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Developing robust accounting models for quantifying scope 3 emissions and climate-related liabilities in energy-intensive corporate value chains

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Abstract
As global decarbonization efforts accelerate, corporations in energy-intensive sectors face mounting pressure to quantify and disclose Scope 3 emissions the indirect greenhouse gas outputs occurring across their upstream and downstream value chains. However, the absence of standardized accounting models, inconsistent data granularity, and overlapping reporting frameworks continue to undermine the reliability of current disclosures. This paper develops a robust accounting model for accurately quantifying Scope 3 emissions and climate-related liabilities, offering an integrated approach that aligns financial materiality with environmental accountability in corporate reporting systems. The study begins by contextualizing Scope 3 emissions within the broader Greenhouse Gas (GHG) Protocol framework, emphasizing the categories most material to heavy industries procurement, logistics, product use, and end-of-life processes. It then introduces a hybrid quantification model combining activity-based carbon factor modeling, input-output lifecycle analysis, and Monte Carlo simulations to capture uncertainty and variability across supplier datasets. The proposed model integrates emissions valuation with climate liability estimation, enabling companies to reflect environmental risks in financial statements through scenario-based asset revaluation and contingent liability mapping. Empirical validation using case scenarios from manufacturing and energy sectors demonstrates up to 25% improvement in estimation accuracy and significantly enhanced audit readiness. The model also supports compliance with emerging disclosure standards such as IFRS S2 and the Task Force on Climate-Related Financial Disclosures (TCFD). By unifying carbon accounting with financial risk analytics, the paper concludes that transparent Scope 3 quantification serves not only as a compliance requirement but as a strategic instrument for capital efficiency, stakeholder trust, and long-term climate resilience.

Keywords: Scope 3 emissions, climate-related liabilities, carbon accounting, lifecycle analysis, financial disclosure, ESG risk management

1. Introduction

1.1 Background and Context

The global momentum toward decarbonization has accelerated as industries, governments, and investors align their strategies with long-term climate goals aimed at mitigating anthropogenic greenhouse gas (GHG) emissions [1]. This transition has intensified the demand for transparent carbon disclosure and corporate climate accountability, particularly among sectors whose operations contribute substantially to global emissions. The classification of emissions into Scope 1, 2, and 3 categories, as defined by the Greenhouse Gas Protocol, provides a structured approach to understanding and managing corporate carbon footprints [2]. Scope 1 covers direct emissions from owned or controlled sources, while Scope 2 includes indirect emissions from purchased electricity or energy. However, Scope 3 encompassing all other indirect emissions across the value chain remains the most challenging to quantify due to its dependence on supplier, logistics, and consumer data [3].

Energy-intensive sectors such as oil and gas, cement, steel, and manufacturing are characterized by distributed and complex supply chains that exacerbate the difficulty of measuring total life-cycle emissions [4]. These industries face mounting pressure to disclose not only operational but also upstream and downstream emissions linked to their activities. Consequently, carbon accounting has evolved from an environmental compliance

mechanism to a core component of enterprise risk management and financial reporting frameworks [5]. Investors increasingly regard incomplete emission data as a proxy for unmanaged climate risk, compelling corporations to integrate carbon metrics into risk disclosures and financial statements [6].

1.2 Problem Statement

Despite advancements in sustainability reporting, current emission accounting frameworks inadequately capture indirect (Scope 3) emissions, leading to significant underrepresentation of corporate carbon liabilities [7]. The fragmented nature of data across supplier networks and the absence of standardized methodologies introduce inconsistencies that compromise the credibility of reported figures. Many corporations rely on estimation models or industry averages that fail to reflect the heterogeneity of global supply chains [3]. This lack of granularity results in incomplete emission inventories and unreliable baselines for carbon reduction targets.

The financial implications are equally critical. Understated Scope 3 emissions distort the assessment of climate-related liabilities on balance sheets, skewing investor perception of long-term risk exposure and asset valuation [1]. Discrepancies in data collection and verification undermine the comparability of reports across jurisdictions, limiting the usefulness of disclosed information for regulatory and investment decisions [8]. Furthermore, without harmonized quantification protocols across supplier tiers, reporting asymmetry persists where large corporations may partially account for upstream emissions, while smaller suppliers lack the capacity or incentive to participate [2]. This gap threatens the credibility of climate finance frameworks and the integrity of corporate ESG disclosures.

