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Conceptual Model for Low-Carbon Procurement and Contracting Systems in Public Infrastructure Delivery

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Abstract

Public infrastructure projects are significant contributors to global carbon emissions, largely due to energy-intensive construction processes, material production, and complex supply chains. The growing urgency to mitigate climate change has highlighted the need for low-carbon procurement and contracting systems that embed sustainability principles into public infrastructure delivery. Such systems prioritize emission reduction across the project lifecycle, from design and material sourcing to construction, operation, and maintenance, aligning economic, environmental, and social objectives. This presents a conceptual model for low-carbon procurement and contracting, integrating governance, technical, operational, and evaluative components to guide sustainable public infrastructure delivery. The model emphasizes policy and regulatory alignment, including carbon reduction targets, green procurement guidelines, and emission reporting standards, to create an enabling environment for low-carbon adoption. It incorporates procurement strategies such as lifecycle carbon assessment, supplier evaluation, and low-carbon specification standards, alongside contracting mechanisms including performance-based contracts, emission accountability clauses, and incentive structures for sustainable practices. Operationally, the framework addresses sustainable materials sourcing, logistics optimization, and integration of digital tools for real-time carbon tracking and monitoring. Continuous evaluation and learning processes are included to measure performance, facilitate iterative improvements, and ensure long-term resilience and sustainability. Key insights reveal the potential of the conceptual model to reduce lifecycle carbon emissions, enhance resource efficiency, and improve environmental and social outcomes in public infrastructure delivery. The framework also highlights the importance of multi-stakeholder collaboration, involving policymakers, procurement authorities, contractors, and communities, to ensure contextually appropriate and effective implementation. By providing a structured approach for embedding low-carbon principles into procurement and contracting, this model offers actionable guidance for both practice and policy. It serves as a foundation for future empirical studies, pilot projects, and capacity-building initiatives aimed at mainstreaming sustainable infrastructure delivery in both developed and emerging economies.

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1. Introduction

Public infrastructure projects, including roads, bridges, energy facilities, and water systems, are critical to economic growth, social development, and urbanization (Sun and Cui, 2018; Cigu *et al.*, 2018). However, these projects are often highly carbon-intensive, contributing significantly to global greenhouse gas emissions through energy-demanding construction processes, extraction and production of materials such as cement and steel, and fragmented, resource-heavy supply chains. The construction

sector alone accounts for a substantial portion of global CO₂ emissions, highlighting the urgent need to integrate climate change mitigation imperatives into public infrastructure delivery (Giesekam *et al.*, 2018; Gielen *et al.*, 2019). Reducing emissions in this sector is essential to meeting national and international climate commitments, including the Paris Agreement targets, and to promoting sustainable development agendas.

The need for low-carbon approaches in public infrastructure is driven by a convergence of environmental, economic, and social pressures. Environmentally, stakeholders are increasingly concerned with minimizing the ecological footprint of construction activities, protecting natural resources, and improving climate resilience (Li *et al.*, 2017; Penz and Polska, 2018). Economically, lifecycle costs are becoming a critical consideration, as energy inefficiencies and carbon-intensive practices increase long-term maintenance and operational expenses. Socially, communities demand infrastructure projects that not only provide functional benefits but also mitigate adverse environmental impacts, enhance public health, and support equitable access to sustainable services (Kim and Song, 2019; Teo *et al.*, 2019). Addressing these pressures requires a fundamental shift from conventional project delivery toward procurement and contracting systems that prioritize carbon reduction and sustainable outcomes across the infrastructure lifecycle.

Conventional procurement and contracting methods, however, face significant limitations in supporting low-carbon objectives. Traditional approaches often prioritize upfront cost minimization rather than lifecycle sustainability, leading to inefficient resource allocation, limited emission accountability, and suboptimal environmental performance (Byrne *et al.*, 2017; Bradley *et al.*, 2018). Fragmented supply chains exacerbate these challenges, as contractors, suppliers, and sub-contractors operate in silos without coordinated strategies for carbon reduction. Performance monitoring mechanisms are typically weak or non-existent, hindering the ability to track emissions, enforce sustainable practices, or implement corrective measures during project execution. Consequently, conventional systems fail to internalize carbon impacts effectively, resulting in infrastructure that meets functional requirements but contributes disproportionately to environmental degradation and climate risk (Govindan and Al-Ansari, 2019; Zapf *et al.*, 2019).

The purpose of this, is to develop a conceptual model for low-carbon procurement and contracting systems in public infrastructure delivery, addressing the critical gaps in conventional approaches. This seeks to provide an integrated framework that aligns governance, technical, operational, and evaluative components to systematically reduce carbon emissions while maintaining efficiency and quality. The model is intended to guide policymakers, public agencies, and contractors in embedding sustainability into procurement processes, contract structures, and supply chain management. This is guided by the following research questions: What governance and institutional mechanisms are necessary to enable low-carbon procurement and contracting in public infrastructure? How can procurement strategies and contract design incorporate lifecycle carbon reduction and emission accountability? Which operational and technical measures enhance carbon performance without compromising cost and project delivery timelines? How can monitoring, evaluation, and learning processes be integrated to ensure continuous

improvement and scalability?

By addressing these questions, this provides a foundation for developing practical, policy-relevant, and context-sensitive solutions that mainstream low-carbon principles in public infrastructure delivery, contributing to climate mitigation, sustainable development, and long-term urban resilience.

