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Smart Grid Technologies for the Efficient Integration of Renewable Energy Systems a Multi-Disciplinary Framework for Sustainable Urban Energy Transition

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Abstract **Original Research Article**

The transition to sustainable urban energy systems requires effective strategies for integrating renewable energy sources into existing electricity networks. This study examines the role of smart grid technologies in enabling the efficient integration of solar, biomass, and hydrogen systems within a multidisciplinary framework for sustainable urban energy transition. Using Lagos, Nigeria, as a case study, the research adopts a quantitative scenario-based approach to evaluate technical, economic, environmental, and policy dimensions of renewable energy integration. Four scenarios were analyzed, including a conventional grid-dominated baseline and three progressive smart-grid-enabled renewable energy pathways. The results show that increased renewable integration significantly improves urban energy performance by raising renewable energy share, reducing grid losses, lowering carbon emissions, and enhancing system reliability. Solar emerged as the primary contributor to early renewable penetration, biomass improved dispatchability and system resilience, while hydrogen provided strategic flexibility for advanced integration. Economically, the solar-biomass-smart-grid pathway offered the best balance between cost and performance, whereas the solar-biomass-hydrogen-smart-grid pathway produced the strongest long-term sustainability outcome despite higher investment requirements. The study concludes that smart grid technologies are essential for coordinating diverse renewable energy sources and for supporting reliable, flexible, and low-carbon urban electricity systems. It further argues that sustainable urban energy transition depends not only on renewable energy deployment, but also on intelligent grid management, supportive policy frameworks, and integrated planning. The study contributes a practical multidisciplinary framework for evaluating renewable-smart-grid pathways in rapidly urbanizing environments.

Keywords: Smart grid, renewable energy integration, solar energy, biomass, hydrogen, urban energy transition, sustainability, Lagos.

1. Introduction

The global energy transition has intensified the search for electricity systems that are cleaner, more resilient, and better suited to rapidly urbanizing societies. Cities are at the center of this transition because they concentrate population, economic activity, infrastructure demand, and climate vulnerability. Recent international analysis emphasizes that urban areas will play a decisive role in achieving clean energy and climate goals, while also requiring major improvements in grid modernization, digitalization, and integrated planning. In this context, smart grid technologies are increasingly viewed as essential for coordinating distributed generation, improving operational visibility, and enabling higher shares of renewable electricity in urban systems (IEA, 2024; UN-Habitat, 2024). Renewable energy technologies are now central to decarbonization strategies, but their large-scale integration into electricity networks creates technical and operational challenges. According to the IEA, renewable electricity capacity is projected to expand rapidly through 2030, with solar photovoltaics accounting for the largest share of growth. At the same time, the IEA notes that grids must become smarter to manage rising renewable penetration, distributed generation, and variability in supply. This makes smart grids more than a supporting technology; they become a core platform for balancing generation, demand, storage, and system reliability in modern power systems (IEA, 2024, 2025a, 2025b). Among renewable options, solar energy is especially important for urban transition because of its scalability, modularity, and growing competitiveness in distributed applications. The IEA reports that distributed and utility-scale solar PV are expected to drive most renewable electricity expansion, supported by lower costs, improving permitting conditions, and broad social acceptance. However, high solar penetration also increases the need for flexibility, storage, and intelligent grid management, especially in dense urban systems where load balancing and network congestion can become more complex. As a result, solar deployment is most effective when embedded within a smart-grid-enabled framework rather than treated as a stand-alone solution (IEA, 2025a, 2025b).

Biomass and hydrogen add further strategic value to renewable integration because they can complement variable renewable resources in different ways. The IEA identifies modern bioenergy as the largest source of renewable energy globally today and highlights its importance in displacing fossil fuels, while IRENA notes that biomass is versatile and can provide electricity in a more controllable manner than variable resources such as solar and wind. Hydrogen, meanwhile, is increasingly recognized as a strategic energy carrier for decarbonization and system flexibility, especially where surplus renewable generation can be converted into longer-duration storage or cross-sector energy services. These characteristics make biomass and hydrogen relevant to urban transition pathways that require dispatchability, resilience, and long-term flexibility in addition to clean electricity generation (IEA, 2025c; IEA, 2025d; IRENA, 2018/2019).

