflicts of Interest: The authors declare no conflict of interest.

Appendix A



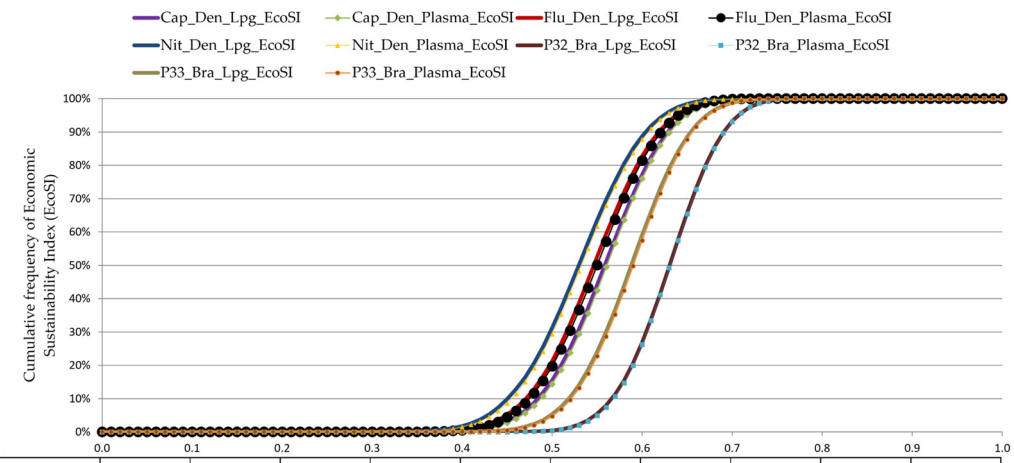
	[0–0.1)	[0.1–0.2)	[0.2–0.3)	[0.3–0.4)	[0.4–0.5)	[0.5–0.6)	[0.6–0.7)	[0.7–0.8)	[0.8–0.9)	[0.9–1]
Cap_Den_Lpg_EnvSI	0.00%	0.00%	1.66%	29.16%	51.72%	17.35%	0.11%	0.00%	0.00%	0.00%
Cap_Den_Plasma_EnvSI	0.00%	0.00%	3.74%	27.42%	25.12%	36.78%	6.95%	0.00%	0.00%	0.00%
Flu_Den_Lpg_EnvSI	0.02%	5.58%	37.15%	45.65%	11.57%	0.04%	0.00%	0.00%	0.00%	0.00%
Flu_Den_Plasma_EnvSI	0.06%	5.80%	27.08%	25.56%	34.35%	7.15%	0.00%	0.00%	0.00%	0.00%
Nit_Den_Lpg_EnvSI	0.00%	5.06%	36.54%	45.84%	12.53%	0.03%	0.00%	0.00%	0.00%	0.00%
Nit_Den_Plasma_EnvSI	0.00%	2.61%	23.49%	25.09%	33.42%	15.33%	0.06%	0.00%	0.00%	0.00%
P32_Bra_Lpg_EnvSI	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	13.83%	60.53%	25.65%
P32_Bra_Plasma_EnvSI	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	20.11%	48.04%	31.85%
P33_Bra_Lpg_EnvSI	0.00%	0.00%	0.00%	0.00%	0.00%	3.67%	42.73%	47.53%	6.07%	0.00%
P33_Bra_Plasma_EnvSI	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	19.85%	42.97%	36.81%	0.36%

Figure A1. Cumulative frequency of the Environmental Sustainability Index (EnvSI).



	[0–0.1)	[0.1–0.2)	[0.2–0.3)	[0.3–0.4)	[0.4–0.5)	[0.5–0.6)	[0.6–0.7)	[0.7–0.8)	[0.8–0.9)	[0.9–1]
Cap_Den_Lpg_SocSI	0.14%	1.56%	6.97%	16.69%	24.79%	24.87%	16.40%	6.89%	1.56%	0.12%
Cap_Den_Plasma_SocSI	0.11%	1.68%	6.98%	16.63%	24.69%	24.78%	16.57%	6.88%	1.59%	0.10%
Flu_Den_Lpg_SocSI	0.12%	1.63%	6.97%	16.62%	24.96%	24.79%	16.38%	6.85%	1.59%	0.10%
Flu_Den_Plasma_SocSI	0.11%	1.66%	6.99%	16.69%	24.72%	24.61%	16.70%	6.83%	1.60%	0.10%
Nit_Den_Lpg_SocSI	0.14%	1.56%	6.97%	16.69%	24.79%	24.87%	16.40%	6.89%	1.56%	0.12%
Nit_Den_Plasma_SocSI	0.11%	1.68%	6.98%	16.63%	24.69%	24.78%	16.57%	6.88%	1.59%	0.10%
P32_Bra_Lpg_SocSI	0.10%	1.57%	6.84%	16.43%	24.97%	24.66%	16.81%	6.95%	1.58%	0.11%
P32_Bra_Plasma_SocSI	0.12%	1.63%	7.06%	16.49%	24.83%	24.83%	16.36%	6.96%	1.61%	0.11%
P33_Bra_Lpg_SocSI	0.12%	1.63%	6.97%	16.62%	24.96%	24.79%	16.38%	6.85%	1.59%	0.10%
P33_Bra_Plasma_SocSI	0.11%	1.66%	6.99%	16.69%	24.72%	24.61%	16.70%	6.83%	1.60%	0.10%