2. Methodology

A systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to identify, evaluate, and synthesize relevant literature on conceptual models for low-carbon procurement and contracting systems in public infrastructure delivery. A comprehensive search strategy was employed across multiple electronic databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, covering publications from 2010 to 2025. Keywords and Boolean operators were used to capture relevant studies, incorporating terms such as “low-carbon procurement,” “green contracting,” “public infrastructure delivery,” “sustainable construction,” “emission reduction strategies,” and “conceptual framework.” Eligibility criteria were established to include peer-reviewed journal articles, conference proceedings, and authoritative reports that addressed either theoretical frameworks or empirical studies on low-carbon procurement practices in public infrastructure contexts, while excluding studies not related to public sector infrastructure or not focused on low-carbon strategies. All identified records were imported into a reference management software, and duplicates were removed. An initial screening of titles and abstracts was performed to exclude irrelevant studies, followed by full-text assessments to determine final eligibility. Data extraction was conducted systematically, capturing information on study objectives, conceptual models, procurement and contracting mechanisms, sustainability metrics, and implementation contexts. The quality of the included studies was appraised using established criteria for conceptual and empirical research, including clarity of model development, relevance to public infrastructure delivery, and methodological rigor. This process was documented in a PRISMA flow diagram, detailing the number of records identified, screened, excluded, and included in the final synthesis. Findings from the selected studies were synthesized narratively and thematically to identify prevailing conceptual approaches, emerging trends, gaps, and opportunities for integrating low-carbon procurement and contracting systems into public infrastructure delivery, thereby providing a robust foundation for the development of an evidence-based conceptual model.

2.1. Theoretical Background

Low-carbon procurement and sustainable contracting are emerging as critical mechanisms for reducing the environmental footprint of public infrastructure projects. Low-carbon procurement refers to the strategic process of sourcing goods, services, and works in a manner that minimizes carbon emissions throughout the lifecycle of infrastructure projects—from design and material extraction to construction, operation, and decommissioning (Das and Jharkharia, 2018; Wuennenberg and Casier, 2018). It emphasizes the selection of low-emission materials, energy-efficient technologies, and supply chain practices that collectively reduce the overall carbon intensity of public

infrastructure delivery. Similarly, sustainable contracting principles integrate environmental, social, and economic considerations into contract design and execution, ensuring that contractors are incentivized to achieve low-carbon outcomes alongside traditional performance metrics such as cost, quality, and schedule adherence.

A wide array of carbon management strategies has been developed to support these objectives. At the project planning stage, life cycle carbon assessment (LCCA) enables stakeholders to quantify embodied and operational emissions, guiding design decisions that favor low-carbon alternatives. Material selection strategies, including the use of recycled, renewable, or low-energy-input materials, directly impact the carbon footprint of construction. Process optimization, such as lean construction techniques, energy-efficient equipment, and modular prefabrication, reduces emissions associated with on-site activities. At the operational level, energy-efficient operation and maintenance practices extend the benefits of low-carbon design, ensuring that infrastructure continues to perform sustainably over its lifecycle. Additionally, carbon accounting and reporting tools, supported by digital technologies, facilitate real-time monitoring, performance evaluation, and compliance with regulatory or voluntary carbon reduction standards (Patsavellas and Salonitis, 2019; Chen *et al.*, 2019).

The relationship between procurement systems and lifecycle carbon reduction is central to sustainable infrastructure delivery. Procurement mechanisms shape project design, supply chain behavior, and contractor incentives, thereby influencing carbon outcomes. For example, integrating carbon reduction criteria into tender evaluation and award processes encourages contractors to adopt innovative, low-carbon solutions. Similarly, performance-based contracts with clear carbon accountability clauses align financial incentives with environmental objectives. By embedding sustainability into procurement decisions, project stakeholders can ensure that carbon reduction becomes a core project requirement rather than an optional consideration, thereby promoting long-term environmental and social benefits (Kadefors *et al.*, 2019; Kesidou and Sovacool, 2019). Several theoretical frameworks underpin the conceptualization and operationalization of low-carbon procurement and contracting. Sustainability assessment frameworks, such as Life Cycle Assessment (LCA) and multi-criteria sustainability evaluation models, provide structured methods for quantifying environmental, social, and economic impacts. These tools enable decision-makers to compare alternative materials, design approaches, and construction methods, facilitating evidence-based, low-carbon choices. Supply chain management theory emphasizes the importance of coordination, collaboration, and integration across multiple actors—including material

suppliers, contractors, and regulatory authorities—to achieve carbon reduction goals. Efficient and transparent supply chains reduce redundancy, optimize logistics, and encourage adoption of sustainable practices throughout the infrastructure lifecycle (Cui and Idota, 2018; Shafiq and Soratana, 2019). Contract theory offers insights into designing agreements that align stakeholder incentives with project objectives. Performance-based contracting, risk-sharing mechanisms, and contractual clauses that include carbon reduction targets are key instruments for ensuring accountability and fostering sustainable behavior among contractors and suppliers.

By integrating these frameworks, low-carbon procurement and contracting systems can be understood as interconnected mechanisms that influence design, materials selection, construction processes, and operational performance. The theoretical perspective emphasizes that carbon reduction is not merely a technical problem but also an organizational and governance challenge, requiring alignment of policies, institutional structures, and market incentives. Furthermore, it highlights the need for evidence-based decision-making, robust monitoring systems, and adaptive governance to ensure that sustainability objectives are met while maintaining project efficiency and cost-effectiveness (Addison *et al.*, 2018; Hernandez *et al.*, 2019).

The theoretical foundation of low-carbon procurement and contracting lies at the intersection of sustainability principles, carbon management strategies, supply chain integration, and contract design. It establishes a framework for understanding how procurement systems can actively drive lifecycle carbon reduction and promote sustainable infrastructure delivery. This theoretical grounding informs the design of conceptual models and practical interventions, providing a roadmap for policymakers, public agencies, and contractors to mainstream low-carbon practices in public infrastructure projects, thereby addressing both climate change imperatives and long-term sustainability goals.

