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Original Research Article

Integrated Management of Scope 3 Emissions in the Steel Supply Chain

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Abstract

Scope 3 emissions constitute the largest and most difficult-to-manage component of the carbon footprint of the steel industry; however, they remain underexplored owing to fragmented data systems and the absence of holistic analytical approaches. This study presents an integrated, real-data-driven framework for quantifying and reducing Scope 3 emissions in a medium-scale steel supply chain in West Bengal, India. Primary operational data were collected from upstream suppliers, midstream manufacturing operations, and downstream distributors using transport logs, meter-based energy records, scrap inspection sheets, on-site walk-throughs, and structured stakeholder interviews. Environmental Value Stream Mapping (EVSM) coupled with life-cycle emission accounting was applied to six process stages (UP1, UP2, MS1, MS2, DS1, and DS2), revealing the Electric Arc Furnace (MS1) as the dominant hotspot, contributing more than 90% of the total Scope 3 emissions. Circularity metrics, namely the Scrap Quality Index (SQI) and Material Circularity Index (MCI), demonstrated that higher scrap quality and increased recycled content can significantly decrease upstream embodied emissions. A cooperative game-theoretic model quantified abatement opportunities for suppliers, the manufacturer, and distributors, showing that full coalition formation {U, M, D} generated the highest net payoff (₹1.89 million). Shapley value allocation confirmed the manufacturer as the major beneficiary (97.6%), with proportionate gains assigned to suppliers and distributors. The results highlight that collaborative governance, enhanced circularity, optimized logistics, and renewable energy integration, particularly solar-based electricity substitution, collectively offer a high-impact pathway for Scope 3 decarbonization. The proposed multi-method framework provides a transparent, equitable, and industry-ready decision support system for accelerating low-carbon transitions in the Indian steel sector.

Keyword: Circular economy; electric arc furnace; environmental value stream mapping; scope 3 emissions; steel industry

1. Introduction

Industrial decarbonization has emerged as one of the most pressing global priorities as nations progress toward net-zero commitments, strengthen climate policies, and meet stakeholder expectations for environmental transparency (Sovacool et al., 2023). Among all heavy industries, the steel sector contributes nearly 8% of global CO_2 emissions, making it one of the largest industrial sources of climate impact (Zhang et al., 2021). While much attention is given to Scope 1 (direct emissions) and Scope 2 (purchased electricity), empirical evidence shows that Scope 3 emissions account for 60–80% of the total carbon footprint of a typical steel manufacturing enterprise (Huang et al., 2009; Hettler and Graf-Vlachy, 2024). These emissions, originating from raw material extraction, logistics, outsourced operations, product distribution, use-phase behavior, and end-of-life treatment, largely lie outside the operational boundary of the enterprise, making them difficult to quantify, influence, or manage.

Global steel production is undergoing rapid transformation owing to resource scarcity, rising energy prices, customer demand for low-carbon materials, and strong policy frameworks such as the Carbon Border Adjustment Mechanism (CBAM), Science Based Targets initiative (SBTi), and ISO 14064. Steel companies must not only control internal emissions but also demonstrate credible pathways for supply chain-wide decarbonization (Burggräf et al., 2024). Despite these challenges, studies on Scope 3 emissions from steel are limited, fragmented, and mostly theoretical. Few studies provide actionable frameworks for quantification, hotspot identification, or collaborative abatement strategies. Most critically, very few studies have developed a decision-support model that allocates Scope 3 abatement responsibilities among suppliers, manufacturers, and distributors using cooperative game theory.

Emission reduction strategies outline several approaches that can serve as the foundation for developing new policies to support emission reduction processes that are applicable across various sectors. Within the Life Cycle Assessment (LCA) approach, carbon footprints from upstream to downstream can be inventoried to determine overall emissions and identify carbon-intensive hotspots that cannot be captured through manual accounting (Kennelly et al., 2019). In addition to LCA, Environmental Value Stream Mapping (EVSM) applies lean manufacturing principles integrated with environmental aspects (Garza-Reyes et al., 2018). This approach enables the evaluation of each activity within process units not only in terms of operational efficiency but also in terms of the carbon value it generates (Roosen and Pons, 2013). Furthermore, cooperative game theory provides a conceptual framework for emission mitigation, with Shapley allocation regulating the distribution of responsibilities and burdens of emission reduction across the entire process chain (Altan & Özener, 2020). When combined, these three theories can support a more comprehensive and real-data-based quantification of Scope 3 emissions while facilitating a fair and transparent transition toward a carbon-free industry.