Figure A2. Cumulative frequency of Social Sustainability Index (SocSI).



	[0–0.1)	[0.1–0.2)	[0.2–0.3)	[0.3–0.4)	[0.4–0.5)	[0.5–0.6)	[0.6–0.7)	[0.7–0.8)	[0.8–0.9)	[0.9–1]
Cap_Den_Lpg_EcoSI	0.00%	0.00%	0.00%	0.32%	15.20%	61.76%	22.42%	0.30%	0.00%	0.00%
Cap_Den_Plasma_EcoSI	0.00%	0.00%	0.00%	0.26%	14.12%	61.61%	23.67%	0.35%	0.00%	0.00%
Flu_Den_Lpg_EcoSI	0.00%	0.00%	0.01%	0.71%	20.56%	61.53%	17.02%	0.18%	0.00%	0.00%
Flu_Den_Plasma_EcoSI	0.00%	0.00%	0.00%	0.51%	19.18%	61.69%	18.43%	0.18%	0.00%	0.00%
Nit_Den_Lpg_EcoSI	0.00%	0.00%	0.02%	1.76%	29.53%	57.45%	11.19%	0.06%	0.00%	0.00%
Nit_Den_Plasma_EcoSI	0.00%	0.00%	0.01%	1.48%	27.87%	58.39%	12.17%	0.08%	0.00%	0.00%
P32_Bra_Lpg_EcoSI	0.00%	0.00%	0.00%	0.00%	0.48%	26.50%	66.30%	6.72%	0.00%	0.00%
P32_Bra_Plasma_EcoSI	0.00%	0.00%	0.00%	0.00%	0.39%	25.80%	66.83%	6.99%	0.00%	0.00%
P33_Bra_Lpg_EcoSI	0.00%	0.00%	0.00%	0.04%	5.30%	53.89%	39.61%	1.16%	0.00%	0.00%
P33_Bra_Plasma_EcoSI	0.00%	0.00%	0.00%	0.02%	4.65%	52.73%	41.30%	1.30%	0.00%	0.00%

Figure A3. Cumulative frequency of Economic Sustainability Index (EcoSI).

Appendix B

Table A1. Indicators of the assessment.

Aspect	Indicator	Equation	Indicator Unit	Target	Parameter	Parameter Unit	Source
Social	workers	triangular (60, 200, 130)	workers	maximize			[39]
	days_away	triangular (0, 5, 2.5)	days away cases	minimize			[56]
Economic	acquisition_cost	(steel_cap [a]) · auction_bid	US$	minimize	auction_bid = triangular (15.4, 364.7, 190)	US$	[18]
					lightweight_cap [b] = 52,020	ton	[39]
					steel_present = triangular (0.72, 0.85, 0.785)	%	[17]
					steel_cap [a] = lightweight_cap [b] · steel_present	ton	
	labor_cost	(steel_cap [a]) · salary	US$	minimize	salary = triangular (53.8, 64.4, 59.1)	US$/ton material processed	[26]
	handling_storage_cost	(steel_cap [a]) · handling_cost	US$	minimize	handling_cost = triangular (82, 123, 102.5)	US$/ton material processed	[18]
	plasma_cutting_cost	((steel_cap [a]) · plasma_productivity · plasma_cost)/(shift_hour · cutters)	US$	minimize	plasma_cost = bimodal (272.45, 318.82, 0.5)	US$/shift	[2]
					lpg_cost = 255.64	US$/shift	
					lpg_productivity = 38	min/ton	
					cutters_percentage = triangular (0.42, 0.71, 0.565)	%	[32,39]
					cutters = workers · cutters_percentage	number of cutters	
					shift_hour = 8	hours	[2]
	lpg_cutting_cost	((steel_cap [a]) · lpg_productivity · lpg_cost)/(shift_hour · cutters)	US$	minimize	plasma_productivity1 = 23, if plasma_cost = 272.45	min/ton	
					plasma_productivity2 = 15, if plasma_cost = 318.82	min/ton	
	revenue	(steel_cap [a]) · price	US$	maximize	price = triangular (331, 427, 379)	US$/ton	[18]

