A FRAMEWORK FOR EVALUATING THE SUSTAINABILITY OF IOT SMART CITY PROJECTS

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Although Internet of Things (IoT) technologies are essential for developing sustainable smart cities, systematically evaluating their multidimensional sustainability benefits is a significant challenge. synthesizes existing approaches and proposes a comprehensive, integrated evaluation framework. The proposed framework combines life cycle assessment (LCA) for environmental impacts, cost-benefit analysis (CBA) for economic justification, and multi-criteria decision analysis (MCDA) to integrate stakeholder perspectives and social dimensions. Ultimately, this hybrid approach provides city planners with a rigorous, transparent, and practical tool to ensure that IoT deployments deliver absolute sustainability gains rather than merely relative efficiencies.

Keywords:
IoT,
smart cities,
sustainability assessment,
evaluation framework,
triple bottom line

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1 Introduction

1.1 Motivation

Sustainability has emerged as a critical megatrend driven by global challenges, including climate change and resource scarcity. The goal is to balance current and future environmental, social, and economic needs. In this context, the circular economy is increasingly recognized as a vital tool for achieving broader sustainability goals, including the United Nations' Sustainable Development Goals. Digitalization, specifically the application of Internet of Things (IoT) technologies, is a fundamental driver of this transformation and the technological backbone of sustainable smart cities (Ahad et al., 2020; Zimmermann, 2025). Several cities and communities in various countries are implementing IoT-based systems and applications to support different aspects of smart cities, thereby embracing the smart city vision.

However, although IoT technologies are widely deployed, it remains difficult to systematically evaluate whether they genuinely deliver on their promises of multidimensional sustainability (Bibri & Krogstie, 2017). Current evaluations often rely solely on technical metrics, failing to capture complex trade-offs, hidden ecological costs (e.g., e-waste and energy consumption), and neglected social factors across the triple bottom line (Ahvenniemi et al., 2017; Pirson, 2023; Shao et al., 2023). The motivation for developing a specialized evaluation framework stems from several key issues:

Complex Interdependencies and Trade-offs: The environmental, economic, and social dimensions of sustainability are deeply interconnected and often create conflicting objectives (Bibri & Krogstie, 2017; Yigitcanlar et al., 2018). These trade-offs are discussed in detail in Section 3.4.

Hidden Environmental Costs and Rebound Effects: IoT infrastructure itself generates ecological burdens - including energy consumption and e-waste - and rebound effects may offset efficiency gains (Ahad et al., 2020; Pirson, 2023). These issues are examined in Section 3.1.

Neglected Social Dimensions: The social dimension - including digital inclusion, citizen participation, and privacy - remains underrepresented in current evaluations (Ahvenniemi et al., 2017; Berville et al., 2025; Sharma et al., 2023), as discussed in Section 3.3.

This multidisciplinary and transformational perspective is not merely theoretical; the author's involvement in the 'IoT Sustainability Lab' project demonstrates the necessity and complexity of evaluating IoT projects from a practical perspective (Wissenschaftsverbund, n.d.).

To address these gaps, this study proposes an integrated evaluation framework that moves beyond isolated metrics. By combining Life Cycle Assessment (LCA) for environmental impacts, Cost-Benefit Analysis (CBA) for economic justification, and Multi-Criteria Decision Analysis (MCDA) to integrate stakeholder perspectives and social dimensions, the framework rigorously assesses the true ecological, economic, and social impacts of IoT smart city projects (Akande et al., 2019; Ipsen et al., 2019; Yigitcanlar et al., 2018).

However, achieving this rigorous assessment requires more than methodological integration; it necessitates multidisciplinary convergence. While Information Systems (IS) focuses on data flows and business logic, engineering expertise is imperative for assessing hardware reliability, sourcing materials, improving energy efficiency, and managing end-of-life. Absent this engineering perspective, the evaluation remains "hardware-blind," disregarding the material costs and physical risks that determine long-term viability (Baumgartner et al., 2025). Additional disciplines - including cybersecurity, law, ethics, human-computer interaction, and domain-specific knowledge (e.g., energy, buildings, transportation) - must also be integrated. This multidisciplinary requirement reflects the theory of digital transformation (DT), where IoT serves as the physical enabler of strategic transformation (Vial, 2019). DT theory concepts, such as Dynamic Capabilities, Sociotechnical Systems Theory, and Business Model Innovation, provide a strategic lens for evaluating IoT's broader implications.