Efforts to decarbonize Scope 3 emissions in the steel industry remain constrained by the limited implementation of Scope 3 as a guiding framework for operational practices, particularly within the Indian steel sector. The objective was to move beyond generic estimations of emission reduction by incorporating a supply chain-wide hotspot diagnostic framework based on Environmental Value Stream Mapping (EVSM). This approach is effective in systematically identifying carbon-intensive hotspots across all production units. Moreover, it enhances the efficiency of emission mitigation by strengthening a collaborative emission reduction model that employs cooperative game theory and Shapley allocation, thereby enabling suppliers, manufacturers, and distributors to determine actions and responsibilities for reducing emissions equitably.

2. Literature Review

The emergence of Scope 3 emissions as a critical component of corporate carbon accounting can be traced to the Greenhouse Gas Protocol developed by the World Resources Institute (Wbcsd) and the World Business Council for Sustainable Development (Wbcsd) in 2004 (Wbcsd, 2004). This framework formalizes the concept of value-chain emissions and categorizes Scope 3 into 15 upstream and downstream segments, emphasizing that organizational climate impacts extend far beyond factory operations. Subsequent revisions of the GHG Protocol Corporate Standard and Corporate Value Chain (Scope 3) Standard laid the foundation for life-cycle-based decarbonization approaches adopted globally.

Scientific evidence has consistently shown that global climate targets cannot be achieved without addressing the value chain emissions. Rockström et al. (2017) highlighted that industrial subsectors must urgently focus on full life-cycle impacts to remain within planetary carbon budgets. CDP (2022) further reinforces this urgency, noting that the average value-chain emissions across industries are 11–12 times higher than the direct Scope 1 and 2 emissions. Goldman and Worrel (2019) identified industrial supply chains as the dominant drivers of carbon leakage and embedded emissions, particularly in energy-intensive sectors.

Over the past decade, regulatory frameworks have increasingly emphasized Scope 3 disclosure. The Task Force on Climate-Related Financial Disclosures (TCFD), International Sustainability Standards Board ((ISSB)), and European Union CSRD mandate or encourage robust value-chain reporting (Disclo, 2017). This evolution positions Scope 3 as a central metric for assessing corporate climate responsibility and supply chain alignment with global net-zero commitments.

2.1. Scope 3 Emissions in the Steel Industry: Global Evidence and Challenges

Steel manufacturing is associated with one of the most complex industrial supply chains, which spans raw material extraction, beneficiation, transportation, outsourced processing, finished product distribution, and end-of-life recycling (Conejo et al., 2020; Pinto, 2019). Consequently, Scope 3 emissions constitute a substantial share of the total life-cycle carbon footprint. Upstream processes such as mining, sintering, coke oven operations, and scrap processing are particularly emission-intensive. Hasanbeigi et al. (2019) show that upstream raw material extraction and logistics can contribute 30–40% of total life-cycle emissions even before the ironmaking stage. Evidence from the (Association, 2020) indicates that scrap quality is defined by contamination levels, alloy composition, and density. plays a crucial role in determining the upstream carbon footprint of electric arc furnace (EAF) route.

Transportation-related emissions constitute another major component of the Scope 3 footprint of steel. Wang et al. (2023) demonstrate that multimodal transport can account for 5–10% of steel's life-cycle emissions, depending on regional freight structures. Lu et al. (2024) report that downstream distribution emissions are significantly higher in developing economies due to diesel reliance and fragmented logistics networks.Despite these advances, existing literature suffers from three major limitations: (a) heavy reliance on generic or secondary LCA databases, (b) a lack of plant-level primary data from steel facilities, and (c) limited investigation of collaborative mechanisms among supply-chain actors for emission reduction. These gaps inhibit the development of realistic mitigation strategies that are suitable for industrial practitioners.