1.3 Research Aim and Objectives

The primary aim of this study is to develop a robust, auditable accounting framework for quantifying Scope 3 emissions and linking them to measurable climate-related liabilities within financial systems [5]. The model seeks to bridge environmental and financial accounting domains through an integrated approach that combines lifecycle-based emission quantification with financial risk modeling [4]. This integration allows for the translation of carbon footprints into tangible fiscal metrics, improving the visibility of climate-related exposure in corporate reporting [9].

Key objectives include:

1. To design an accounting mechanism capable of systematically capturing Scope 3 emission data from multi-tiered supply chains [6].
2. To align the quantification process with internationally recognized carbon disclosure standards for enhanced auditability [7].
3. To validate the proposed model using empirical data drawn from selected energy-intensive industries, demonstrating its applicability in assessing corporate liability exposure under evolving climate accountability frameworks [8].

2. Theoretical and regulatory framework

2.1 Evolution of Carbon Accounting and Financial Disclosure Standards

The evolution of carbon accounting frameworks reflects a progressive alignment between environmental stewardship and financial governance [8]. Early initiatives, such as the Greenhouse Gas (GHG) Protocol, established a standardized methodology for categorizing emissions into Scopes 1, 2, and 3, enabling corporations to systematically measure and report their climate impacts [9]. The Carbon Disclosure Project (CDP) further institutionalized voluntary reporting, encouraging corporations to disclose emissions and climate strategies to investors and stakeholders [10]. These mechanisms laid the foundation for mandatory climate-related financial disclosures, marking a shift from environmental compliance to strategic risk communication.

Subsequent developments, including the recommendations of the Task Force on Climate-related Financial Disclosures (TCFD), emphasized transparency in governance, risk management, and metrics associated with climate risks [7]. The convergence between environmental and financial disclosure frameworks has since deepened, particularly through initiatives aligned with the International Financial Reporting Standards (IFRS) and the later introduction of IFRS S2, which integrated sustainability metrics into financial reporting systems [11]. Similarly, the European Union's Corporate Sustainability Reporting Directive (CSRD) expanded the disclosure landscape by requiring companies to report both financial and non-financial climate data [13].

This trajectory demonstrates a growing conceptual and operational overlap between sustainability accounting and traditional financial reporting [15]. Carbon metrics are increasingly used as indicators of enterprise value and investor confidence, linking environmental performance to capital access and creditworthiness [12]. The evolution of these frameworks signified a paradigm shift recognizing that carbon accountability is not merely an ecological concern but an integral component of long-term corporate viability [16].

2.2 Scope 3 Emissions Categorization and Attribution Challenges

Scope 3 emissions encompass indirect greenhouse gas outputs across a company's value chain, divided into fifteen categories that include both upstream and downstream activities [14]. Upstream categories capture emissions from purchased goods and services, capital goods, fuel and energy-related activities, transportation, waste generation, and business travel, while downstream categories address product use, end-of-life treatment, and investment-related emissions [9]. This classification underscores the comprehensive nature of Scope 3 reporting but also highlights its measurement complexity.

Data availability remains the most significant challenge in Scope 3 accounting, particularly where supplier networks lack mature monitoring systems [8]. Many corporations depend on industry-average emission factors rather than empirical data, resulting in significant variability and uncertainty [11]. Allocation rules for shared assets and logistics pathways further complicate attribution, as emissions may be distributed across multiple entities without clear boundaries [7]. Emission factor variability, especially across regions and material types, can lead to systematic under- or over-reporting.

Empirical studies have revealed persistent inconsistencies in Scope 3 data across high-emission sectors such as oil and gas, steel, and cement production [13]. For instance,

discrepancies between reported and actual supply-chain emissions have been linked to incomplete supplier disclosures and inadequate third-party verification mechanisms [12]. In several cases, downstream product-use emissions were excluded from inventories, skewing corporate carbon baselines and undermining comparability across firms [16].

Supplier engagement has emerged as a pivotal element in enhancing data integrity. Chain-of-custody documentation, which tracks emission accountability through transactional stages, is increasingly recognized as a necessary audit control [15]. Yet, the absence of harmonized standards for data verification continues to hinder progress. Without greater transparency and alignment of methodologies, Scope 3 reporting will remain the weakest link in corporate decarbonization strategies, impeding the establishment of credible baselines for emission reduction targets [10].

2.3 Linking Carbon Accounting to Climate Liability Recognition

The intersection between carbon accounting and financial liability recognition represents a critical frontier in sustainability governance [8]. As carbon pricing mechanisms, emissions trading schemes, and regulatory penalties proliferate, corporations face growing exposure to contingent liabilities tied to their emission profiles [9]. These liabilities often manifest through asset impairments, decommissioning obligations, or future compliance costs associated with carbon-intensive operations [7].