2.2. Drivers and Rationale for Low-Carbon Systems

The transition to low-carbon infrastructure systems has become a global imperative, driven by the urgent need to mitigate climate change, enhance environmental sustainability, and promote resilient urban and industrial development. Low-carbon systems are characterized by reduced greenhouse gas emissions throughout the lifecycle of infrastructure assets, encompassing design, construction, operation, and decommissioning. The rationale for adopting such systems stems from the interplay of regulatory, economic, social, and technological drivers, which collectively shape policy priorities, investment decisions, and operational practices as shown in figure 1 (Awa *et al.*, 2019; Markolf *et al.*, 2018).

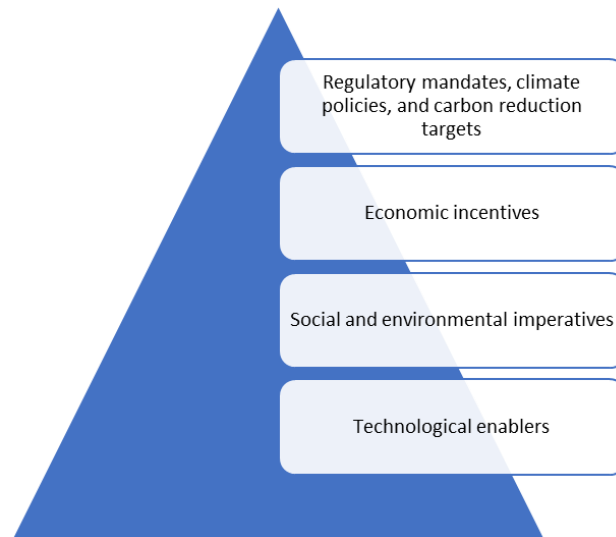


Fig 1: Drivers and Rationale for Low-Carbon Systems

Regulatory mandates, climate policies, and carbon reduction targets constitute a primary driver for low-carbon infrastructure systems. Governments worldwide are enacting legally binding regulations and voluntary frameworks to limit emissions, promote sustainable development, and align with international climate commitments such as the Paris Agreement. Carbon reduction targets at national, regional, and local levels compel infrastructure developers to integrate low-carbon materials, energy-efficient technologies, and sustainable operational practices into their projects. Building codes, energy efficiency standards, and green certification programs provide formal compliance pathways, ensuring that infrastructure projects meet defined emission thresholds. Regulatory enforcement, combined with reporting requirements, creates accountability and incentivizes early adoption of low-carbon strategies in both public and private infrastructure projects.

Economic incentives represent another critical driver. Low-carbon infrastructure often delivers long-term cost savings through energy efficiency, reduced material consumption, and minimized operational and maintenance expenditures. Carbon pricing mechanisms, including carbon taxes and cap-and-trade systems, internalize the environmental cost of emissions, making low-carbon solutions financially attractive (Narassimhan *et al.*, 2018; Stavins, 2019). Green financing instruments, such as green bonds, climate funds, and concessional loans, provide additional capital for sustainable infrastructure development, reducing upfront investment barriers and accelerating deployment. These economic mechanisms create tangible financial rationales for adopting low-carbon practices while aligning private sector interests with environmental sustainability objectives.

Social and environmental imperatives further underpin the rationale for low-carbon systems. Public accountability and heightened awareness of climate change drive demand for environmentally responsible infrastructure, while communities increasingly expect transparency in carbon management and sustainability reporting. Low-carbon systems contribute to community resilience by reducing the vulnerability of urban and industrial environments to climate-related hazards, such as heatwaves, flooding, and air pollution. Ecological protection is also a central consideration, as minimizing carbon emissions reduces indirect pressures on ecosystems, limits habitat degradation,

and mitigates environmental risks associated with resource extraction and energy production. The integration of social and environmental priorities reinforces the ethical, reputational, and strategic imperatives for low-carbon adoption.

Technological enablers play a vital role in facilitating the implementation of low-carbon infrastructure systems. Digital procurement platforms allow for the selection of sustainable materials, suppliers, and construction practices, ensuring transparency and traceability in sourcing. Carbon accounting tools provide project-level assessments of greenhouse gas emissions, enabling real-time monitoring, benchmarking, and reporting across infrastructure lifecycles. Performance monitoring systems, coupled with data analytics, allow for continuous optimization of energy consumption, material usage, and operational efficiency, supporting the realization of emissions reduction targets. Additionally, advances in digital twins, sensor technologies, and automated construction processes enhance precision, reduce waste, and enable adaptive management of infrastructure systems under dynamic environmental and operational conditions.

The drivers and rationale for low-carbon systems are interdependent and mutually reinforcing. Regulatory mandates create compliance pressures that are complemented by economic incentives, while social and environmental imperatives provide legitimacy and public support for low-carbon strategies (Gunningham, 2017; Ball *et al.*, 2018). Technological enablers bridge these drivers by offering practical tools for implementation, monitoring, and continuous improvement. Together, these factors underpin a holistic rationale for integrating low-carbon principles into infrastructure planning, design, and operation, ensuring that urban, industrial, and energy systems contribute to climate mitigation, sustainability, and long-term resilience.

Low-carbon infrastructure systems are driven by a convergence of regulatory, economic, social, and technological factors. Climate policies and carbon reduction mandates provide the legal and strategic impetus, while economic incentives, including cost savings, carbon pricing, and green financing, offer practical motivation. Social and environmental imperatives emphasize community resilience, public accountability, and ecological protection, enhancing legitimacy and societal value. Technological tools, such as digital procurement, carbon accounting, and performance

monitoring, enable effective implementation and continuous improvement. Understanding and leveraging these drivers is essential for policymakers, practitioners, and investors to accelerate the adoption of low-carbon infrastructure, reduce environmental impacts, and promote sustainable, resilient, and economically viable urban and industrial systems.

