

Collaborative Pathways for Decarbonisation: Addressing Gaps in Governance, Investment, and Carbon Control

Jie He, Liz Varga

Abstract—Sustainable infrastructure systems are critical to achieving net-zero goals, yet they face challenges like regulatory fragmentation, misaligned financial incentives, and carbon measurement complexities. Despite growing recognition of these challenges, gaps exist between sustainability objectives and investment practices. This study concerns the gaps, barriers, and interdependencies in carbon reduction management across sustainable infrastructure systems, focusing on how collaboration between the investment and sustainability sectors can promote decarbonisation efforts aligned with net-zero goals. This study, in particular, focusses on whether and how standardised carbon metrics and investment incentive structures can support sustainable infrastructure investment. Through a series of semi-structured expert interviews with stakeholders from academia and industry, this study explores emission scope complexities, governance and regulatory constraints, and economic and market challenges. This paper also examines the interdependencies among barriers and enablers influencing collaboration and explores whether strategic integrated frameworks can further support decarbonisation efforts of infrastructure systems. Using Interpretive Structural Modelling (ISM) and MICMAC Matrice d'Impacts Croisés Multiplication Appliquée à un Classement (Cross-Impact Matrix Multiplication Applied to Classification) analysis, this study structures constraints and influences among identified gaps based on their driving power and dependence relationships, identifying key intervention points. The findings further suggest that supply chain coordination and policy alignment could play a critical role in mitigating these barriers. The results highlight leverage points, where coordinated actions could significantly enhance collaboration between the investment and sustainability sectors while accelerating decarbonisation efforts. This research helps to address challenges specific to carbon reduction management as well as establishing a foundation for integrating standardised practices into sustainable infrastructure investment strategies.

Keywords—carbon control, decarbonisation, governance barriers, investment incentives, supply chain emissions, sustainable infrastructure

I. INTRODUCTION

THE global goal of net zero emissions placed unprecedented pressure on infrastructure systems to decarbonise. There are obstacles that continue to restrict progress towards sustainable infrastructure development, despite the increasing recognition of this imperative. However, the complex relationship among regulatory frameworks [1], investment practices [2], and carbon control mechanisms [3] remains constraints to transformation. Current research predominantly adopts single-stakeholder perspectives, limiting its capacity to address the transboundary nature of carbon control and reduction management challenges. For instance, regulatory perspective analyses emphasise policy misalignments between national climate targets and sectoral implementation mechanisms [1][4], whereas economic perspective studies focus on the valuation gap between short-term financial models and long-term decarbonisation returns [2]. Fragmented governance structures across jurisdictions, misalignment between short-term financial incentives and long-term sustainability goals, and carbon measurement and verification technical challenges limit decarbonisation efforts. The recent increasing number of sectoral decarbonisation roadmaps—from steel [5] to cement [6] [7] and energy systems [8][11]—further illustrates this fragmentation, prioritising technological solutions over governance and behavioural dimensions [9] [10].

The paper addresses a gap by examining the interrelationships between governance, investment, and carbon control barriers across sustainable infrastructure systems. Specifically, it investigates whether and how collaborative approaches between the investment and sustainability sectors can facilitate decarbonisation efforts aligned with net zero goals. The study focuses primarily on the potential role of standardised carbon metrics and innovative investment incentive structures in supporting sustainable infrastructure development. By identifying key leverage points for interventions, this study aims to contribute to the theoretical understanding and practical

Jie He is a doctoral student with the Department of Civil, Environmental & Geomatic Engineering, University College London (UCL), London, UK (e-mail: jie.he.20@ucl.ac.uk).

Liz Varga is Professor of Complex Systems with the Department of Civil, Environmental & Geomatic Engineering, Head of UCL's

Infrastructure Systems Institute, University College London (UCL), London, UK (e-mail: l.varga@ucl.ac.uk). Digital Object Identifier: <https://doi.org/10.55066/proc-icec.2025.1169>

implementation of effective decarbonisation strategies. Although previous research has identified barriers to carbon control and reduction management, they just examine the factors in isolation or in pairs. This paper explores the interdependences among these barriers (indicated by the “dependence power”) and enablers (indicated by the “driving power”) by applying Interpretive Structural Modelling (ISM) and MICMAC analysis. This analytical framework enables the mapping of the hierarchical relationships and identification of key intervention points with the potential to catalyse systemic change across the infrastructure sector.