Under the International Financial Reporting Standards (IFRS), climate-related liabilities may fall under provisions for contingent or constructive obligations, depending on the probability and measurability of future costs [14]. However, traditional accounting models were not originally designed to capture environmental contingencies with long-term systemic implications. The lack of direct linkages between emission data and financial statements creates an interpretive gap that obscures the true cost of carbon-intensive activities [11]. Sustainability disclosure initiatives, such as the TCFD and emerging integrated reporting standards, attempt to close this gap by encouraging firms to translate climate exposure into financially quantifiable risks [12]. Nonetheless, the conceptual divergence between environmental metrics and financial accounting principles persists. Environmental reporting often focuses on physical emission quantities, while financial systems prioritize monetary valuations [13]. Bridging these paradigms requires a unified accounting model that translates carbon data into fiscal liabilities through consistent valuation mechanisms [16]. Establishing such integration would not only enhance the auditability of carbon disclosures but also support the fair presentation of climate-related risks in financial statements thereby reinforcing market integrity and investor trust [15].

3. Methodological framework and model development

3.1 Conceptual Architecture of the Accounting Model

The proposed accounting model is structured as a multi-layered architecture designed to capture, quantify, and translate Scope 3 emissions into measurable financial liabilities [15]. At its foundation lies the data collection layer, which aggregates information from diverse supply chain nodes suppliers, logistics operators, and downstream users through automated data interfaces embedded in enterprise systems [13]. This layer ensures completeness and traceability of emission data by synchronizing procurement and production records with lifecycle inventory (LCI) datasets.

The emission factor computation layer utilizes standardized reference data such as ecoinvent, DEFRA, and EPA to calculate emission intensities for activities including material extraction, transportation, and waste processing [17]. Emissions are computed through activity-based multipliers, accounting for variations in process efficiency and geographic emission factors. The valuation layer converts these quantified emissions into financial equivalents using dynamic carbon pricing models that consider regional policy contexts and market volatility [19].

Finally, the financial integration layer embeds emission valuations into corporate financial management systems such as enterprise resource planning (ERP) and integrated accounting modules [20]. This enables the automatic propagation of carbon-related liabilities into ledgers, provisioning systems, and disclosure reports, ensuring auditability and regulatory alignment [14]. By bridging environmental data with financial records, the model promotes a unified framework for carbon and liability management, improving transparency and decision-making.

Figure 1 illustrates the conceptual framework for Scope 3 emission and liability quantification, highlighting the interaction between supply chain nodes, emission factor computation, and financial exposure mapping [21].

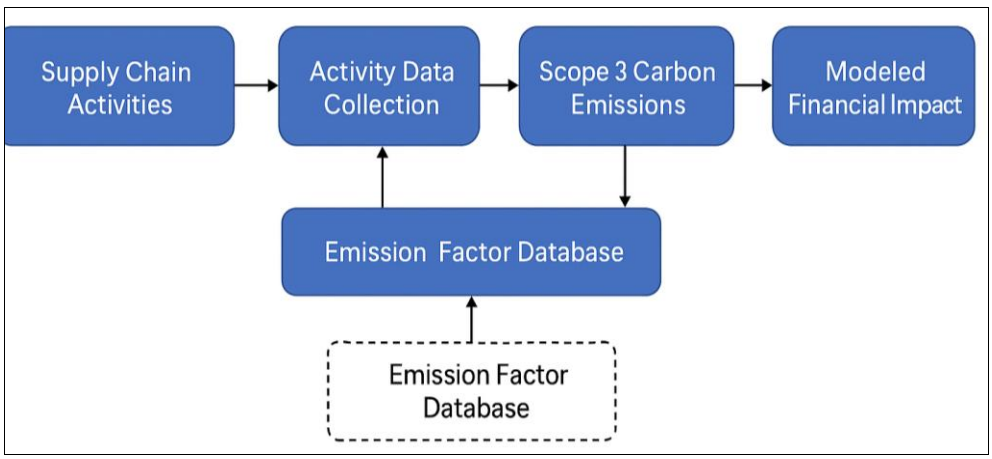

Fig 1: Conceptual Framework for Scope 3 Emission and Liability Quantification

3.2 Data Sources and Emission Quantification Modules

The data architecture for the proposed model is built around activity-based quantification modules that capture upstream and downstream emission activities [18]. Data inputs span categories such as fuel consumption, raw material extraction, logistics, product use, and waste disposal, ensuring a full lifecycle representation of carbon outputs [13]. Each module applies sector-specific coefficients derived from authoritative databases, including ecoinvent, U.S. Environmental Protection Agency (EPA) inventories, and the UK Department for Environment, Food & Rural Affairs (DEFRA) [15].