Related work has addressed aspects of this challenge, but with notable limitations. Cavalieri et al. (2024) present a survey-based socio-ecological assessment tool for manufacturing supply chains, but deliberately omit the economic dimension and rely on organizational theories rather than systemic life-cycle models. Baltuttis et al. (2022) focus exclusively on the economic value of industrial IoT solutions, distinguishing between direct "frontstage" and indirect "backstage" value along B2B2C value chains. However, they do not address environmental or social impacts. Lanfranchi (2025) examines the intersection of IoT and environmental sustainability but overlooks the broader Triple Bottom Line framework and lacks empirical grounding through field studies. These limitations underscore the need for the integrated, multidimensional approach proposed in this study.

We address the following research question: How can these distinct methodologies be combined into a single, integrated framework that provides methodological rigor while remaining practically applicable for city stakeholders?

The study proceeds as follows: Section 2 provides the theoretical foundations, Section 3 discusses the sustainability dimensions, Section 4 reviews methodological approaches, Section 5 presents the integrated framework, and Section 6 offers a discussion and future research directions.

1.2 Methodology

To provide a comprehensive and interpretive overview of the current state of knowledge regarding the sustainability evaluation of IoT smart city projects, this study employs a critical narrative literature review (Paré et al., 2015; Tate et al., 2015) as a basis for systematically developing an integrated evaluation framework through conceptual framework building. The research process was operationalized into distinct phases to ensure methodological transparency:

Literature synthesis and problem identification: A narrative review approach was deliberately chosen, as it allows for critical synthesis of fragmented findings in the dynamic and emerging field of IoT sustainability. Additionally, the interdisciplinary nature of the topic - spanning technology, ecology, economics, and social sciences - further necessitated this flexible approach to map the landscape of isolated technical metrics and identify core multidimensional gaps.

Requirement elicitation and theoretical grounding: The framework's design decisions were directly informed by gaps identified in the literature. Theoretically, it is grounded in the Triple Bottom Line (TBL) approach (integrating environmental, economic, and social dimensions) and Socio-Technical Systems Theory (acknowledging the interplay between human, organizational, and technological layers). From this foundation, the core requirement was derived: a hybrid evaluation model capable of resolving socio-technical and economic-ecological trade-offs.

Framework construction and integration logic: The theoretical components were operationalized through methodological triangulation. LCA, CBA, and MCDA were conceptually integrated not as parallel tools, but as sequential building blocks, designed to satisfy the requirements elicited in the previous phase.

The literature search followed a broad, exploratory, deep review approach rather than a systematic review methodology. Accordingly, no PRISMA protocol was applied, and no formal inclusion or exclusion criteria were documented. The search was conducted across multiple databases, including SciSpace, Google Scholar, and SciSpace Full Text, to ensure both breadth and depth of coverage. Multiple query combinations were employed, encompassing key terms related to IoT, smart cities, sustainability, and evaluation methods. No year filter was applied, keeping the search open-ended across all available publication years. Additionally, snowballing was applied by tracing references from key publications to identify further relevant sources that may not have surfaced through database searches alone.

A systematic literature review was deliberately avoided because its rigid protocol and quantitative data analysis focus are less suited to a highly dynamic and interdisciplinary research field currently in the conceptual design stage (Grant & Booth, 2009). The methodological flexibility of a narrative approach allows for dynamic refinement of search parameters and theoretical focal points during the iterative research process. This flexible form also enables critical synthesis of fragmented findings (Snyder, 2019), which is essential for "gap spotting" and legitimizing new research questions (Alvesson & Sandberg, 2011). Ultimately, this review serves as a strategic guide to establish a solid theoretical foundation for the proposed integrated framework rather than acting as a purely statistical, retrospective inventory.

2 Background and Theoretical Foundations

2.1 Smart Cities and IoT Technologies

Smart cities use digital technologies and data analysis to optimize urban services and infrastructure. IoT forms the technological backbone of this by equipping physical objects with sensors, actuators, and communication capabilities. These networked systems enable the continuous collection, transmission, and analysis of data on urban processes in real time (Ahad et al., 2020; Bibri & Krogstie, 2017).

The integration of IoT with artificial intelligence (AI) expands the possibilities for predictive analytics and autonomous decision-making in urban systems. Alwar et al. (2024) demonstrate how the combination of IoT and AI can support sustainable smart city development, with the technologies working synergistically to maximize efficiency gains. The technological infrastructure typically comprises several layers: the sensor layer (data collection), the network layer (data transmission), the platform layer (data processing and storage), and the application layer (services and user interaction) (Prasad et al., 2025).