The paper proceeds as follows: Section II reviews the relevant literature on decarbonisation barriers in sustainable infrastructure systems. Section III outlines the methodological approach, including the application of ISM and MICMAC analysis. Section IV presents the findings from academic and industry perspectives, while Section V discusses the implications for collaborative approaches to decarbonisation. The paper concludes in Section VII with reflections on the study’s contributions and limitations, as well as directions for future research.

II. LITERATURE REVIEW

The decarbonisation of sustainable infrastructure systems represents a critical pathway to achieving global net-zero targets, yet progress remains hindered by multifaceted barriers spanning governance, finance, and technical domains. Regulatory misalignment between national policies and sector-specific decarbonisation goals often perpetuates reliance on carbon-intensive practices [1]. For instance, although the EU’s binding emission reduction targets for 2030 provide a directional framework, voluntary Scope 3 reporting mechanisms fail to address supply chain emissions effectively, creating loopholes in sectors like construction and transportation [2][3]. This dissonance is exacerbated by jurisdictional conflicts in transboundary infrastructure systems, where varying carbon pricing regimes and permitting processes across regions lead to regulatory arbitrage [4]. Economic analyses show systematic contradictions between short-term financial models and long-term decarbonisation imperatives. Traditional net present value (NPV) calculations systematically disadvantage sustainable infrastructure projects due to inadequate carbon price internalisation, with shadow carbon prices in cost-benefit analyses often falling below €50/tCO₂—insufficient to alter investment decisions [5]. This valuation gap is acute in emerging markets, where currency volatility and political risks deter private capital from financing renewable energy microgrids and green hydrogen projects [6][7].

Innovative financial instruments such as carbon-linked exchange-traded funds (ETFs) demonstrate potential to overcome these barriers by aggregating risk across project portfolios [14]. However, their effectiveness hinges on workforce capacity to navigate complex financial

derivatives—a dependency often overlooked in economic models [7]. The automotive manufacturing sector’s experience with Scope 3 emission reduction illustrates how supplier engagement programmes can align financial incentives when coupled with emission-linked procurement criteria [3][8][12][13]. The quantification and management of Scope 3 emissions emerge as a critical technical hurdle, with indirect emissions accounting for 56–70% of infrastructure-related carbon footprints [2][3]. Although advancements in cloud-based life cycle assessment (LCA) tools enable carbon emission tracking, their implementation could face two core challenges: i) methodological inconsistencies – divergent allocation methods for shared processes in complex supply chains lead to double-counting or omission of emissions [3], and ii) verification limitations – current blockchain-based verification systems struggle with latency issues, creating audit trail gaps in multi-tier supplier networks [8]. The hydrogen blending pilot project HyDeploy demonstrates how real-time monitoring technologies can enhance emission accounting accuracy in gas networks [9]. However, scaling such solutions requires harmonising international reporting standards—a challenge compounded by intellectual property barriers in sensor technologies [10].

III. METHODOLOGY

The study employs Interpretive Structural Modelling (ISM) and MICMAC analysis [20][21] to examine the interrelationships between factors influencing carbon reduction control and management across sustainable infrastructure systems. The paper focuses on identifying key enablers and barriers as well as the dependencies among them, and questions whether and how standardised carbon metrics and investment incentive structures can support sustainable infrastructure investments.

The study follows a qualitative, expert-driven approach using a series of semi-structured interviews. To explore the gaps, barriers and enablers of carbon reduction management across infrastructure systems and to consider the how collaboration between the investment and sustainability sectors can promote decarbonisation efforts aligned with net-zero goals, the paper draws on two key stakeholder perspectives: academia and industry experts. The academia represents the related researchers’ perspective, offering critical insights and arguments into theoretical framework, quantification methodologies, standardisation approaches, empirical validation of decarbonisation strategies, and systemic analysis of decision making in carbon control and reduction management across infrastructure systems. The industry experts provide critical expertise on the practical feasibility of implementation, addressing technical constraints, supply chain challenges, and data availability barriers. Together, these three perspectives above capture a wide

set of enablers and barriers as well as the collaborative considerations for decarbonisation, allowing for a structured analysis of interdependencies using Interpretive Structural Modelling (ISM) and MICMAC analysis.