2.3. Conceptual Model Components

The conceptual model for low-carbon procurement and contracting in public infrastructure delivery is designed to integrate governance, procurement strategies, contracting mechanisms, operational practices, and monitoring systems to systematically reduce carbon emissions and enhance sustainability outcomes. Each component addresses specific dimensions of project delivery while collectively creating a framework that aligns technical, institutional, and regulatory factors (Lobo and Whyte, 2017; Hall and Scott, 2019).

Effective governance forms the foundation for implementing low-carbon procurement systems. Policy frameworks establish mandatory carbon reduction targets, green procurement guidelines, and standards for sustainable infrastructure. These policies ensure that low-carbon objectives are embedded into public sector mandates, tendering procedures, and funding criteria. Regulatory oversight enforces compliance with carbon limits, reporting requirements, and sustainable practices, providing accountability and minimizing the risk of greenwashing. Furthermore, stakeholder coordination across government agencies, contractors, suppliers, and civil society ensures that responsibilities are clearly defined, incentives are aligned, and collaborative decision-making supports project goals. Institutional capacity building, including training and technical support, strengthens the ability of stakeholders to implement low-carbon strategies effectively.

Procurement strategies operationalize sustainability objectives by translating low-carbon priorities into actionable requirements. Low-carbon specifications guide material selection, energy-efficient technologies, and construction methods, ensuring that sustainability is incorporated from the design phase. Supplier evaluation mechanisms assess contractors and suppliers based on their carbon performance, environmental certifications, and ability to meet emission reduction targets. Contract structuring integrates sustainability criteria into tender documentation, evaluation metrics, and award decisions, promoting alignment between procurement processes and low-carbon outcomes. By embedding these elements into procurement practices, the model encourages market actors to adopt innovative solutions that reduce emissions throughout the supply chain.

Contracts are critical tools for ensuring that sustainability objectives are implemented and enforced. Performance-based contracts link remuneration and incentives to measurable outcomes, such as carbon reduction achievements or energy efficiency improvements. Lifecycle cost integration evaluates the total environmental and economic costs over the project lifecycle, encouraging low-carbon solutions that may have higher upfront costs but provide long-term benefits. Emission accountability clauses explicitly assign responsibility for carbon impacts to contractors and suppliers, creating legal and financial incentives for compliance (Burger and Wentz, 2017; Mitkidis, 2019). These mechanisms ensure that low-carbon objectives are not peripheral but central to contractual obligations.

Operationalizing low-carbon strategies requires sustainable materials sourcing, including the use of recycled, renewable, or low-energy-input materials. Logistics optimization reduces carbon emissions through efficient transportation, supply chain coordination, and minimized waste. Carbon tracking systems, supported by digital platforms, allow real-time monitoring of project emissions, enabling corrective actions and ensuring adherence to carbon reduction targets. Technical measures also include energy-efficient construction techniques, modular prefabrication, and process innovations that reduce environmental impact without compromising quality or timelines.

Continuous assessment is essential for ensuring that low-carbon objectives are met and for driving iterative improvements. Performance indicators measure project outcomes in terms of emissions reduction, resource efficiency, and sustainability impacts. Carbon reporting mechanisms document achievements and support transparency to stakeholders and regulatory bodies. Feedback loops allow lessons learned from one project to inform subsequent projects, facilitating continuous improvement and knowledge transfer. The integration of learning processes ensures that the system evolves over time, adapts to emerging technologies and practices, and scales effectively across diverse public infrastructure projects.

Collectively, these components create a cohesive conceptual model that aligns institutional support, procurement and contracting strategies, operational practices, and monitoring mechanisms to drive low-carbon outcomes in public infrastructure. By integrating governance, technical, and evaluative dimensions, the model enables systematic carbon reduction while maintaining project efficiency, cost-effectiveness, and quality. It provides a practical framework for policymakers, public agencies, and contractors to embed sustainability into infrastructure delivery, bridging the gap between strategic climate objectives and operational project implementation (Delmon, 2017; Hueskes *et al.*, 2017).

2.4. Implementation Strategies

The implementation of low-carbon infrastructure systems requires a strategic combination of technological, organizational, and policy measures to ensure meaningful reductions in greenhouse gas emissions throughout the lifecycle of urban and industrial projects. Effective strategies integrate digital tools, capacity building, stakeholder engagement, empirical learning from case studies, and mechanisms for scaling and replication. These elements collectively provide a structured approach to translating low-carbon objectives into practical and measurable outcomes across public and private infrastructure programs.

Digital tools constitute a foundational pillar in the implementation of low-carbon systems. Carbon measurement and accounting platforms enable project teams to quantify emissions associated with materials, energy use, and operational processes in real time (Yang *et al.*, 2018; Tao *et al.*, 2018). These tools facilitate transparent reporting, regulatory compliance, and performance benchmarking across projects. Decision-support systems integrate lifecycle assessment (LCA) methodologies, enabling planners and engineers to evaluate alternative materials, design options, and operational strategies based on their carbon footprint. Furthermore, digital dashboards, data visualization, and predictive analytics support adaptive management by allowing continuous monitoring of emissions and

identification of areas for improvement. By embedding digital capabilities into procurement, design, and operational workflows, low-carbon principles can be systematically applied and verified throughout the infrastructure lifecycle. Training, capacity building, and stakeholder engagement are essential complementary strategies. Effective low-carbon adoption depends on developing the knowledge, skills, and competencies of engineers, planners, contractors, and decision-makers. Targeted training programs on carbon accounting, sustainable materials selection, energy efficiency, and green procurement practices enhance technical proficiency and facilitate informed decision-making. Stakeholder engagement ensures that all relevant actors—including government agencies, private developers, financiers, and communities—are aligned with low-carbon objectives and participate in the co-creation of strategies. Participatory approaches foster buy-in, enhance compliance with standards, and increase social legitimacy, which is particularly important in public infrastructure programs where transparency and accountability are critical. Capacity-building initiatives, combined with engagement platforms, provide the institutional foundation necessary to mainstream low-carbon practices and embed them in standard operating procedures.