Table A1. *Cont.*

Aspect	Indicator	Equation	Indicator Unit	Target	Parameter	Parameter Unit	Source
Environmental	towing_emission	(total_consumption_trip · ton_methane · coeq_methane) + (total_consumption_trip · ton_nitrous_oxide · coeq_nitrous_oxide) + (total_consumption_trip · ton_carbon_dioxide · coeq_carbon_dioxide)	tCO_2eq	minimize	towing_engine_power = 13,500	kW	[57]
					towing_power_usage = 0.15	%	[58]
					towing_specific_fuel_consumption = 0.195	kg/kWh	[59]
					conversion_hours = 24	hours	
					conversion_ton = 1000	ton	
					daily_consumption = (towing_engine_power · towing_power_usage · towing_specific_fuel_consumption · conversion_hours)/(conversion_ton)	ton/dia	
					num_tug = 3	units	[33]
					towing_speed = triangular (3, 5, 4)	knots	[33]
					distance_cap_den = 5689	nautical mile	[41]
					distance_flu_den = 8000	nautical mile	[33]
					distance_nit_den = 6040	nautical mile	Calculated by OPENCNP software (version 5.10.2)
					distance_p32_bra = 978	nautical mile	
					distance_p33_bra = 990	nautical mile	
					total_consumption_trip = (daily_consumption · num_tug ·· (distance_cap_den ^{c}))/(towing_speed · conversion_hours)	ton	
					ton_methane = 0.0003	ton	[59]
					ton_nitrous_oxide = 0.00008	ton	
					ton_carbon_dioxide = 3.17	ton	
					coeq_methane = 28	tCO_2eq	[60]
					coeq_nitrous_oxide = 265	tCO_2eq	
					coeq_carbon_dioxide = 1	tCO_2eq	

Table A1. *Cont.*

Aspect	Indicator	Equation	Indicator Unit	Target	Parameter	Parameter Unit	Source
	plasma_cutting_emission	(plasma_eletricity_consumption · electricity_den [d])/conversion_ton	tCO_2eq	minimize	cutting_lenght = bimodal (3500, 4150, 0.5)	mm	[2]
					cutting_speed = bimodal (300, 600, 0.5)	mm/min	
					plasma_power_demand = 5.5 KVA · 0.85 = 4.7	kW	[61]
					conversion_minutes = 60	min	
					block_weight = 2.8	ton	[2]
					plasma_eletricity_consumption = (plasma_power_demand · cutting_lenght ·· conversion_minutes · (steel_cap [a]))/(cutting_speed · block_weight)	kWh	
					electricity_bra = 0.2856	$kgCO_2eq/kWh$	Ecoinvent 3.6 database
					electricity_den = 0.4057	$kgCO_2eq/kWh$	
	lpg_cutting_emission	((steel_cap [a]) · lpg_consumption · lpg_impact_factor)/conversion_ton	tCO_2eq	minimize	lpg_consumption = 2.81	kg/ton material processed	[28]
					lpg_impact_factor = 0.611729	$kgCO_2eq/kg$	Ecoinvent 3.6 database
	crane_emission	(crane_consumption_mj · diesel_impact_factor)/conversion_ton	tCO_2eq	minimize	num_crane = 3	unit	[62]
					crane_diesel_consumption = 3.4	kg/ton material processed	[59]
					diesel_density = 0.832	kg/L	
					conversion_MJ = 36	MJ	
					crane_consumption_mj = (num_crane · crane_diesel_consumption · (steel_cap [a]) · conversion_MJ)/(diesel_density)	MJ	
					diesel_impact_factor = 0.094	$kgCO_2eq/MJ$	Ecoinvent 3.6 database

[a] it can be replaced by steel_flu, steel_nit, steel_p32, or steel_p33. [b] it can be replaced by lightweight_flu, lightweight_nit, lightweight_p32, or lightweight_p33. [c] it can be replaced by distance_flu_den, distance_nit_den, distance_p32_bra, or distance_p33_bra. [d] it can be replaced by electricity_bra.

Table A2. Relationship between indicators and scenarios.