The need for integrated renewable systems is particularly significant in cities of the Global South, where rapid urban growth often coincides with unreliable grids, rising electricity demand, and heightened exposure to environmental stress. UN-Habitat argues that sustainable urban energy systems require not only low-carbon energy sources, but also efficient distribution infrastructure and lower end-use consumption. Similarly, the IEA stresses that urban energy transitions should combine clean energy deployment with integrated planning, data use, and electricity security. These arguments suggest that a fragmented approach to renewable deployment is unlikely to deliver sustained urban energy transformation; instead, cities need coordinated frameworks that connect technology, grid intelligence, policy support, and sustainability objectives (IEA, 2024; UN-Habitat, 2024). Despite growing scholarship on renewable energy and smart grids, an important gap remains in the integration of multiple renewable technologies within a single urban transition framework. Many studies focus on one technology at a time, most commonly solar, or examine smart grids primarily from a technical systems perspective. Yet urban energy transition is inherently multidisciplinary, involving engineering performance, economic feasibility, environmental outcomes, and policy readiness. The IPCC has long emphasized that renewable energy must be assessed in relation to climate mitigation, energy systems integration, and sustainable development, while more recent IEA work shows that urban decarbonization increasingly depends on smart, connected, and adaptable electricity networks. This creates a strong basis for examining solar, biomass, and hydrogen together within an integrated smart-grid framework (IEA, 2024; IPCC, 2011).

Against this background, this study investigates smart grid technologies for the efficient integration of renewable energy systems (solar, biomass, and hydrogen) within a multi-disciplinary framework for sustainable urban energy transition. The study is motivated by the need to move beyond single-technology assessments and toward a systems-oriented understanding of how renewable resources can be coordinated in urban electricity networks. Specifically, it examines how smart grid technologies can improve renewable integration, reduce inefficiencies, support reliability, and strengthen sustainability outcomes when multiple renewable pathways are considered together. In doing so, the study contributes to the literature by linking technical integration with economic, environmental, and policy dimensions of urban energy transition (IEA, 2024; IEA, 2025d; UN-Habitat, 2024).

Figure 1: Conceptual Framework for Smart Grid-Enabled Renewable Energy Integration in Urban Transition

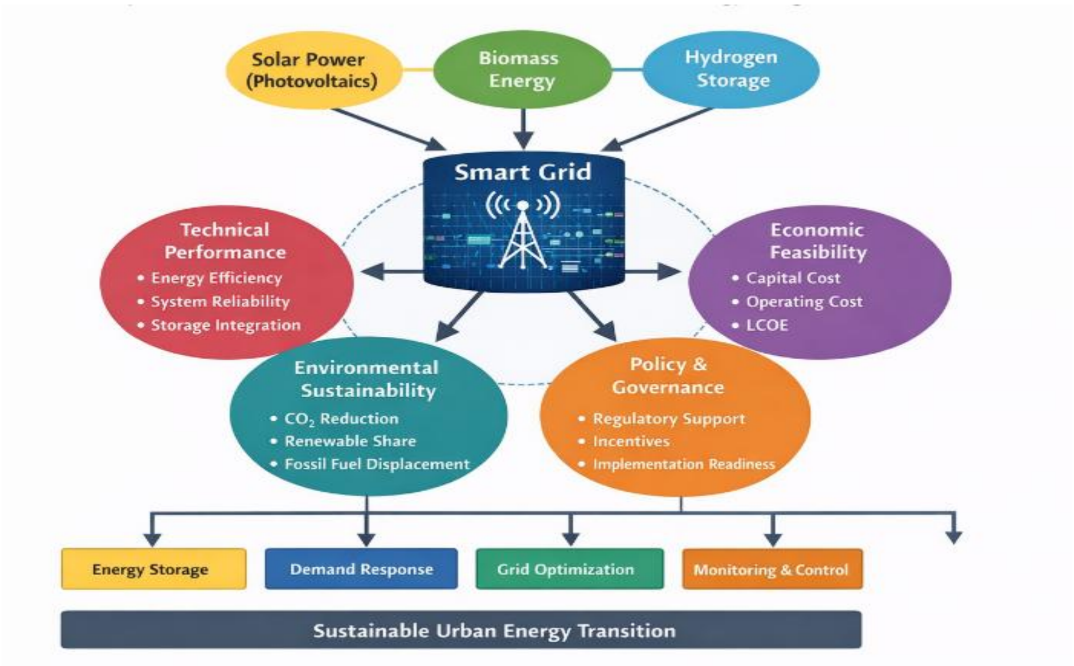

Figure 1 presents the conceptual framework of the study. It illustrates how smart grid technologies serve as the central coordinating system for integrating solar, biomass, and hydrogen into the urban energy network. The figure shows that, through functions such as monitoring, control, storage support, and demand response, the smart grid enhances the technical, economic, environmental, and policy performance of renewable energy integration. It therefore provides the foundation for achieving a more reliable, efficient, and sustainable urban energy transition.