Case studies of successful low-carbon procurement and contracting projects provide empirical evidence that guides implementation. For example, infrastructure projects incorporating green building certifications, modular construction with recycled materials, and energy-efficient transport systems have demonstrated measurable reductions in lifecycle emissions. These case studies highlight best practices in materials selection, supplier engagement, risk management, and performance verification, providing templates for replication in similar contexts. Lessons learned from these projects also inform policy frameworks, investment strategies, and technological adoption, reducing uncertainty and improving the efficiency of subsequent low-carbon initiatives. The documentation and dissemination of such evidence are critical for creating a learning environment that accelerates adoption across diverse sectors and geographies (Bhavnani *et al.*, 2017; Kilbourne *et al.*, 2019). Scaling and replication strategies are vital for expanding the impact of low-carbon systems beyond individual projects. Standardization of processes, metrics, and reporting frameworks enables consistency across public infrastructure programs, facilitating cross-project comparisons and integrated planning. Replication of proven low-carbon interventions—such as low-emission materials, energy-efficient designs, and digital monitoring systems—ensures economies of scale and increases the likelihood of achieving sector-wide emissions reductions. Policy alignment, including incorporation of low-carbon requirements into procurement guidelines, incentives, and regulatory standards, reinforces adoption at scale. Integration with urban development plans, infrastructure master plans, and national climate strategies provides a systemic framework for replication, ensuring that low-carbon principles are institutionalized rather than implemented in isolated projects. The interplay between digital tools, capacity building, case-based learning, and scaling mechanisms forms a coherent implementation framework. Digital platforms provide data and analytical support, training and stakeholder engagement enable human and institutional capacity, empirical evidence demonstrates feasibility and effectiveness, and standardized

replication strategies expand impact. This integrated approach ensures that low-carbon infrastructure is not only designed effectively but also implemented, monitored, and scaled in a manner that delivers measurable environmental, economic, and social benefits.

The implementation of low-carbon infrastructure systems depends on the strategic integration of technology, knowledge, evidence, and systemic replication (Peng and Bai, 2018; Hunter *et al.*, 2019). Digital tools enable precise measurement, reporting, and decision support; training and stakeholder engagement build capacity and foster collaboration; case studies provide practical insights and validate interventions; and scaling strategies institutionalize best practices across public infrastructure programs. By combining these strategies, stakeholders can accelerate the adoption of low-carbon principles, reduce lifecycle greenhouse gas emissions, enhance sustainability outcomes, and support the transition toward resilient and environmentally responsible urban and industrial infrastructure systems.

2.5. Comparative Analysis

The adoption of low-carbon procurement and contracting systems represents a transformative approach to public infrastructure delivery, emphasizing sustainability, lifecycle carbon reduction, and operational efficiency. A comparative analysis with conventional procurement approaches highlights the effectiveness, adaptability, and systemic implications of embedding low-carbon principles in infrastructure projects.

Conventional procurement and contracting approaches primarily prioritize cost minimization, schedule adherence, and basic technical compliance. While efficient in delivering functional infrastructure, these approaches often overlook lifecycle environmental impacts, including greenhouse gas emissions, resource depletion, and ecological degradation (Walker *et al.*, 2018; Hasik *et al.*, 2019). In contrast, low-carbon systems integrate carbon reduction objectives throughout the procurement, contracting, and operational phases. Studies demonstrate that low-carbon procurement strategies—such as performance-based contracts, carbon accountability clauses, and lifecycle cost integration—can achieve significant reductions in embodied and operational carbon emissions. For example, projects incorporating sustainable material selection, lean construction processes, and modular prefabrication report measurable reductions in energy use and material waste compared to traditional approaches. Furthermore, low-carbon systems enhance long-term cost efficiency by reducing energy consumption, maintenance requirements, and climate-related damage costs. While upfront investments may be higher, the lifecycle benefits often outweigh initial expenditures, providing both environmental and economic value.

The applicability of low-carbon procurement systems varies across socio-economic contexts. In developed economies, strong regulatory frameworks, advanced technological infrastructure, and mature supply chains facilitate the adoption of low-carbon practices at scale. Public agencies can implement sophisticated carbon tracking, enforce emission accountability clauses, and incentivize innovative low-carbon materials and construction techniques. Conversely, in emerging and developing economies, resource constraints, limited institutional capacity, and fragmented supply chains pose challenges to implementation. However, context-

specific adaptations—such as simplified carbon accounting, targeted supplier engagement, and incremental adoption of sustainable materials—enable gradual integration of low-carbon principles. Pilot projects in emerging economies have shown that even modest interventions, such as specifying low-carbon materials or incorporating emission targets in contracts, can produce tangible reductions in carbon footprint while building local capacity for future scaling.

Low-carbon procurement systems introduce trade-offs that must be carefully managed. For instance, integrating sustainability requirements may increase upfront costs or extend project timelines, potentially conflicting with traditional budget and schedule priorities. However, synergies often emerge through enhanced operational efficiency, reduced energy consumption, and improved stakeholder collaboration, which offset initial investments. System-wide impacts are significant: by embedding carbon accountability and sustainable practices throughout procurement and contracting, low-carbon systems influence material supply chains, contractor behavior, and project management practices. These changes can produce cumulative benefits, including reduced emissions across multiple projects, strengthened market incentives for sustainable materials, and improved alignment with national climate policies. Moreover, the systemic adoption of low-carbon approaches fosters a culture of accountability, transparency, and continuous learning, contributing to long-term improvements in both environmental performance and project delivery quality (Busch *et al.*, 2018; Elliott *et al.*, 2019).