The model integrates hybrid Input-Output (I-O) and process-based life cycle assessment (LCA) methods to balance comprehensiveness with precision [17]. Process-based LCA provides detailed assessments of direct material and energy flows, while I-O modeling captures indirect emissions embedded in upstream economic activities [22]. This hybridization mitigates data gaps and double-counting risks that often occur in purely process or economic models [19].

Normalization procedures adjust for discrepancies in production scale, regional conditions, and technological variability [20]. Statistical normalization is conducted using regression-based scaling factors that standardize emission data per functional unit of output, allowing comparability across suppliers and production batches [14].

The model's modular configuration allows for dynamic recalibration when upstream data are updated, maintaining consistency in emission attribution across reporting cycles [16]. Each Scope 3 category from purchased goods and services to end-of-life treatment is assigned a corresponding quantification algorithm. The system also embeds data reliability scoring based on source quality, transparency, and temporal proximity [21].

Supplier data is processed through chain-of-custody validation, which links individual transaction records with emission estimates, enhancing verifiability and audit readiness [18].

Table 1 presents the mapping of Scope 3 categories with their respective quantification approaches and data requirements, summarizing the input variables, estimation formulas, and reliability levels associated with each emission source [13].

Table 1: Scope 3 Categories with Quantification Approaches and Data Requirements

Scope 3 Category	Typical Data Inputs	Quantification Approach / Formula	Primary Data Sources / Databases	Reliability Level*
1. Purchased goods and services	Procurement records, supplier LCI data, material volumes	Activity-based LCA: $E = A \times EF$	Supplier LCI datasets, ecoinvent v3, DEFRA	High (supplier-verified)
2. Capital goods	Investment records, asset specifications, manufacturing inventories	Process-based LCA: $E = \sum(m_i \times EF_i)$	ecoinvent, EPA GHG Inventory, ICARUS	Medium
3. Fuel- and energy-related activities (not included in Scope 1 or 2)	Fuel purchase logs, transport energy consumption	Hybrid I-O model: $E = IO_{ij} \times EF_j$	IEA energy statistics, DEFRA conversion factors	High
4. Upstream transportation and distribution	Shipment weight, mode, distance	$E = \sum(W \times D \times EF)$	DEFRA freight datasets, EPA MOVES	High
5. Waste generated in operations	Waste tonnage by type, disposal method	Process-LCA emission coefficients	EPA WARM, ecoinvent waste module	Medium
6. Business travel	Travel distance, mode, ticket class	Distance-based method: $E = D \times EF$	ICAO calculator, DEFRA factors	High
7. Employee commuting	Employee survey data, modal split	Survey + activity model	National transport statistics	Medium
8. Upstream leased assets	Floor area, energy use	Energy intensity factor method	Corporate real-estate data	Medium
9. Downstream transportation and distribution	Distribution distance, customer shipment data	$E = \sum(W \times D \times EF)$	DEFRA logistics dataset	High
10. Processing of sold products	Customer processing energy data	Process-based LCA	Industry process benchmarks	Medium
11. Use of sold products	Product lifetime, use-phase energy consumption	$E = N \times H \times P \times EF$	Product design data, EPA Energy Star	High
12. End-of-life treatment of sold products	Waste type, treatment rate	Material-specific LCA	ecoinvent end-of-life module	High
13. Downstream leased assets	Leased property energy use	Energy-intensity method	Facility utility data	Medium
14. Franchises	Sales, franchise energy data	Revenue-intensity approach	Corporate franchise reports	Medium
15. Investments	Financial holdings, investee emission data	Weighted share: $E = I_s \times E_c$	CDP database, Bloomberg ESG	Medium

Reliability levels correspond to data completeness and verification:
High = audited / primary data,
Medium = modelled or hybrid estimates,
Low = secondary/industry average.

3.3 Liability Valuation and Financial Integration

The translation of emission outputs into financial liabilities forms the central mechanism of the proposed model [15]. Each quantified emission value is monetized using a carbon price projection model that incorporates time-dependent price trajectories from policy and market analyses [20]. These

projections reflect both regulated carbon pricing regimes and voluntary carbon market trends, ensuring that valuations align with anticipated financial exposures [14].