The preliminary findings presented in this paper are collected through in-depth expert interview conducted with the academic researchers (from four different infrastructure fields) and three industry experts, and three sustainability and infrastructure consultants. Each of the interview lasted one hours. From each transcript, 6 to 8 initial factors were identified after the first-round transcript reading and understanding. Then, move to the second round understanding and deep analysing, leading to the reasonable merge or divide based on the initial factors. After these two rounds understanding, 7 to 10 factors were finally identified covering a range of considerations including gaps of emission data measurement, barriers of information reporting, emission scope complexities, social issues, financial and economic constraints, and regulatory and policy barriers. The ISM was applied to structure the factors based on their hierarchical influence. This involved pairwise comparisons, leading to a structural model that maps relationships between challenges and enablers. ISM helps break down complex, interdependent variables into a clear hierarchical framework, allowing for targeted policy and business interventions [21]. Subsequently, MICMAC analysis was conducted to classify the identified factors based on their driving power and dependence level. MICMAC enables the categorisation of factors into autonomous, dependent, linkage, and driving variables, helping determine which elements exert the greatest influence on green roof scalability [20]. Due to space limitations, in the findings section, the analysis results are only shown for the key drivers (those with the highest driving power) and key dependent factors (those with the highest dependency) for each stakeholder perspective.

IV. FINDINGS

A. Academia perspective

The analysis for academic researchers identifies the key factors with the highest driving power as (Table 1): supply chain and Scope 3 emissions management complexity, carbon valuation in decision-making, economic-environmental balance, carbon accounting and data reporting systems limitations, green investment barriers. The second highest factors influencing driving power involve economic and financial barriers, equity and cost distribution, regulatory and policy constraints, political economy, and public participation with policy design, which includes the integration of non-monetary values. As one of the academic interviewees mentioned, it is difficult to establish boundaries and to avoid double counting in supply chain and Scope 3 emissions because there is sector-wide inconsistency in how these are measured and

reported. For instance, the interviewee said, “The water sector is currently focused on Scope 1 and 2 with 2030 net zero targets, while Scope 3 has more distant targets due to complexity.” Supply chain and Scope 3 emission reporting help bridge gaps in systemic climate governance. This indicates that including Scope 3 emissions in reporting is complex and may result in confusion or double counting,

TABLE 1
SUMMARY OF KEY DRIVERS AND KEY DEPENDENT FACTORS FROM ACADEMIA

Factors with highest driving power	Factors with highest dependency
Supply Chain (Scope 3) Emissions Management	Regulatory Constraints on Low-Carbon Solutions
Carbon Valuation in Decision-Making	Investment Cycles
Economic-Environmental Balance (Affordability and Cost Pressures)	
Carbon Accounting and Data Reporting Systems Limitations	
Green Investment Barriers (Inadequate Incentives for Green Investment)	
Factors with second highest driving power	Factors with second highest dependency
Economic and Financial Barriers	Fugitive Emissions Measurement Uncertainty
Equity and Cost Distribution	Investment Framework Stability
Regulatory and Policy Constraints	Scope 3 Emissions Governance Challenges (Misalignment Between National Targets and Exported Emissions)
Corporate Influence on Climate Policy (Political Economy)	
Public Participation and Policy Design	

but it is essential for a systems approach.

For comprehensive decarbonisation, major technical and administrative challenges arise in defining, measuring, and minimising double-counting in supply chain emissions like Scope 3 emissions. Carbon valuation in decision-making also act as a major driver. Shadow price of carbon in cost-benefit analyses is too low to impact decisions. Traditional NPV calculations favour higher-carbon solutions when carbon isn't adequately valued. A conflict exists between achieving net zero objectives and maintaining affordable services for consumers in the context of economic-environmental equilibrium. Low-carbon options may not be the most cost-effective, complicating decision-making processes. Balancing decarbonisation with affordable service provision raises issues of who pays, how costs are distributed, and