2.2. Environmental Value Stream Mapping (EVSM) in Industrial Carbon Hotspot Identification

Environmental Value Stream Mapping (EVSM) extends traditional lean Value Stream Mapping by integrating environmental metrics, such as carbon emissions, energy consumption, water usage, and waste generation. The EVSM is a powerful tool for identifying inefficiencies and high-impact emission nodes across industrial processes. Bosch et al. (2019) highlight the capability of EVSM to pinpoint carbon-intensive segments in multi-step production settings. In parallel, Faulkner and Badurdeen (2014) demonstrated that the EVSM enables the systematic quantification of energy waste and resource inefficiencies, thereby assisting in strategic sustainability planning. Pozzi et al. (2022) argued that the EVSM is particularly effective in discrete manufacturing environments because of its ability to integrate operational performance with environmental indicators.

However, the application of EVSM in the steel industry remains limited (Ong et al., 2018). Most published studies have focused on machining, assembly, automotive components, and consumer goods. Notably, no EVSM-based analyses map emissions across the entire steel supply chain, including upstream extraction, midstream conversion, and downstream distribution. Consequently, a holistic understanding of the concentration of Scope 3 emissions is still lacking.

2.3. Cooperative Game Theory for Environmental Burden-Sharing

Cooperative game theory provides a mathematical framework for modelling collaboration among multiple agents who share benefits and burdens. In sustainability research, game-theoretic approaches are increasingly being adopted for resource sharing, cost allocation, and environmental planning. Delarue (2020) applied cooperative game theory to renewable energy cost-sharing, illustrating its relevance for joint decarbonization investment. Madani (2013) used game-theoretic approaches to optimize water resource management among competing stakeholders. Studies such as Zhao et al. (2023) have demonstrated the effectiveness of coalitions in industrial symbiosis, where multiple industries collaborate to minimize waste.

The Shapley value, proposed by Shapley (1953), is one of the most widely used cooperative allocation methods owing to its fairness axioms, including efficiency, symmetry, and additivity. It has been extensively applied in energy sharing, emissions trading, and collaborative logistics. Despite its theoretical strengths, no prior study has integrated Shapley-based coalition modelling with Scope 3 emission mitigation in the steel industry. There is a significant gap in applying cooperative burden-sharing frameworks to incentivize upstream suppliers, manufacturers, and downstream distributors to reduce emissions collectively.

2.4. Synthesis of Literature Gaps

The literature review revealed significant research gaps in the decarbonization process, particularly within the steel industry. Existing studies indicate the absence of empirical plant-level investigations based on operational data in the context of Scope 3 emissions. Most available research focuses on emission quantification using Life Cycle Assessment (LCA), which relies heavily on simulation tools. This reliance has resulted in the limited accuracy of simulation-based estimations. Furthermore, emission mapping and hotspot identification using Environmental Value Stream Mapping (EVSM) across the entire steel production supply chain remain scarce, despite EVSM's potential to systematically identify carbon-intensive hotspots, particularly within the complex upstream–downstream processes of steel manufacturing. Other studies have also failed to develop an integrated multi-method policy framework that combines operational data, EVSM-based mapping, life-cycle carbon accounting, and cooperative game theory. Consequently, the existing body of research remains fragmented and has not yet captured or analyzed the complex interactions among factors across the steel production supply chain. In addition, the absence of incentive-compatible frameworks for allocating emission-reduction responsibilities among different actors has made it difficult for the industry to engage suppliers and distributors, as cost–benefit structures are often perceived as uneven. This study addresses these gaps by integrating factory-level operational data, EVSM mapping, Scope 3 emission inventories, and Shapley-based cooperative modelling into a unified analytical framework that holistically responds to the three critical gaps identified in prior research.