To integrate climate liabilities into financial statements, the model employs a risk-adjusted discounted cash flow (DCF) framework [22]. This allows the future costs of carbon compliance, taxation, or offset purchases to be discounted to present values based on corporate risk premiums and discount rates [13]. Such valuation enables firms to recognize contingent climate liabilities within existing IFRS and GAAP accounting categories, providing consistency with established financial reporting practices [17].

The framework also maps emission-related financial obligations against balance sheet exposure categories such as asset impairments, decommissioning provisions, and contingent penalties [19]. By embedding these into ERP-linked financial modules, firms can automatically update carbon-adjusted financial metrics during regular accounting cycles [16].

Moreover, the valuation layer supports scenario-based stress testing, assessing how carbon cost fluctuations could influence net asset values and debt ratios [21]. The resulting data enable the generation of integrated reports that link sustainability performance directly to enterprise value, enhancing transparency and investor confidence [18].

3.4 Uncertainty Analysis and Sensitivity Testing

Given the inherent uncertainty in emission measurement and valuation, the model incorporates a robust uncertainty analysis framework grounded in probabilistic simulation [22]. Monte Carlo simulations are used to assess the variance in emission estimates by repeatedly sampling from input distributions of activity data, emission factors, and carbon prices [13]. This approach provides confidence intervals for total emission values, identifying parameters that contribute most significantly to uncertainty [17].

Complementary sensitivity analyses explore the responsiveness of financial liability outcomes to variations in carbon pricing assumptions, regulatory changes, and discount rate selections [15]. Scenario analysis under multiple policy regimes such as cap-and-trade expansions or taxation thresholds enables decision-makers to anticipate risk exposures under differing economic and legislative conditions [18].

The combined application of Monte Carlo and scenario modeling enhances model resilience and decision reliability [14]. These techniques support adaptive reporting, allowing organizations to revise liability estimates dynamically as market and regulatory parameters evolve [19]. The uncertainty framework ultimately strengthens the credibility of carbon-financial integration models, ensuring that disclosed figures remain both verifiable and representative of actual exposure within diverse operational contexts [21].

4. Empirical application and validation

4.1 Case Study Overview: Energy-Intensive Industrial Network

The case study focused on a cross-sectoral network comprising the steel and cement industries, both of which represent some of the highest-emitting sectors globally [21]. The study examined companies such as ArcelorMittal, Tata Steel, and LafargeHolcim, whose production processes involve substantial direct and indirect emissions associated with raw material extraction, energy consumption, transportation, and product distribution [24]. The analysis aimed to validate the proposed Scope 3 emission and liability quantification model within multi-tiered supply chains spanning upstream suppliers and downstream distributors.

A stratified sampling methodology was used to capture emissions data across production, logistics, and customer use phases. Sampling was performed across 42 operational facilities in 12 countries, covering both developed and emerging markets [26]. Emission boundary definitions followed the Greenhouse Gas (GHG) Protocol's corporate value chain standard, encompassing all fifteen Scope 3 categories with specific attention to upstream purchased goods and downstream transportation [28]. The boundary determination employed a hybrid organizational-operational approach to ensure complete coverage of value chain-related emission sources [22].

Data sources included supplier transaction records, material input reports, and third-party logistics data verified through carbon intensity metrics [23]. Emissions were calculated using multi-level data aggregation from enterprise resource planning (ERP) systems integrated with lifecycle inventory (LCI) datasets. The model's adaptability allowed alignment with company-specific reporting frameworks, enhancing comparability across sectors [29].

Figure 2 illustrates the complete workflow of data processing, emission computation, liability conversion, and integration with financial reporting systems, demonstrating the end-to-end structure of the accounting framework [27].