2.2 Sustainability Concepts and the Triple Bottom Line

The concept of sustainability in smart cities is based on the triple bottom line approach, which integrates environmental, economic, and social dimensions (Krúpová et al., 2025). These three pillars are interdependent and must be considered as a whole to enable a comprehensive sustainability assessment. The environmental dimension focuses on minimizing environmental impacts, including greenhouse gas emissions, resource consumption, and waste generation. The economic dimension encompasses cost-efficiency, return on investment (ROI), and long-term economic viability. The social dimension addresses aspects such as quality of life, social justice, inclusion, and citizen participation (Ahvenniemi et al., 2017; Akande et al., 2019). Shao et al. (2023) emphasize that a sustainable smart city framework must give equal consideration to all three dimensions in order to make trade-offs transparent and enable balanced decisions. The theoretical foundation also requires consideration of planetary boundaries and the question of whether IoT solutions lead to absolute or merely relative sustainability improvements - a topic further explored in the future research agenda (Section 6.1) (Ahad et al., 2020; Pirson, 2023).

3 Sustainability Dimensions in IoT Smart City Projects

The environmental dimension is most comprehensively quantified in the literature, often using life cycle assessments (LCAs) (Baumgartner et al., 2025; Berville et al., 2025; Ipsen et al., 2019). On the one hand, IoT systems offer significant environmental benefits by optimizing resource use and reducing greenhouse gas emissions (Berville et al., 2025; Ipsen et al., 2019). On the other hand, they themselves cause environmental damage through the energy consumption of the infrastructure (data centers, networks) and the generation of electronic waste (Ahad et al., 2020; Pirson, 2023). Systemic analyses demonstrate that, in addition to technical components, peripheral factors (e.g., materials used) and rebound effects must be considered to accurately determine the ecological footprint. (Duygan et al., 2022; Kluczek et al., 2021; Ragab et al., 2023).

From an economic perspective, IoT projects entail high initial investments in hardware and installation, as well as ongoing operating costs, which pose significant barriers to adoption, particularly for municipalities (Bibri & Krogstie, 2017; Yigitcanlar et al., 2018). A justifiable assessment over the entire lifecycle must balance these costs against operational savings - such as those achieved through smart building control or route optimization (Bouramdane, 2023; Duygan et al., 2022). In addition, economic benefits that are difficult to quantify, such as innovation drivers and improved service quality, must be included in the assessment (Shamsuzzoha et al., 2021; Yigitcanlar et al., 2018).

The social dimension has been the least systematically addressed in the literature to date, yet it is crucial for the long-term acceptance of smart city projects (Duygan et al., 2022). Key positive aspects that must be evaluated include social justice, digital inclusion, citizen participation, and improvements in quality of life (Ahvenniemi et al., 2017; Bouramdane, 2023). At the same time, this dimension requires a critical evaluation of social risks, including the digital divide, privacy concerns, and potential surveillance (Akande et al., 2019; Berville et al., 2025; Sharma et al., 2023).

In practice, the three dimensions of sustainability are characterized by complex interdependencies (Bibri & Krogstie, 2017; Yigitcanlar et al., 2018). A highly economically efficient solution can be ecologically detrimental (e.g., due to increased energy consumption), while ecologically beneficial systems often fail due to economic barriers (Bibri & Krogstie, 2017; Yigitcanlar et al., 2018). To make these inherent trade-offs transparent and enable balanced decision-making, integrated assessment approaches are essential (Shao et al., 2023; Kramers et al., 2014).

4 Methodological Approaches to Sustainability Assessment

To operationalize the multidimensional sustainability dimensions discussed in Section 3, an integrated methodological triangulation is essential. The proposed framework relies on three primary pillars, each carefully selected to address a specific sustainability dimension while compensating for the inherent limitations of the others:

LCA for Ecological Precision: LCA is a standardized method (ISO 14040/14044) used to quantify the ecological dimension. In the context of IoT, it evaluates direct and indirect environmental impacts from production through disposal, identifying ecological "hotspots". While highly precise, its limitation lies in its almost exclusive focus on the environment and difficulties in capturing systemic rebound effects.

CBA for Economic Assessment: To address the economic dimension, CBA quantifies high initial hardware investments and long-term operational savings in monetary terms. It provides decision-makers with a clear economic justification through metrics like 'return on investment' (ROI). However, CBA struggles to monetize non-market-based benefits, such as environmental or social effects, and neglects distributional impacts.