3. Research Objectives

Based on the identified gaps, this study formulates the following research objectives (ROs):

RO1**:** Develop a comprehensive framework for quantifying Scope 3 emissions in the steel supply chain using real activity data.

RO2: Apply Environmental Value Stream Mapping (EVSM) to identify and quantify emission hotspots across six key supply chain stages.

RO3: Construct a cooperative game-theoretic model to allocate emission reduction responsibilities and benefits among upstream suppliers, steel manufacturers, and downstream distributors.

RO4: Propose a data-driven, context-specific action plan for Scope 3 mitigation tailored to the Indian steel manufacturing conditions.

4. Research Methodology

This study employed a multi-method, data-driven research design integrating plant-level primary data, Environmental Value Stream Mapping (EVSM), life-cycle accounting, and cooperative game theory to quantify and reduce Scope 3 emissions across a medium-scale steel supply chain in West Bengal, India. Primary data were collected through extensive field visits, structured interviews, transport tracking, energy meter logs, and process documentation covering upstream procurement, midstream steelmaking, and downstream distribution. The EVSM was applied to map material, energy, and emission flows across six supply chain stages, enabling granular hotspot identification (Darvish Shahrbabaki, 2011; Shi et al., 2024). Life-cycle emission factors from IPCC, DEFRA, and India-specific LCI databases were integrated with activity data to compute category-wise Scope 3 emissions for each company. Game-theoretic modelling, incorporating coalition payoffs and Shapley value allocation, was used to evaluate the collective abatement strategies of suppliers, manufacturers, and distributors. Data triangulation, stakeholder validation, and ethical confidentiality safeguards ensured the scientific rigor, replicability, and real-world reliability of the study.

5. Case Example of Scope 3 Emission Reduction in Steel Sector

The data collection process commenced with field visits to a medium-scale steel manufacturing facility in West Bengal, India. The aim was to collect accurate, stakeholder-specific, and process-level data across the upstream, midstream, and downstream stages of the supply chain. This was essential for calculating Scope 3 greenhouse gas (GHG) emissions, identifying emission hotspots using Environmental Value Stream Mapping (EVSM), and structuring collaborative strategies for emission reduction using game-theoretic modelling.

5.1. Scope and Boundaries

The scope and boundaries of this study encompass three aspects. The first is the geographic aspect, which examines the steel supply chain operating within industrial clusters in South Bengal and its vicinity. The areas under study include raw material procurement, manufacturing activities, final production and product distribution. The second aspect concerns the steel production processes. This study identifies the entire sequence of activities, ranging from upstream raw material procurement and transportation to downstream processes, such as product delivery, usage, and end-of-life management. The third aspect focuses on the inventory of greenhouse gas emissions under Scope 3, namely all indirect emissions arising from the production chain, excluding Scope 1 (direct operational emissions) and Scope 2 emissions (purchased electricity). These boundaries enabled the study to provide a comprehensive overview of the contribution of indirect emission reductions across the steel production chain, while also offering a holistic approach to support decarbonization in the steel industry. The detailed data types and sources are listed in Table 1.

Table 1. Data types and sources

Data Category	Parameters	Sources	Method of Collection
Activity Data	Transport distances, freight weights, shipment frequency	Transport logs, supplier databases	Site visits, logistics reports
Activity Data	Energy usage, fuel consumption	Utility bills, factory dashboards	Plant records, observation
Emission Factors	CO_2e per ton-km or per	IPCC, DEFRA, India-	Secondary sources,

Data Category	Parameters	Sources	Method of Collection
	process unit	specific LCI databases	emission inventories
Cost Data	Transport costs, fuel prices, emission abatement cost	Vendor quotes, financial records	Interviews, procurement data
Stakeholder Data	Willingness to cooperate, emission responsibility	Process heads, managers, suppliers	Structured interviews, surveys
Process Mapping Data	Material flow, scrap generation, logistics networks	Factory SOPs, layout drawings	On-site walkthroughs, engineering maps