The comparative analysis demonstrates that low-carbon procurement and contracting systems are more effective than conventional approaches in reducing lifecycle carbon emissions, improving operational efficiency, and promoting sustainable infrastructure delivery. While adaptability depends on local governance, institutional capacity, and economic conditions, context-specific strategies enable integration across both developed and emerging economies. The trade-offs associated with cost and complexity are mitigated by synergies that enhance project performance, resource efficiency, and climate resilience. System-wide adoption creates cumulative environmental, economic, and social benefits, illustrating the strategic value of low-carbon procurement as a core component of sustainable public infrastructure delivery.

2.6. Key Findings and Emerging Trends

The adoption of low-carbon infrastructure systems has gained increasing prominence as cities, industries, and governments pursue strategies to mitigate climate change, reduce operational costs, and enhance sustainability outcomes (Rosenbloom *et al.*, 2018; Zhao *et al.*, 2019). Recent research, pilot projects, and policy analyses reveal several key findings and emerging trends that highlight technological innovations, regional and sectoral adoption patterns, and the integration of smart technologies for emissions reduction. Understanding these developments provides a foundation for policymakers, practitioners, and researchers seeking to scale low-carbon systems effectively.

Innovations in low-carbon materials represent a primary driver shaping infrastructure design and performance. The development of recycled aggregates, high-performance concrete with reduced cement content, bio-based composites, and modular prefabricated elements has significantly reduced

the carbon intensity of construction activities. These materials not only minimize embodied emissions but also enhance durability, modularity, and lifecycle performance, supporting both environmental and economic objectives. Complementing these material innovations are digital procurement platforms that facilitate the sourcing of low-carbon and sustainable inputs. By enabling transparent supplier selection, tracking material origins, and assessing environmental performance, these platforms enhance accountability and optimize the supply chain for carbon efficiency. Carbon accounting tools further enable precise quantification of greenhouse gas emissions across project lifecycles, supporting compliance with regulatory mandates, reporting standards, and corporate sustainability commitments. Together, these innovations provide practical mechanisms for implementing low-carbon principles in infrastructure development.

Regional and sectoral variations in adoption reflect differences in regulatory alignment, market maturity, and resource availability. Developed economies often lead in implementing low-carbon systems due to advanced policy frameworks, incentives, and institutional capacity (Rosenbloom, 2017; Fankhauser and Jotzo, 2018). In regions such as Europe and North America, mandatory green building codes, climate targets, and public procurement policies have accelerated the uptake of low-carbon infrastructure, with pilot projects demonstrating measurable reductions in lifecycle emissions. In contrast, adoption in emerging economies is often constrained by limited financing, technical expertise, and fragmented policy landscapes. Sectoral differences also influence adoption patterns: the building and construction sector has seen rapid integration of low-carbon materials and green certifications, whereas transport, energy, and water infrastructure sectors vary in their uptake depending on technological readiness, investment capacity, and regulatory drivers. Recognizing these spatial and sectoral variations is essential for designing context-sensitive strategies and policies that facilitate broader adoption of low-carbon infrastructure.

Integration of smart technologies and real-time monitoring represents an emerging trend with transformative potential. Digital twins, Internet of Things (IoT) sensors, and advanced analytics allow for continuous monitoring of energy consumption, material use, and emissions performance throughout infrastructure lifecycles. These systems enable predictive maintenance, adaptive operational adjustments, and optimized resource allocation, reducing both direct and indirect carbon emissions. Smart procurement and decision-support platforms further enhance efficiency by linking material selection, energy modeling, and carbon accounting to real-time data analytics. Such integration not only improves environmental performance but also strengthens resilience and operational efficiency, demonstrating the value of digital innovation in supporting low-carbon objectives.

Another notable trend is the convergence of sustainability, financial incentives, and social imperatives. Low-carbon infrastructure delivers tangible economic benefits through reduced operational costs, access to green financing, and enhanced investment attractiveness. Simultaneously, it addresses societal expectations for environmentally responsible development, transparency in emissions reporting, and improved community resilience. Projects that successfully integrate these multiple objectives often serve as replicable models, accelerating adoption in both public and

private sectors.

Key findings and emerging trends highlight the increasing sophistication and diffusion of low-carbon infrastructure systems. Innovations in materials, digital procurement, and carbon accounting tools enable measurable reductions in emissions and improve lifecycle performance. Regional and sectoral variations underscore the importance of context-specific policies, financing mechanisms, and technical capacity to facilitate adoption. Integration of smart technologies and real-time monitoring enhances operational efficiency, adaptive capacity, and resilience while supporting emission reduction targets. Collectively, these findings indicate a maturing field in which technological, regulatory, and societal drivers converge to accelerate the transition toward sustainable, low-carbon urban and industrial infrastructure (Song *et al.*, 2017; Kim *et al.*, 2019). Continued research, policy alignment, and investment in digital and material innovations will be crucial to scaling these approaches, optimizing performance, and achieving long-term climate and sustainability objectives.

2.7. Research Gaps and Challenges

Despite the growing recognition of low-carbon procurement and contracting as essential strategies for sustainable public infrastructure, several research gaps and practical challenges continue to constrain their widespread adoption and effectiveness. Addressing these gaps is critical for developing evidence-based policies, improving implementation practices, and ensuring long-term sustainability outcomes in both developed and emerging economies as shown in figure 2.