MCDA for Social Integration: To capture the underrepresented social dimension and resolve the complex trade-offs between ecology and economy, MCDA methods (e.g., AHP, TOPSIS) are applied. MCDA excels at combining quantitative and qualitative data and systematically incorporating diverse stakeholder perspectives into the evaluation.

The Hybrid Integration Logic: As no single method is sufficient, the proposed framework's hybrid integration logic sequentially combines these three pillars. This triangulation yields a significantly more comprehensive and robust assessment than isolated metrics. The following chapter operationalizes this integration logic into a structured, applicable framework.

5 Framework Development for Sustainability Assessment

In the following, we develop an integrated framework for evaluating the multidimensional sustainability of IoT projects in smart cities. This section outlines how to structure a holistic assessment that combines methodological rigor with practical applicability. To this end, the subsequent four elements are particularly formulated:

1. Conceptual Foundations: This includes the definition of basic principles such as the triple bottom line approach, life cycle orientation, and the systemic perspective.
2. Structural components: The structure of the framework is divided into seven building blocks, ranging from goal setting and hybrid method selection to monitoring.
3. Implementation Steps: A practical guide with six concrete phases for applying the framework to real-world projects.
4. Indicators and Metrics: A detailed set of specific environmental, economic, social, and integrative KPIs for measuring sustainability impacts.

5.1 Conceptual Foundations

A robust evaluation framework for IoT smart city projects requires a multidimensional foundation. It is primarily based on the triple bottom line approach, which treats the environmental, economic, and social dimensions as equally important (Ahvenniemi et al., 2017; Shao et al., 2023; Krúpová et al., 2025). Also essential are a strict life-cycle orientation (from production to disposal) and a systemic perspective that captures direct, indirect, and systemic feedback loops within the overall urban system (Ahad et al., 2020; Berville et al., 2025; Duygan et al., 2022; Ipsen et al., 2019). Furthermore, the framework must incorporate multiple stakeholder perspectives and be adaptable to the city's specific local context (Akande et al., 2019; Bouramdane, 2023; Ferro-Escobar et al., 2022; Quijano et al., 2022).

5.2 Structural Components

The proposed framework consists of seven key components: (1) Objectives and Scope Definition: Clarification of system boundaries, objectives, and stakeholder interests, (2) Method Selection and Integration: The targeted combination of LCA, CBA, and MCDA (as detailed in Section 4) to ensure a holistic assessment across all dimensions, (3) Data collection and management: Identification of necessary data, establishment of standards, and handling of uncertainties, (4) Indicator system: Definition of key performance indicators (KPIs) and reference values, (5) Evaluation and analysis: Practical implementation of analyses (including sensitivity tests) as well as identification of synergies and trade-offs, (6) Interpretation and communication: Derivation and presentation of recommendations for action tailored to the target audience, (7) Monitoring and adaptive control: Continuous monitoring, establishment of feedback loops, and adaptation of the system.

5.3 Implementation Steps

For practical implementation, the framework is implemented in six consecutive phases: (1) Preparation: Interdisciplinary team formation, stakeholder mapping, and resource planning, (2) Methodology design: Adaptation of evaluation methods, development of data collection tools, and pilot testing, (3) Data collection: Collection of quantitative data (sensors, LCA databases) and qualitative data (interviews, surveys), (4) Analysis and evaluation: Conducting method-specific evaluations (LCA, CBA, MCDA) and synthesizing the final results (Bibri, 2019; Ipsen et al., 2019; Yigitcanlar et al., 2018), (5) Interpretation: Stakeholder workshops to discuss results and prepare reports, (6) Implementation and monitoring: Implementation of recommendations for action and continuous, adaptive learning.

5.4 Indicators and Metrics

The framework uses a robust system of SMART indicators (Specific, Measurable, Achievable, Relevant, Time-bound), which should be developed through a participatory process (Akande et al., 2019; Quijano et al., 2022). These metrics are divided into:

Environmental: e.g., CO_2 eq emissions per functional unit, primary energy demand (kWh), e-waste generation rate (kg/year), recycling rate (%) (Ahad et al., 2020; Berville et al., 2025; Kluczek et al., 2021).

Economic: e.g., total life-cycle costs (CAPEX/OPEX), net present value (NPV), return on investment (ROI), payback period (years) (Bibri & Krogstie, 2017; Bouramdane, 2023; Duygan et al., 2022).