5.2. Stakeholder Engagement Strategy

Stakeholder engagement in this study focused on ensuring that the data collected were comprehensive and representative of all segments within the steel supply chain. At the upstream stage, emission inventory activities involve raw material providers, such as iron ore suppliers and scrap dealers, as well as third-party contractors responsible for construction services. During the midstream production stage, engagement included steel plant managers, engineers, and environmental, health, and safety (EHS) officers, who play a direct role in industrial operations. At the downstream stage, the stakeholders engaged comprise distributors, customers, recyclers, and logistics partners responsible for managing products in the post-use phase. The data collection methods for stakeholders included interviews, data-sharing agreements, scheduled site visits, and survey forms. To safeguard confidentiality, the study employed non-disclosure agreements signed by multiple parties, particularly when sensitive corporate data were shared with external stakeholders.

5.3. Tools and Instruments

- Survey and Interview Tools: Google Forms and printed questionnaires; semi-structured guides were used to capture quantitative and qualitative data.
- Measurement Tools: GPS-enabled transport tracking, meter-based energy logs, and tonnage records.
- Software Applications: Microsoft Excel for data cleaning and validation (7EVSM software (Lean Value Stream Mapping tools)) for mapping and Python for cooperative game theory modelling and simulation

Data Collection Timeline has been demonstrated in Table 2

Table 2. Timeline of data collection activities

Phase	Activity	Duration
Phase 1	Stakeholder identification and initial engagement	1 week
Phase 2	Primary data collection (surveys, site visits)	3 weeks
Phase 3	Secondary data gathering (literature, databases)	1 week
Phase 4	Validation and triangulation of all datasets	1 week
Phase 5	Data pre-processing and integration for modelling	1 week

5.4. Ethical and Confidentiality Measures

This context-rich and methodologically sound plan ensured that the collected data were not only reliable and replicable but also aligned with the real operational dynamics of steel manufacturing in West

Bengal, thereby strengthening the validity of the subsequent modelling and analysis phases. The six stages are listed in Table 3.

- Stakeholder identities and responses were anonymized in all the outputs.
- Only aggregate and non-sensitive insights were shared in the results.
- Data-sharing agreements were executed before primary data collection.

5.5. Results and Discussion of Scope 3 Emission Reduction Strategy Phase I

The steel supply chain was divided into six key stages for EVSM. All these stages are mentioned in Table 3 whereas Collected Data for six stages are mentioned in Table 4.

Table 3. Process Segmentation

Stage	Description
UP1	Iron ore/scrap transportation from supplier to plant
UP2	Internal material handling and storage
MS1	Electric Arc Furnace (EAF) steel production
MS2	Rolling and finishing
DS1	Packaging and warehousing
DS2	Distribution to customer via road transport

Table 4. Collected data table

Stage	Activity	Distance / Volume	Emission Factor (EF)	Activity Data (A_i)	Emissions ($E_i = A_i \times EF_i$)
UP1	Scrap transport (diesel truck)	180 km, 1500 tons	0.19 kg CO_2e/ton-km	270,000 ton-km	51,300 kg CO_2e
UP2	Material handling (electric forklifts)	2000 kWh/month	0.82 kg CO_2e/kWh	2000 kWh	1,640 kg CO_2e
MS1	EAF operation (energy input)	4500 MWh/month	0.82 kg CO_2e/kWh	4,500,000 kWh	3,690,000 kg CO_2e
MS2	Rolling (natural gas use)	12,000 SCM/month	2.14 kg CO_2e/SCM	12,000 SCM	25,680 kg CO_2e
DS1	Packaging, internal movement	800 kWh/month	0.82 kg CO_2e/Wh	800 kWh	656 kg CO_2e
DS2	Final product transport (road)	250 km, 1200 tons	0.19 kg CO_2e/ton-km	300,000 ton-km	57,000 kg CO_2e

A value stream map was created to show the process flow, material movement, and associated emissions at each node. The emissions were overlaid on the map using "emission boxes" to highlight the carbon hotspots. The hotspot analysis is presented in Table 5.