potential social inequities, meaning that added challenges of measuring social benefits beyond simple financial metrics. Carbon accounting and reporting across sectors are negatively impacted by incomplete, inconsistent, or costly emission measurement. For instance, there are differences between standard emission factors and the actual emissions that have been measured. Despite the increasing appetite for green investment, risk aversion and the absence of appropriate financial mechanisms, such as guarantees and long-term contracts, constrain capital flows to sustainable infrastructure. Increased capital expenditures, uncertain returns, and uncertain financing negatively impacted sustainable infrastructure investment. Investment patterns are influenced by fossil fuel and low-carbon alternative profitability, so decarbonisation may be slow without stronger incentives or disincentives. The incorporation of non-monetary values, such as public participation and policy design, acts as a major motivator. Current decision frameworks encounter difficulties in incorporating social, biodiversity, and resilience benefits, which, despite being challenging to quantify, are essential for achieving sustainable outcomes. Existing regulations are insufficiently aligned with technological and systems innovations, restricting the adoption of novel solutions, such as nature-based approaches, and lacking incentives for crucial decarbonisation.

The factors with the highest dependence are regulatory constraints on low-carbon solutions, and investment cycles (Table 1). The factors with the second highest dependence include fugitive emissions measurement uncertainty, investment framework stability, and misalignment challenges between national targets and exported emissions, particularly regarding challenges of Scope 3 emissions governance. These dependent factors are influenced by the driving factors. For example, regulations favour traditional "grey infrastructure" over nature-based solutions. Current regulations prioritise simple monitoring and measurable point-source emissions while supporting grey infrastructure at the expense of nature-based solutions. This might restrict innovative, potentially lower-carbon methods, resulting in difficulties when implementing integrated solutions. Regarding current investment cycles, the water sector has five-year investment cycles with predetermined business plans. This limits flexibility to adapt decarbonisation strategies to new knowledge and technologies. For emerging sectors like green hydrogen, attracting foreign capital is crucial, but depends on political stability, credible contracts, and government reliability. Government incentives and supportive policy frameworks are needed to attract investment in climate-neutral technologies due to their higher costs.

There is a major gap in accurately measuring emissions from biological processes in water treatment. There is significant uncertainty in emissions factors, especially for fugitive emissions from biological processes. Such

emission measurement is costly and incomplete, leading to low confidence in reported emissions. High capital costs, macroeconomic instability, and uncertain returns deter investment. Currency fluctuations and lack of credible long-term contracts further undermine investor confidence. One of the major challenges to infrastructure decarbonisation is managing emissions across complex supply chains. Reporting on Scope 3 emissions has the potential to address fundamental gaps in climate governance. Although reporting Scope 3 and supply chain emissions is complex and may lead to double counting, it is necessary for a systems approach. Establishing appropriate boundaries for Scope 3 emissions and preventing double-counting continues to be challenging, due to sector-wide discrepancies in measurement methodologies and reporting practices.

B. *Industry perspective*

From the industry experts' perspectives, data and measurement gaps are the major driving factor (Table 2). There is the reliance on outdated carbon metrics and immature tools for real-time tracking and verification. The continued use of outdated emissions factors represents a fundamental barrier to accurate carbon assessment. The lack of up-to-date, project- or product-specific emissions factors undermines the ability of organisations to benchmark, forecast, or credibly report on carbon performance. The interviewee further observed that even when product-specific Environmental Product Declarations (EPDs) exist, there is "a lack of knowledge in the industry and then that's just not that much progress towards building that knowledge content within the industry". Consequently, immature measurement tools and a lack of reliable, real-time data make it difficult to assess, manage, and reduce carbon emissions in

TABLE 2
SUMMARY OF KEY DRIVERS AND KEY DEPENDENT FACTORS FROM INDUSTRY EXPERTS

Factors with highest driving power	Factors with highest dependency
Data and Measurement Gaps	Collaboration Fragmentation
Supply Chain Immaturity	Workforce Knowledge Gaps
Factors with second highest driving power	Factors with second highest dependency
Budget and Contractual Constraints	Regulatory and Procurement Barriers
	Implementation Gaps in Standards (PAS2080)
	External Systemic Risks and Challenges
	Greenwashing and Reporting Failures

infrastructure projects.