FPSO Name	Scenarios Name				Indicators Used According to Cutting Technology (LPG or Plasma)
	Global Sustainability Index (GloSI)	Environmental Sustainability Index (EnvSI)	Social Sustainability Index (SocSI)	Economic Sustainability Index (EcoSI)	
Capixaba Fluminense Cidade de Niterói P-32 P-33	Cap_Den_Lpg_GloSI Flu_Den_Lpg_GloSI Nit_Den_Lpg_GloSI P32_Bra_Lpg_GloSI P33_Bra_Lpg_GloSI	Cap_Den_Lpg_EnvSI Flu_Den_Lpg_EnvSI Nit_Den_Lpg_EnvSI P32_Bra_Lpg_EnvSI P33_Bra_Lpg_EnvSI	Cap_Den_Lpg_SocSI Flu_Den_Lpg_SocSI Nit_Den_Lpg_SocSI P32_Bra_Lpg_SocSI P33_Bra_Lpg_SocSI	Cap_Den_Lpg_EcoSI Flu_Den_Lpg_EcoSI Nit_Den_Lpg_EcoSI P32_Bra_Lpg_EcoSI P33_Bra_Lpg_EcoSI	workers, days_away, acquisition_cost, labor_cost, handling_storage_cost, lpg_cutting_cost, revenue, towing_emission, lpg_cutting_emission, crane_emission
Capixaba Fluminense Cidade de Niterói P-32 P-33	Cap_Den_Plasma_GloSI Flu_Den_Plasma_GloSI Nit_Den_Plasma_GloSI P32_Bra_Plasma_GloSI P33_Bra_Plasma_GloSI	Cap_Den_Plasma_EnvSI Flu_Den_Plasma_EnvSI Nit_Den_Plasma_EnvSI P32_Bra_Plasma_EnvSI P33_Bra_Plasma_EnvSI	Cap_Den_Plasma_SocSI Flu_Den_Plasma_SocSI Nit_Den_Plasma_SocSI P32_Bra_Plasma_SocSI P33_Bra_Plasma_SocSI	Cap_Den_Plasma_EcoSI Flu_Den_Plasma_EcoSI Nit_Den_Plasma_EcoSI P32_Bra_Plasma_EcoSI P33_Bra_Plasma_EcoSI	workers, days_away, acquisition_cost, labor_cost, handling_storage_cost, plasma_cutting_cost, revenue, towing_emission, plasma_cutting_emission, crane_emission

Table A3. Adjusted monetary values.

Indicator	Data (Year)	Correction (2025)	Unit	Source
auction_bid	14.44 (2023)	15.35	US$/ton material processed	[18]
	266.80 (2015)	364.69		
salary	26.67 (1997)	53.83	US$/ton	[26]
	32 (1997)	64.41		
handling_cost	96.38 (2023)	102.48	US$/ton	[18]
plasma_cost	188 (2020)	230.91	Euro/shift	[2]
	220 (2020)	270.21		
	-	272.45	US$/shift	[2]
	-	318.82		
lpg_cost	176.4 (2020)	216.66	Euro/shift	[2]
	0	255.64	US$/shift	

Table A4. Indicator weighting schemes.

Scenarios of GloSI	Indicators	Baseline	Environmental-Heavy	Social-Heavy	Economic-Heavy
Cap_Den_Lpg_GloSI Flu_Den_Lpg_GloSI Nit_Den_Lpg_GloSI P32_Bra_Lpg_GloSI P33_Bra_Lpg_GloSI	workers	0.1	0.125	0.2500	0.125
	days_away	0.1	0.125	0.2500	0.125
	acquisition_cost	0.1	0.050	0.0500	0.100
	labor_cost	0.1	0.050	0.0500	0.100
	handling_storage_cost	0.1	0.050	0.0500	0.100
	lpg_cutting_cost	0.1	0.050	0.0500	0.100
	revenue	0.1	0.050	0.0500	0.100
	towing_emission	0.1	0.167	0.0833	0.083
	lpg_cutting_emission	0.1	0.167	0.0833	0.083
	crane_emission	0.1	0.167	0.0833	0.083
Cap_Den_Plasma_GloSI Flu_Den_Plasma_GloSI Nit_Den_Plasma_GloSI P32_Bra_Plasma_GloSI P33_Bra_Plasma_GloSI	workers	0.1	0.125	0.2500	0.125
	days_away	0.1	0.125	0.2500	0.125
	acquisition_cost	0.1	0.050	0.0500	0.100
	labor_cost	0.1	0.050	0.0500	0.100
	handling_storage_cost	0.1	0.050	0.0500	0.100
	lpg_cutting_cost	0.1	0.050	0.0500	0.100
	revenue	0.1	0.050	0.0500	0.100
	towing_emission	0.1	0.167	0.0833	0.083
	lpg_cutting_emission	0.1	0.167	0.0833	0.083
	crane_emission	0.1	0.167	0.0833	0.083

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