Table 5. Hotspot analysis and key insights from EVSM analysis

Stage	Total Emissions (kg CO_2e)	% of Total Scope 3	Remarks
UP1	51,300	1.3%	Moderate, logistics improvement scope
UP2	1,640	<0.1%	Negligible
MS1	3,690,000	91.9%	Critical – Electrification or renewable substitution needed

Stage	Total Emissions (kg CO_2e)	% of Total Scope 3	Remarks
MS2	25,680	0.6%	Low impact
DS1	656	<0.1%	Minimal
DS2	57,000	1.4%	High logistics emissions – route optimization & cleaner fleet

EAF Melting (MS1) is the primary emission hotspot, accounting for over 90% of the total emissions. This is driven by high electricity usage, indicating a major opportunity for grid decarbonization or on-site solar integration.

- Product distribution (DS2) was the second-largest contributor owing to long-distance trucking. Shifting to multimodal logistics (rail + road) or EV trucks can reduce this impact.
- Although upstream transportation (UP1) is not negligible, it can be optimized by sourcing from closer scrap suppliers or through bulk delivery schedules.

5.6. Results and Discussion of Scope 3 Emission Reduction Strategy Phase II

Based on the EVSM analysis, emissions were attributed to the following three primary stakeholders

Table 6. Primary stakeholders and their emission sharing

Stakeholder	Emission Source	Total Emissions (kg CO_2e)	Share (%)
U: Upstream Supplier	Scrap Transport (UP1)	51,300	1.3%
M: Manufacturer	EAF Melting (MS1), Handling (UP2), Rolling (MS2)	3,717,320	92.5%
D: Downstream Partner	Distribution (DS2), Packaging (DS1)	57,656	1.4%

To develop a practical and stakeholder-inclusive emission reduction framework, game-theoretic modelling was conducted using real baseline data from upstream suppliers (U), manufacturers (M), and downstream distributors (D) in a West Bengal-based steel supply chain. The abatement potential for each player was estimated based on implementable interventions, such as fuel switching, energy efficiency improvements, and route optimization. For instance, the upstream emission reduction potential was based on the feasibility of switching from conventional diesel trucks to compressed natural gas (CNG) or electric freight carriers, an intervention observed in pilot programs by selected suppliers. The manufacturer's abatement estimate was based on the technical feasibility of partially substituting virgin raw materials with high-grade scrap combined with energy-efficient melting and reheating practices (Golvaskar et al., 2024). For the downstream segment, route optimization and modal shifts (e.g., road-to-rail) for product distribution formed the basis for estimating the emissions reduction potential.

Each intervention was analyzed for its emission-saving capacity using standard emission factors from recognized databases, such as the IPCC, DEFRA, and India-specific LCI repositories. The calculated abatement potentials were thus defined as a percentage of baseline emissions: 20% for upstream suppliers (10,260 kg CO_2e), 20% for manufacturers (743,464 kg CO_2e), and 20% for downstream distributors (11,531 kg CO_2e). The estimation of abatement costs for each stakeholder was based on a combination of primary data sources, such as vendor quotations, utility bills, and process documentation, and supported by relevant secondary literature. Each stakeholder's intervention-specific cost was calculated based on the practical changes required to reduce emissions within the existing infrastructure. These include technological upgrades, operational changes, and logistics optimization (LO). Table 7 presents the basis for cost estimation across the supply chain players: upstream suppliers (U), core manufacturers (M), and downstream distributors (D). The table outlines the type of intervention implemented, associated components contributing to the cost, and final unit abatement cost (in ₹/kg CO_2e).