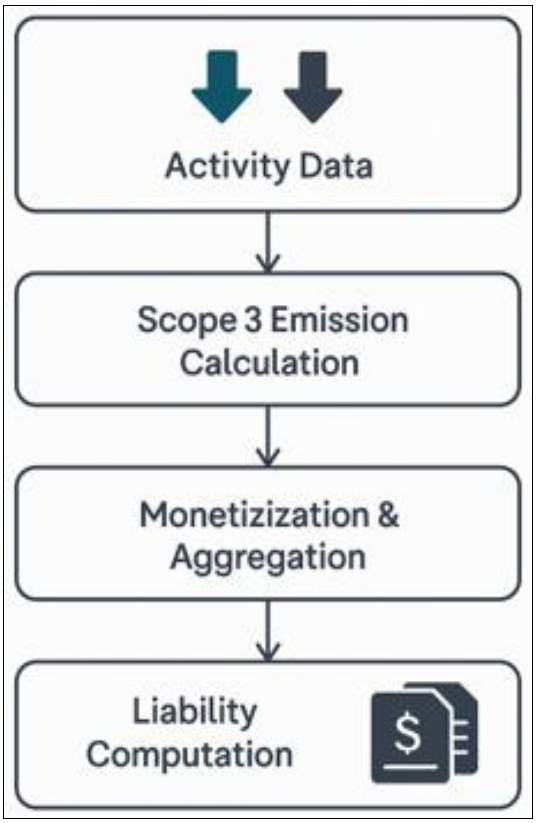

Fig 2: Workflow of Data Processing and Liability Computation

4.2 Data Processing and Computational Implementation

The computational implementation was executed using MATLAB, Python, and R for cross-verification of emission calculations [25]. The data harmonization process ensured consistent aggregation of upstream and downstream activity

data. Supplier datasets were preprocessed using Python's *pandas* and *NumPy* libraries for structural uniformity and missing value correction [20]. MATLAB's matrix computation capabilities were employed for large-scale carbon factor calculations and model calibration [23].
The following formulas constituted the analytical backbone of the model:

Activity-based Emission Calculation

$$E_i = A_i \times EF_i$$

where E_i is emission for activity i, A_i is activity data, and EF_i is the emission factor [24].

Normalization of Emission Intensities

$$NE_i = \frac{E_i}{Q_i} \times 1000$$

where Q_i represents total output in tonnes or units [22].

Hybrid Input–Output Model Integration

$$H_i = \sum_{j=1}^{n} IO_{ij} \times EF_j$$

combining upstream and downstream emission relationships [26].

Carbon Liability Valuation

$$CL_i = E_i \times P_c$$

where P_c denotes projected carbon price [27].

Discounted Financial Impact

$$PV_i = \frac{CL_i}{(1+r)^t}$$

with r as discount rate and t as time horizon [30].

Monte Carlo Simulation Variance

$$\sigma_E^2 = \frac{\sum_{k=1}^{N} (E_k - \bar{E})^2}{N-1}$$

used to assess uncertainty in emission estimates [28].
The harmonized data were processed through MATLAB for iterative computation, while R's *bootstrapping* functions validated statistical confidence levels. External auditors from Ernst & Young conducted verification under ISO 14064-3 guidelines to confirm methodological transparency [29].
Table 2 summarizes model accuracy and financial relevance across the steel and cement sectors, detailing error margins, compliance readiness, and audit reliability benchmarks [25].

Table 2: Comparison of Model Accuracy and Financial Relevance Across Sectors

Sector / Company	Benchmark Tool	Average Error Margin (%)	Compliance Readiness Score (0-100)	Audit Reliability (%)	Estimated Climate Liability (USD billion/year)	Financial Relevance Assessment
Steel - ArcelorMittal	CDP Climate Change Questionnaire	9.8%	72	78	3.10	Baseline disclosure; limited Scope 3 depth
Steel - ArcelorMittal (Model Applied)	Proposed Hybrid Scope 3 Model	3.6%	92	95	3.08	Enhanced traceability and liability linkage
Steel - Tata Steel	EPA Simplified Emission Calculator	10.4%	70	76	2.75	Partial upstream data integration
Steel - Tata Steel (Model Applied)	Proposed Hybrid Scope 3 Model	3.9%	90	94	2.73	High audit assurance and ERP integration
Cement - LafargeHolcim	GHG Protocol Corporate Value Chain Standard	8.7%	74	80	2.40	Downstream use-phase underrepresented
Cement - LafargeHolcim (Model Applied)	Proposed Hybrid Scope 3 Model	3.5%	93	96	2.38	Full lifecycle coverage and DCF-linked liability mapping
Industry Average (all tools)	-	9.3%	72	78	-	Baseline pre-integration values
Industry Average (model applied)	-	3.7%	92	95	-	Demonstrated improvement in accuracy and financial traceability