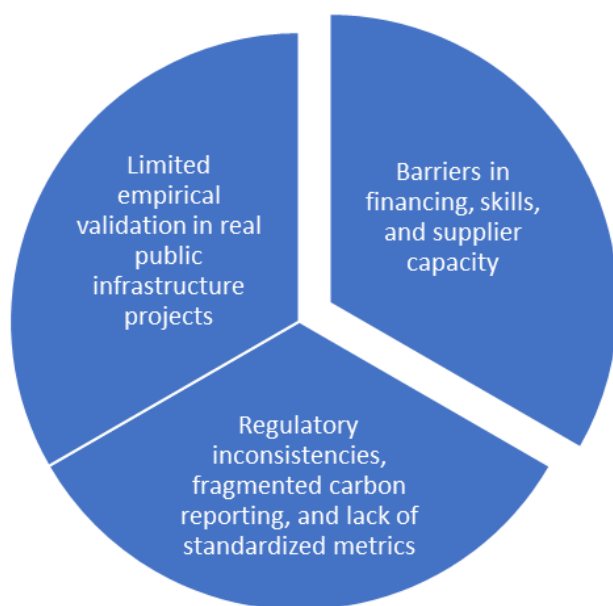


Fig 2: Research Gaps and Challenges

A primary research gap lies in the scarcity of empirical studies that validate the effectiveness of low-carbon procurement and contracting systems in actual public infrastructure projects. While theoretical models and pilot initiatives provide promising insights into carbon reduction potential, there is insufficient data on real-world performance, lifecycle emissions, cost implications, and operational feasibility. Many studies rely on simulation-based analyses or small-scale demonstrations, limiting the

ability to generalize findings across diverse contexts. The lack of robust empirical evidence hampers policymakers' and practitioners' confidence in investing in low-carbon approaches, as uncertainties remain regarding practical challenges, scalability, and long-term benefits (Hampton, 2018; Šūmane *et al.*, 2018). Systematic field evaluations, longitudinal studies, and comparative analyses with conventional procurement practices are needed to bridge this gap.

Implementation of low-carbon procurement strategies is also constrained by financial, technical, and organizational limitations. Upfront costs associated with low-carbon materials, advanced monitoring systems, and sustainable construction methods may be perceived as prohibitive, particularly in emerging economies or resource-constrained public agencies. Additionally, there is a shortage of technical expertise among procurement officials, project managers, and contractors to effectively integrate carbon reduction criteria, lifecycle assessment methods, and performance-based contracting into infrastructure delivery. Supplier capacity is another significant barrier; many contractors and material suppliers lack experience with low-carbon products or processes, and market incentives for sustainable solutions are often weak. Without targeted capacity-building programs, financial support mechanisms, and supplier engagement strategies, low-carbon procurement initiatives may struggle to achieve meaningful results at scale.

Another critical challenge is the absence of consistent regulatory frameworks and standardized methodologies for measuring, reporting, and verifying carbon performance in public infrastructure projects. Different jurisdictions adopt varying definitions of low-carbon practices, diverse emission calculation protocols, and inconsistent reporting requirements, creating confusion and limiting cross-project comparability. Fragmented carbon reporting makes it difficult to track progress, identify best practices, or benchmark performance, reducing accountability among contractors and public agencies. Furthermore, the lack of universally accepted standardized metrics for lifecycle carbon, embodied emissions, and sustainability outcomes constrains evaluation and decision-making, hindering the broader adoption of low-carbon procurement strategies. Developing harmonized regulatory guidelines, performance indicators, and reporting standards is essential for establishing credibility, enabling benchmarking, and facilitating knowledge transfer.

The adoption of low-carbon procurement and contracting systems faces interrelated research and practical challenges. Limited empirical validation constrains evidence-based policy development and confidence in real-world effectiveness. Financial, technical, and organizational barriers impede implementation, particularly in emerging economies. Regulatory inconsistencies, fragmented reporting, and the absence of standardized metrics further undermine transparency, accountability, and comparability. Addressing these gaps requires multi-pronged strategies: conducting empirical research across diverse project contexts, developing capacity-building programs for procurement officials and contractors, providing financial incentives for sustainable practices, and establishing standardized metrics and regulatory frameworks (Galvin and Tywoniak, 2019; Blokland *et al.*, 2019). By systematically addressing these challenges, policymakers, practitioners, and researchers can enhance the feasibility, scalability, and

impact of low-carbon procurement systems, ensuring that public infrastructure contributes meaningfully to climate mitigation, sustainable development, and long-term resilience.

2.8. Future Directions

The trajectory of low-carbon infrastructure systems is increasingly shaped by the convergence of advanced digital technologies, standardized metrics, multi-stakeholder collaboration, and enabling policy and investment frameworks. These future directions aim to enhance the efficiency, scalability, and accountability of low-carbon procurement, contracting, and operational practices while ensuring that environmental, social, and economic objectives are integrated into infrastructure planning and delivery as shown in figure 3.