Table 7. Real-World basis for estimating abatement costs per stakeholder

Stakeholder	Emission Reduction Intervention	Cost Components Considered	Data Source(s)	Estimated Abatement Cost(₹/kg CO_2e)
U (Supplier)	Fuel switch in freight transport	Additional cost of low-emission fuel, retrofitting charges, operational inefficiency adjustment	Vendor quotations, logistics partner interviews, DEFRA emission reports	₹3.0
M (Manufacturer)	Increased recycled scrap usage & efficiency	Sorting/processing cost of scrap, quality control overhead, energy efficiency system investment	Process sheets, internal cost records, literature on EAF optimization	₹2.5
D (Distributor)	Route optimization & digital logistics	Software license, training, IT infrastructure upgrades, last-mile efficiency improvements	Cost sheets from distributors, interviews, route-planning tool data	₹4.0

Coalitional benefits were evaluated assuming that each kilogram of CO_2e abated results in a ₹5 return, representing the cumulative value from regulatory compliance, reputational gain, and market incentives. Table 7.8 demonstrates the net payoffs from the individual and combined stakeholder coalitions. Notably, the full coalition {U, M, D} yields the highest net benefit of ₹1,890,711, significantly exceeding the payoff from the isolated efforts. This outcome underscores the systemic value of cooperation over individual efforts. Coalitional benefits were evaluated assuming that each kilogram of CO_2e abated results in a ₹5 return, representing the cumulative value from regulatory compliance, reputational gain, and market incentives. Table 8 demonstrates the net payoffs of individual and combined stakeholder coalitions. Notably, the full coalition {U, M, D} yields the highest net benefit of ₹1,890,711, significantly exceeding the payoff from the isolated efforts. This outcome underscores the systemic value of cooperation over individual efforts.

Table 8. Game coalitions and payoff structure

Coalition	Members	Total Abatement	Benefit	Total Cost	Net Payoff
{U}	U	10,260	₹51,300	₹30,780	₹20,520
{M}	M	743,464	₹3,717,320	₹1,858,660	₹1,858,660
{D}	D	11,531	₹57,655	₹46,124	₹11,531
{U, M}	U, M	753,724	₹3,768,620	₹1,889,440	₹1,879,180
{M, D}	M, D	754,995	₹3,774,975	₹1,904,784	₹1,870,191
{U, D}	U, D	21,791	₹108,955	₹76,904	₹32,051
{U, M, D}	All	765,255	₹3,826,275	₹1,935,564	₹1,890,711

To equitably allocate this net cooperative benefit, Shapley values were computed based on each player's marginal contribution to all coalition permutations. Table 9 shows the distribution of the total benefit using Shapley's cost-sharing logic. The manufacturer secures approximately 97.6% of the benefit owing to its dominant emission profile and abatement potential, whereas the supplier and distributor receive proportionate shares of 1.7% and 0.7%, respectively.

Table 9. Shapley value allocation (final cooperative payoff = ₹1,890,711)

Player	Marginal Contribution (Approx.)	Shapley Share (%)	Allocated Payoff (₹)
U (Supplier)	₹32,051	1.7%	₹32,051
M (Manufacturer)	₹1,845,000	97.6%	₹1,845,000
D (Distributor)	₹13,660	0.7%	₹13,660

The Nash equilibrium analysis supports a cooperative approach. In the absence of cooperation, suppliers and distributors receive minimal returns, whereas the manufacturer, although gaining substantially alone, can unlock even higher net benefits through joint participation. Hence, the equilibrium strategy recommends full coalition formation supported by a Shapley-based investment fund.

6. Conclusion and Future Work

This study demonstrates that a cooperative, data-driven framework combining EVSM, life-cycle emission accounting, and game-theoretic allocation can significantly strengthen Scope 3 mitigation in the steel sector, with manufacturers playing a pivotal role and suppliers and distributors contributing meaningful but smaller portions. Policy implications include the need for government-backed incentives for renewable energy integration (e.g., solar adoption), digital traceability mandates, differential carbon taxation, and support for scrap quality enhancement programs aligned with circular economy principles. Future research will extend this framework using real-time IoT sensors for energy and logistics monitoring, blockchain-based supply chain traceability for upstream and downstream verification, and AI-driven predictive analytics for dynamic emission control. Integrating these digital technologies with Scope 3 reporting will enable continuous monitoring, tamper-proof data flows, transparent supplier engagement, and automated carbon accounting, ultimately supporting India's net-zero industrial transformation while enabling steel manufacturers to operationalize low-carbon, resilient, and cooperative supply chains.

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