Another key driving factor is the supply chain immaturity that constitutes a critical barrier to infrastructure decarbonisation. This immaturity is characterized by a lack of available low-carbon product

data, resistance to change across the sector, and persistent profit-driven inefficiencies and waste practices. First, suppliers fail to offer innovative products, EPDs, or product-specific emissions metrics, forcing project teams to use outdated, industry-average emissions factors. Since suppliers can't provide EPDs or innovative solutions, designers default to outdated averages to avoid appearing to favour vendors, one interviewee said. This data gap limits material selection and embodied carbon benchmarking and reduction. Second, uncertainty about "good" decarbonisation practises can restrict widespread adoption of novel low-carbon materials and processes. Stakeholders across the value chain admitted that "nobody really knows what good looks like," creating cultural inertia that reduces experimentation with innovative solutions. Third, current commercial incentives waste demolition and residual materials. Contractors often "maximize profit via waste," selling concrete and steel remnants without asset owners' consent. In the absence of penalties or recovery mechanisms, high-carbon disposal may persist as the default, reducing circular-economy opportunities. On the dependence power side, collaboration fragmentation and workforce knowledge gaps are the most two major factors (Table 2). Decarbonisation is not the responsibility of a single individual or organisation, such as a customer, supplier, or regulator. Ambiguous accountability for generating solutions and conflicting motivations may lead to the disintegration of collaboration. Moreover, external factors such as slow adoption of electric vehicles, delays in grid decarbonisation, and material shortages further complicate collaboration within the infrastructure sector. The lack of control over these externalities, combined with unclear ownership of decarbonisation responsibilities, leads to siloed efforts and missed opportunities for coordinated action. The knowledge of the workforce is closely associated with the maturity of the supply chain. Interviewees noted that suppliers do not possess the capacity to deliver EPDs or innovative low-carbon materials, while project teams and clients often lack the necessary training to request or interpret such data. The existing knowledge gaps maintain dependence on traditional suppliers and limit the implementation of optimal practices.

V. DISCUSSION

A recurring challenge across both stakeholder groups is the complexity and inconsistency in measuring, reporting, and managing supply chain emissions—particularly Scope 3 emissions—and the resulting impact on decision-making and investment cycles. Both academia and industry highlight that data and knowledge gaps, as well as supply chain immaturity, are persistent barriers to effective decarbonisation efforts. The MICMAC analysis highlights that both academic researchers and industry experts observe the stability of investment frameworks—illustrated by fixed multi-year business plans and

misaligned financing mechanisms—as significantly influenced by upstream factors, including policy cycles, regulatory alignment, and economic incentives. For academia, the driving factors include the complexity of supply chain and Scope 3 emissions management, carbon valuation in decision-making, and the limitations of carbon accounting and reporting systems. These are compounded by economic and financial barriers, regulatory and policy constraints, and challenges in integrating non-monetary values into policy design [23]. Additionally, industry experts indicate out that the inadequate availability of data and measurement tools—such as outdated emissions factors and insufficient real-time tracking and verification capabilities—serves as a crucial constraint on decarbonisation efforts. For industry, the primary drivers are data and measurement gaps, outdated carbon metrics, and the immaturity of supply chains, which hinder the adoption of innovative low-carbon solutions and accurate carbon assessment. Both perspective groups identify regulatory and investment dependencies as key obstacles. Academia highlights regulatory constraints that favour traditional infrastructure and short investment cycles, which may limit the sector's ability to adapt to new knowledge and technologies. Uncertainties in emissions measurement, especially for fugitive emissions from biological processes, and misalignments between national targets and exported emissions exacerbate these dependencies. Industry experts, on the other hand, emphasise the fragmentation of collaborations and workforce knowledge gaps as major dependent factors. The lack of clear accountability and the slow pace of external developments, such as grid decarbonisation and material supply [8][24], further complicate coordinated action across the sector. Addressing these intertwined challenges would involve aligning investment cycles with long-term decarbonisation targets through flexible financing models and evolving regulatory frameworks, alongside scaling up robust measurement infrastructure and standardized emissions factors.