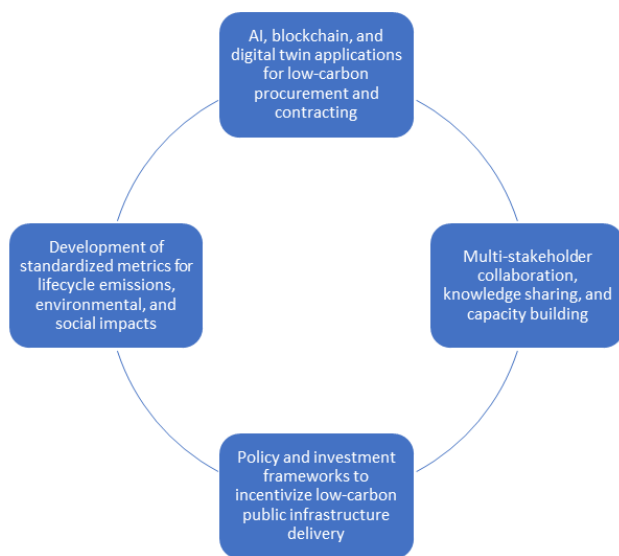


Fig 3: Future Directions

Artificial intelligence (AI), blockchain, and digital twin technologies are at the forefront of innovation in low-carbon infrastructure (Khan, 2019; Rinkkala *et al.*, 2019). AI applications enable predictive modeling, optimized material selection, and adaptive energy management, enhancing both the environmental performance and cost-effectiveness of infrastructure projects. Blockchain facilitates transparent, traceable, and secure supply chains, ensuring that low-carbon materials and sustainable practices are verifiably incorporated into procurement and contracting processes. Digital twins provide virtual replicas of infrastructure assets, allowing real-time monitoring of emissions, energy use, and operational performance throughout the lifecycle. The integration of these technologies enables data-driven decision-making, promotes accountability, and supports continuous improvement, offering a transformative approach to achieving low-carbon objectives at scale.

The development of standardized metrics for lifecycle emissions, environmental impacts, and social outcomes is another critical future direction. Current assessments of low-carbon infrastructure often rely on heterogeneous methodologies, limiting comparability and transparency. Standardized indicators—such as carbon intensity per unit of construction, water and energy footprint, and community resilience measures—provide consistent frameworks for evaluating performance across projects and sectors. These

metrics support regulatory compliance, inform investment decisions, and allow for benchmarking and performance optimization. By aligning reporting and assessment frameworks, stakeholders can systematically track progress toward sustainability and climate goals while ensuring that social and environmental co-benefits are considered alongside economic performance.

Multi-stakeholder collaboration, knowledge sharing, and capacity-building initiatives are essential to scaling low-carbon infrastructure. Effective adoption requires the participation of government agencies, private developers, financiers, technical experts, and local communities. Collaborative platforms facilitate the exchange of best practices, case study insights, and technological innovations, reducing duplication of effort and accelerating learning. Capacity-building programs equip professionals with the technical skills and institutional knowledge necessary for integrating low-carbon principles into design, procurement, and operational decision-making. Engaging stakeholders throughout the project lifecycle ensures that interventions are contextually appropriate, socially accepted, and operationally feasible, strengthening the resilience and sustainability of urban and industrial infrastructure systems.

Policy and investment frameworks play a pivotal role in incentivizing the adoption of low-carbon infrastructure. Regulatory instruments, such as building codes, procurement standards, and carbon pricing mechanisms, establish compliance requirements and market signals that encourage sustainable practices. Investment mechanisms, including green bonds, blended finance, and climate funds, reduce financial barriers and mobilize private sector participation. Policy frameworks that integrate low-carbon objectives into urban planning, infrastructure development strategies, and public procurement programs enable systematic and scalable adoption, aligning incentives with long-term sustainability goals (Tan *et al.*, 2017; Cotton, 2019). These frameworks also create opportunities for monitoring, evaluation, and refinement, ensuring that interventions remain responsive to evolving environmental and social challenges.

The future of low-carbon infrastructure systems is characterized by the integration of digital technologies, standardized performance metrics, collaborative knowledge networks, and supportive policy and investment frameworks. AI, blockchain, and digital twins enhance decision-making, transparency, and operational efficiency. Standardized lifecycle metrics enable consistent evaluation and benchmarking. Multi-stakeholder engagement and capacity-building foster learning and ensure context-specific implementation, while robust policy and investment instruments provide the necessary incentives to scale low-carbon practices. By pursuing these directions, stakeholders can accelerate the transition toward sustainable, resilient, and low-emission infrastructure systems that address environmental, social, and economic imperatives, contributing to long-term climate and development objectives (Mendizabal *et al.*, 2018; Lv *et al.*, 2018).

3. Conclusion

Low-carbon procurement and contracting systems represent a transformative approach to public infrastructure delivery, integrating environmental sustainability into the core of project planning, execution, and evaluation. This conceptual model emphasizes the alignment of governance, procurement

strategies, contractual mechanisms, operational measures, and monitoring processes to achieve systematic reductions in lifecycle carbon emissions. By embedding sustainability criteria in procurement and contracting decisions, public agencies can incentivize contractors, optimize supply chains, and promote innovative low-carbon solutions, ultimately enhancing resource efficiency, reducing operational costs, and improving the environmental and social performance of infrastructure projects.

The benefits of adopting low-carbon systems are multifaceted. Environmentally, they enable measurable reductions in greenhouse gas emissions, encourage the use of sustainable materials, and foster climate-resilient infrastructure. Economically, low-carbon practices contribute to lifecycle cost savings, minimize inefficiencies, and stimulate green market development. Socially, they support equitable infrastructure provision, enhance public accountability, and strengthen community resilience. Conceptually, the integration of governance, procurement, contracting, operational, and monitoring components provides a cohesive framework for translating sustainability objectives into actionable strategies, bridging policy aspirations and practical implementation.

For policymakers, public agencies, contractors, and researchers, this model underscores the importance of multidisciplinary collaboration. Effective adoption requires coordinated efforts in regulatory alignment, capacity building, supplier engagement, and technological integration, alongside the development of standardized carbon metrics and reporting mechanisms. Researchers are encouraged to generate empirical evidence through longitudinal studies, pilot projects, and comparative analyses to validate the effectiveness and scalability of low-carbon systems.

Mainstreaming low-carbon procurement and contracting practices in public infrastructure delivery is not only a strategic response to climate imperatives but also a pathway to sustainable development, economic efficiency, and societal well-being. Achieving this requires an integrated, multi-stakeholder approach that simultaneously addresses governance, technical, financial, and operational dimensions, ensuring that low-carbon principles become an intrinsic part of public infrastructure planning and delivery.

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