Social: e.g., digital inclusion index, citizen participation rate (%), data protection compliance score, accessibility coverage (%) (Ahvenniemi et al., 2017; Berville et al., 2025; Bouramdane, 2023).

Integrative: e.g., urban resilience index, system scalability score, overall stakeholder satisfaction rating (Bouramdane, 2023).

The selection and weighting of indicators should be carried out in a participatory manner, involving relevant stakeholders, to ensure legitimacy and acceptance (Akande et al., 2019; Bouramdane, 2023). Quijano et al. (2022) emphasize the importance of KPI-driven evaluation frameworks that enable replicability and comparability across different cities.

6 Discussion and Future Research Directions

This section focuses on critically reflecting on the sustainability assessment of IoT projects and translating theoretical insights into practice.

Regarding challenges and limitations, evaluating IoT projects is complicated by limited data availability throughout the lifecycle (Ahad et al., 2020; Ipsen et al., 2019) and the difficulty of defining system boundaries. Specific methodological hurdles include capturing systemic effects across the lifecycle (Ahad et al., 2020; Pirson, 2023), the monetization of non-market-based benefits for cost-benefit analyses (Yigitcanlar et al., 2018), and the systematic integration of social indicators (Ahvenniemi et al., 2017; Berville et al., 2025; Sharma et al., 2023).

Best practices and success factors: Successful evaluations require early integration into project planning (Quijano et al., 2022) and systematic stakeholder engagement in interdisciplinary teams (Ahvenniemi et al., 2017; Akande et al., 2019; Bouramdane, 2023; Kramers et al., 2014; Ipsen et al., 2019). As detailed in this paper, successful evaluations require methodological pluralism - specifically the hybrid combination of LCA, CBA, and MCDA - to make trade-offs transparent and deliver robust results.

Implications for policy and practice: At the policy level, regulatory frameworks, standardization, and capacity building for municipalities are required (Quijano et al., 2022). In practice, a shift in mindset toward "digital sobriety" (conscious, needs-based use of technology) is required (Berville et al., 2025), as well as the consistent alignment of IoT systems with the principles of the circular economy (Kluczek et al., 2021; Berville et al., 2025; Krúpová et al., 2025). To operationalize this alignment in practice, decision-makers can apply models such as the Digital Function for Circular Economy (DF4CE) framework. This framework explicitly maps how digital functions, such as data collection and analysis, enable specific circular strategies, such as recycling, reuse, and reduction (Zimmermann, 2025).

Based on the identified limitations, the literature outlines the following key research needs:

Social indicators: Development of standardized methods for measuring social impacts such as digital inclusion and data protection (Ahvenniemi et al., 2017; Sharma et al., 2023; Berville et al., 2025). Furthermore, future investigations must address critical socio-technical challenges, such as data privacy, system interoperability, and mechanisms to encourage diverse stakeholders to securely share information across integrated data platforms (Zimmermann, 2025).

Long-term effects and planetary boundaries: Systematic longitudinal studies on rebound effects and the integration of planetary boundaries to measure absolute rather than merely relative sustainability gains (Ahad et al., 2020; Pirson, 2023).

Technological and methodological advancements: Optimization of integrated evaluation frameworks (Kramers et al., 2014; Shao et al., 2023; Ipsen et al., 2019) as well as research into AI and machine learning for automated data collection and predictive modeling (Bibri & Krogstie, 2017; Prasad et al., 2025).

Furthermore, a systematic analysis of existing case studies is essential, as theoretical evaluation approaches vary widely in real-world practice and must be adapted to specific contexts. Existing cases often reveal critical aspects and empirical realities that are overlooked in theoretical models. An example is provided by the evaluation of smart waste management in Södertälje (Brunklaus et al., 2022). This case study demonstrated that the climate impact of the actual IoT solution (sensors and networks) was marginal, while peripheral factors such as trash bags posed the greatest burden. This empirically demonstrates the absolute necessity of a broad, systemic perspective in evaluation.

7 Conclusion

The research makes it clear that the potential of the IoT for smart city development is immense, but a multidimensional, methodologically rigorous evaluation is required. While environmental aspects (via LCA) and economic aspects (via CBA) are often easily quantifiable, the social dimension is crucial for long-term legitimacy. Since no single method is sufficient, hybrid approaches are the most effective way to make trade-offs transparent. Ultimately, the IoT is merely a tool, not an end in itself; its true value depends on needs-based implementation and evidence-based, participatory evaluation.

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