The findings show that many perceived barriers and enablers are in fact dependent on a smaller number of key driving factors. For instance, the standardised carbon metrics could improve carbon data quality and may reduce greenwashing; however, the effectiveness of such metrics is contingent on resolving underlying regulatory misalignments and ensuring that standards are kept current and enforceable. Strategic investment incentives, such as carbon-linked procurement scoring or lifecycle cost mandates, may realign budgetary and contractual priorities with decarbonisation objectives. Yet, the success is heavily dependent on the capacity of the workforce to train, understand, implement, and monitor these new requirements. Regulatory constraints and the availability of rough carbon data are interdependent. Outdated or misaligned standards negatively impact the implementation of more precise and project-specific

carbon metrics. The regulatory stagnation maintains dependence on generic emissions factors and restricts the sector's ability to benchmark or promote low-carbon solutions. The lack of credible long-term contracts further undermines investor confidence in sustainable infrastructure projects. The financial uncertainty creates a gap between accessible capital and the substantial investments needed for large-scale infrastructure decarbonisation initiatives [25]. The interdependence of global supply chains challenges attribution and measurement, and sector-specific methodologies restrict standardised reporting. Cross-border supply chains with different regulatory frameworks make carbon reduction strategies difficult to implement. Global energy markets and cross-border supply chains undermine national decarbonisation efforts and require complex international cooperation [4]. As energy markets [26], particularly oil and gas, become more global, isolated national policies become less effective, necessitating a multidimensional strategy that recognises supply chain interconnections that result in emissions. Geopolitical tensions, diverse legal frameworks, and bottom-up international governance structures add complexity. Effective management involves coordinated approaches to reduce demand and supply, minimise cross-border leakage, and cooperate internationally. Carbon leakage, where emission-intensive activities move to regions with fewer regulations, threatens global decarbonisation without coordination. Collaboration could also be hampered by misalignment between government agencies, investors, and firms [28]. Gaps in understanding and communication may result in suboptimal regulatory environments and missed investment opportunities.

A. Interdependencies in carbon control and reduction management across infrastructure systems

Policy and market externalities – The influence of policy mechanisms, market pricing, and sector-specific carbon pricing extends beyond individual sectors, producing externalities that propagate throughout interconnected infrastructure systems. For instance, carbon pricing in the energy sector may alter the cost structures and operational decisions in transportation or water management. This could underscore the imperative for integrated, cross-sectoral policy design to avoid suboptimal outcomes and to maximise the aggregate effectiveness of decarbonisation initiatives [27][28]. Failure to account for these externalities can result in carbon leakage or the displacement of emissions rather than their reduction.

International coordination – The globalisation of supply chains and the interdependence of energy markets exacerbate national decarbonisation initiatives. Carbon leakage, the phenomenon where emissions reductions in one area are counterbalanced by increases in another, continues to be a significant challenge [29]. Management of transboundary issues may involve substantial international cooperation and regulatory and incentive

harmonisation. Nevertheless, existing international legal frameworks for carbon management are primarily bottom-up, depending on voluntary commitments and national discretion. This fragmentation restricts the successful implementation of systemic change, highlighting the imperative for more cohesive and enforceable international agreements to synchronise incentives and enable coordinated action.

The effective management of carbon emissions within infrastructure systems could require a thorough comprehension of their intricate interdependencies across various scales. The collaboration of technical system dynamics, policy externalities, and international governance poses both challenges and opportunities for decarbonisation initiatives [24]. Although advanced modelling techniques offer helpful tools for addressing these complexities, their effectiveness may rely on the establishment of cohesive policy frameworks that transcend sectoral boundaries and jurisdictional divides. These interdependencies require technical innovation and institutional evolution towards more coordinated, systems-oriented governance structures that can manage cross-cutting externalities and align differing incentives towards decarbonisation objectives.

B. Standardised carbon metrics and strategic investment incentives: support for sustainable infrastructure investment

Enhancement of reporting frameworks – Standardised carbon metrics and comprehensive reporting frameworks could enhance the transparency of climate-related risk exposures in infrastructure projects [9]. These measures may improve transparency, reduce uncertainty in investment decision-making, and enable more thorough analytical methods for infrastructure financing. Moreover, the implementation of standardised metrics facilitates ongoing evaluations of decarbonisation advancements, permitting adaptive management approaches and the adjustment of investment portfolios in response to changing climate demands.