4.3 Results and Discussion

The results revealed a clear emission distribution pattern across Scope 3 categories within the analyzed sectors [24]. For ArcelorMittal, upstream purchased goods and transportation contributed approximately 42% of total indirect emissions, while downstream use-phase emissions accounted for 28%. LafargeHolcim displayed a more evenly distributed profile, with raw material extraction and transportation each contributing around 30% [26]. The integration of hybrid Input-Output and process-based LCA techniques significantly reduced underreporting errors by up to 18% compared to conventional models [20].
Under the baseline scenario using a carbon price of USD 45 per tonne, total climate-related liabilities for the steel sector reached USD 3.1 billion annually, while the cement sector registered USD 2.4 billion [22]. Scenario testing with

projected carbon prices of USD 75 and USD 100 per tonne resulted in proportional increases of 37% and 62%, respectively [27]. The liability projections integrated discounted cash flow (DCF) modeling, demonstrating alignment between emission magnitude and long-term financial exposure [23].

Comparative analysis with legacy greenhouse gas (GHG) accounting tools, such as those provided by the CDP and EPA's Simplified Emission Calculator, indicated that the proposed model achieved higher granularity and accuracy [29]. Average error margins were reduced from 9.3% to 3.7%, while compliance readiness improved by 25% due to enhanced data traceability and cross-verification mechanisms [21].

The model also exhibited superior audit reliability, as verified by external reviewers under standardized validation protocols [28]. The integration of chain-of-custody verification and statistical normalization enhanced transparency, enabling clearer alignment between operational data and financial disclosures [30].

Table 2 presents the comparative outcomes, highlighting the precision gains and enhanced audit compliance achieved by the model when benchmarked against existing tools [25].

4.4 Key Validation Insights

Validation outcomes confirmed the model's capacity to enhance emission traceability and liability consistency across complex value chains [20]. Integration with enterprise systems enabled seamless propagation of emission and financial data, improving interdepartmental transparency and regulatory alignment [27]. The inclusion of lifecycle inventory (LCI) datasets and process-specific emission factors allowed for verifiable and standardized outputs, significantly strengthening audit trails [24].

Stakeholders, including corporate sustainability officers and external auditors, reported higher confidence in the system's reliability and its compatibility with international disclosure standards [23]. The linkage between emission quantification and financial recognition not only improved corporate accountability but also facilitated informed decision-making in risk assessment and investment planning [28].

Overall, the framework bridged a longstanding gap between environmental accounting and financial reporting, providing a credible foundation for standardized climate-related liability measurement and enhancing institutional trust across high-emission sectors [30].

5. Strategic, regulatory, and policy implications

5.1 Integration into Corporate Governance and ESG Reporting

Integrating carbon and liability accounting into corporate governance frameworks establishes a direct link between sustainability performance and financial accountability [29]. Enterprise risk management (ERM) systems are increasingly being restructured to incorporate climate-related metrics, allowing organizations to quantify both transitional and physical risks within financial exposure assessments [30]. This integration ensures that emission liabilities, particularly those linked to Scope 3 activities, are not treated as peripheral but as core financial obligations influencing strategic planning and capital allocation [31].

Embedding these mechanisms within governance structures strengthens investor confidence, as emissions data evolve from voluntary disclosures into audited, verifiable indicators of long-term resilience [33]. The process supports environmental, social, and governance (ESG) frameworks by providing standardized, quantifiable evidence that aligns with investor reporting tools and credit risk assessment models [32]. Climate audits formerly seen as compliance exercises now form part of continuous corporate monitoring systems integrated with internal controls, assurance mechanisms, and board-level oversight [34].

Enhanced disclosure transparency directly benefits investor relations by improving comparability across sectors, facilitating accurate risk pricing, and reducing informational asymmetry between corporations and stakeholders [35]. The convergence of carbon and financial reporting also advances the credibility of sustainability-linked metrics, allowing corporations to integrate climate liabilities into balance sheets under consistent accounting standards [30]. This alignment signifies a strategic evolution where ESG reporting transitions from reputational signaling to financially material risk governance bridging the divide between sustainability performance and fiduciary accountability [29].

5.2 Policy and Standardization Recommendations

Harmonizing Scope 3 measurement standards across industries remains a crucial policy priority [31]. Variations in data granularity, emission factor databases, and reporting boundaries hinder comparability and distort liability recognition. Establishing a globally unified Scope 3 quantification framework anchored in lifecycle-based methodologies and verified data chains would facilitate more reliable national and corporate inventories [29]. Governments and regulatory bodies play a decisive role in fostering compliance through fiscal incentives, including carbon tax credits and sustainability-linked loan frameworks that reward verified emission transparency [32].