Methodological limitations in non-monetary valuation – Despite the progress in developing standardised metrics, relevant methodological challenges persist in the quantification and integration of non-monetary benefits into investment frameworks. Current valuation approaches fail to adequately capture the multidimensional value proposition of sustainable infrastructure, particularly regarding social co-benefits, biodiversity preservation, and enhanced system resilience [23]. This limitation potentially results in systematic undervaluation of sustainable infrastructure projects when assessed through conventional financial metrics exclusively. The inherent difficulty in monetising critical non-financial benefits represents an obstacle to comprehensive infrastructure valuation [31]. This fragmentation in valuation methodologies potentially perpetuates biases toward projects with readily

quantifiable financial returns at the expense of those offering substantial but less tangible sustainability benefits.

Risk mitigation through strategic policy interventions – Strategic investment incentives, such as government guarantees, long-term offtake contracts, and integrated carbon market mechanisms, serve as key instruments for bridging the financial viability gap in infrastructure adaptation and decarbonisation initiatives [28] [30]. These policy interventions could redistribute risk between public and private stakeholders, thereby improving the risk-adjusted returns for private investors and mobilising capital toward projects that align with long-term sustainability objectives but present unfavourable near-term financial characteristics.

The effectiveness of standardised carbon metrics and strategic investment incentives could depend on robust implementation frameworks, appropriate incentive calibration, and the gradual incorporation of non-financial values in decision-making processes. The interrelationships within global supply chains and the challenges of coordinating internationally complicate carbon control initiatives, requiring advanced analytical methods that consider system-wide effects and possible unintended outcomes of policy measures. Consequently, sustainable infrastructure investment could require technical carbon metrics and incentive refinement and governance innovations that enable cross-sectoral and transboundary cooperation.

VI. CONCLUSION

The study provides new insights into the interdependencies among the barriers and enablers of carbon reduction control and management across sustainable infrastructure systems, while considering the perspectives of both academia and industry. A central finding is the importance of distinguishing between key driving factors—such as the complexity of supply chain and Scope 3 emissions management, carbon valuation in decision-making, and data and measurement gaps—and the dependent factors that result from them, such as regulatory constraints, investment cycles, collaboration fragmentation, and workforce knowledge gaps.

The paper demonstrates that a relatively small set of driving factors exerts a disproportionate influence on the broader landscape of barriers and enablers. For example, the persistent challenges in measuring and reporting supply chain emissions, especially Scope 3, are not only technical but also rooted in regulatory misalignments, outdated carbon metrics, and immature supply chain practices. These upstream issues, in turn, shape the effectiveness of carbon accounting, the credibility of green investment, and the sector's ability to benchmark and promote low-carbon solutions. Both academia and industry perspectives converge on the view that data and knowledge gaps, as well as fragmented supply chains, are foundational barriers that could be addressed to enable

progress in decarbonisation. The findings also underscore the critical role of standardised carbon metrics and strategic investment incentives. Whereas standardised metrics can enhance data quality and transparency, their effectiveness is contingent upon resolving regulatory misalignments and ensuring that standards are current and enforceable. Strategic investment incentives, such as carbon-linked procurement scores or long-term contracts, can realign financial priorities with decarbonisation objectives, but their success depends on workforce capacity and robust implementation frameworks. Furthermore, the findings underscore the necessity of integrating non-monetary values and cross-sectoral policy design to maximize decarbonisation outcomes in interconnected infrastructure systems. Future research could expand the empirical base, incorporate quantitative validation, and explore the dynamic impacts of technological and regulatory change. Applying the analytical framework to diverse infrastructure contexts and international settings could further refine understandings of global supply chain interdependencies and inform the development of harmonised standards and coordinated governance structures. As a result, this study establishes the groundwork for developing the theory and practice of decarbonising sustainable infrastructure, which will directly affect the achievement of net-zero goals on a large scale.

Several research limitations should be noted. Due to the limited paper space and time, a small number of semi-structured interviews may not capture the full diversity of perspectives across all infrastructure subsectors or geographic contexts in the study's qualitative, expert-driven approach. Whereas sufficient for in-depth analysis, the sample size limits generalisability. Second, the ISM and MICMAC analysis focus on key drivers and dependencies may overlook less prominent but still important decarbonisation factors. Third, current the stakeholder knowledge may not reflect rapidly evolving technological, regulatory, or market developments correctly. Finally, methodological challenges remain in integrating non-monetary values and capturing cross-sectoral policy externalities, which may limit the comprehensiveness of the systems analysis.

APPENDIX

UCL Research Ethics Committee Approval ID Number: 26061/002.

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