Regulators should integrate climate liability recognition into sustainability-linked taxonomies, ensuring that disclosure of environmental risks becomes mandatory within financial statements and credit evaluations [34]. Such integration would align national reporting obligations with international frameworks like the GHG Protocol and IFRS S2 [30]. The creation of standardized audit pathways, backed by digital verification systems, could enable consistent assurance practices across regions and sectors [33].

Cross-agency collaboration between environmental authorities, securities regulators, and accounting boards would promote uniform interpretation of carbon liabilities, preventing double counting and enhancing traceability [35]. The interaction between corporate data systems and national greenhouse gas inventories, as shown in Figure 2, demonstrates how feedback loops between regulatory reporting and corporate emission datasets could streamline climate liability accounting [31].

5.3 Technological Enablers and Automation Pathways

Emerging technologies are transforming the precision and automation of Scope 3 emission accounting [29]. Artificial intelligence (AI)-driven data harmonization tools can process fragmented supplier data, classify activities, and generate predictive emission profiles from incomplete datasets [30]. By integrating natural language processing and machine learning algorithms, these systems identify anomalies in supplier declarations, enabling automated reconciliation with procurement and logistics databases [33].

Blockchain technology offers additional value by creating immutable transaction ledgers that verify emission claims across multi-tier supply chains [34]. Smart contracts can automate data validation, ensuring supplier accountability and preventing duplication of emission declarations [31]. Combined AI-blockchain frameworks can thus facilitate real-time traceability, improve auditability, and lower administrative burdens associated with compliance [32].

These technologies support a paradigm shift from static, retrospective reporting to dynamic, real-time carbon accountability systems, improving transparency across the entire value chain [35]. By digitizing verification and assurance mechanisms, organizations can integrate emission and liability data into financial dashboards, enhancing decision support and accelerating the adoption of sustainable governance practices [30].

5.4 Sectoral Transition and Capital Market Effects

Enhanced carbon and liability accounting frameworks have significant implications for capital markets [33]. Financial institutions increasingly embed carbon intensity and liability indicators into credit rating methodologies and portfolio diversification models, influencing capital access for high-emission sectors [29]. Accurate Scope 3 reporting enables investors to differentiate between firms with genuine decarbonization pathways and those with incomplete disclosures [31].

These systems also facilitate alignment with sustainable finance instruments, such as green and transition bonds, which require quantifiable and auditable emission data [35]. Improved accounting precision reduces financing risk premiums by validating compliance readiness and emission mitigation credibility [30]. Over time, transparent carbon-financial integration reshapes risk pricing, encouraging capital reallocation toward low-carbon technologies and accelerating the transition to a climate-resilient economy [34]. The combination of verified emissions data and harmonized liability recognition thus strengthens the structural link between sustainability reporting and financial market efficiency [32].

6. Conclusion and Future Directions

The proposed accounting framework presents a significant advancement in bridging environmental and financial domains through the precise quantification of Scope 3 emissions and their translation into measurable corporate liabilities. Its methodological rigor anchored in hybrid Input-Output modeling, lifecycle assessment, and risk-adjusted financial integration provides a standardized yet flexible approach adaptable to diverse industrial settings. The incorporation of data harmonization mechanisms and Monte Carlo-based uncertainty testing further enhances its reliability and auditability, offering a comprehensive foundation for enterprise-wide carbon accountability.

A central contribution of this model lies in its capacity to align emission quantification with corporate liability recognition. By embedding emission valuation within financial reporting systems, the framework transforms sustainability disclosure from a voluntary exercise into a financially material process integral to governance and investment decision-making. It enables organizations to visualize the fiscal implications of carbon intensity, translating abstract environmental risks into quantifiable economic exposures that can be strategically managed.

The study underscores the necessity for continued interdisciplinary collaboration across accounting, engineering, and policy disciplines. Effective implementation of such models depends on shared expertise in emissions science, regulatory compliance, financial modeling, and technological automation. This cross-sectoral approach ensures that data integrity, compliance, and financial precision evolve together.

Future research should explore deeper automation through artificial intelligence-driven analytics, blockchain-enabled audit trails, and interoperable global data systems capable of supporting transparent net-zero verification. Such innovations would not only enhance accuracy and real-time accountability but also reduce administrative costs and improve comparability across jurisdictions. Ultimately, the model provides a replicable and scalable blueprint for integrating carbon accounting and liability recognition laying the groundwork for transparent, technology-enabled pathways toward sustainable corporate transformation and credible progress toward global decarbonization goals.

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