2. Literature Review

2.1 Conceptual Foundations of Smart Grids and Urban Energy Transition

The literature consistently shows that smart grids have evolved from a narrow power-engineering concept into a broader platform for coordinating distributed generation, storage, flexible demand, and digital control. In recent review work, Ohanu et al. (2024) describe the smart grid as an intelligent, responsive, and bidirectional network that is increasingly necessary as renewable energy penetration rises. Similarly, *Integration of Smart Grid with Renewable Energy Sources: Opportunities and Challenges-A Comprehensive Review* (2023) emphasizes that communication networks, demand-side management, storage, and cybersecurity are now central to grid modernization. A related 2025 systematic review on renewable integration techniques likewise argues that advanced control, storage management, predictive models, and infrastructure upgrades are the principal mechanisms by which smart grids absorb variable renewable energy. Together, these reviews frame smart grids not merely as upgraded electricity networks, but as enabling systems for large-scale renewable integration and operational resilience (Ohanu et al., 2024; *Integration of Smart Grid with Renewable Energy Sources*, 2023; *Impact and Integration Techniques of Renewable Energy Sources on Smart Grid Operations*, 2025).

Urban energy transition literature extends this argument by situating smart grids within city-scale decarbonization and infrastructure planning. Sharma et al. (2025) review smart-city transition studies and conclude that urban energy transition requires not only low-carbon technologies but also digital transformation, resilient infrastructure, and strong stakeholder coordination. Zheng et al. (2023) reach a similar conclusion from a systematic review of smart grids and smart urban energy systems, arguing that the field remains fragmented and needs holistic, multi-scale, cyber-physical-social frameworks. Earlier foundational reviews by Keirstead et al. (2012) on urban energy system models and Lund et al. (2017) on smart energy systems also show that city energy transition cannot be understood solely through electricity supply; it must include cross-sector integration, planning scale, and demand-side interactions. This body of work is directly relevant to the present study because it supports a multi-disciplinary approach to urban renewable integration rather than a purely technical one (Sharma et al., 2025; Zheng et al., 2023; Keirstead et al., 2012; Lund et al., 2017). At the policy and systems level, international institutions reinforce the same conclusion. The IEA (2024) argues that cities need integrated planning, data sharing, grid investment, and digital solutions to manage growing electricity demand while decarbonizing urban systems. UN-Habitat (2024) similarly presents cities as central to climate action, noting that urban systems are both highly vulnerable to climate impacts and responsible for a substantial share of emissions. IRENA's work on smart electrification also emphasizes digitalization, smart meters, data platforms, and flexible system operation as critical enablers of higher renewable shares. These sources strengthen the conceptual basis for linking smart grids to renewable integration in urban transition studies (IEA, 2024; IRENA, 2023; UN-Habitat, 2024).

2.2 Smart Grids and Renewable Energy Integration

A major strand of the literature examines how smart grids facilitate the integration of diverse renewable resources. Ohanu et al. (2024) provide a broad review of recent developments in renewable-resource integration and identify system flexibility, distributed generation management, and inertia-related concerns as recurring issues. *Smart Grids and Renewable Energy Systems: Perspectives and Grid Integration Challenges* (2024) similarly argues that digitization and automation are essential for maintaining flexibility and reliability as renewable penetration increases. The MDPI review *A Comprehensive Review of the Current Status of Smart Grid Integration of Renewable Energy Sources* (2024) also highlights renewable integration as central to sustainable and resilient power infrastructure. Across these studies, the shared conclusion is that smart grids enable renewable integration by improving visibility, controllability, and balancing capacity, but they also introduce new demands in communication, interoperability, and system protection (Ohanu et al., 2024; *Smart Grids and Renewable Energy Systems*, 2024; *A Comprehensive Review of the Current Status of Smart Grid Integration of Renewable Energy Sources*, 2024).

Recent reviews further stress that integration challenges are no longer confined to engineering stability alone. The 2025 review on smart-grid operations categorizes current integration problems into grid stability and control, infrastructure constraints, storage and energy management, and intermittency management, while recommending hybrid optimization and predictive tools for peak shaving and cost reduction. In parallel, the 2023 review of smart-grid integration with renewable sources emphasizes legislation, regulation, privacy, and communication architecture as equally important factors. This implies that successful renewable integration depends on technical performance and governance conditions together, which aligns closely with the multidisciplinary orientation of the present study (*Impact and Integration Techniques of Renewable Energy Sources on Smart Grid Operations*, 2025; *Integration of Smart Grid with Renewable Energy Sources*, 2023).

2.3 Solar Energy Integration in Urban Smart Grids

Solar photovoltaics occupy a particularly prominent place in the literature because of their scalability and suitability for distributed urban deployment. Nwaigwe et al. (2019) review PV-grid integration and conclude that solar has become central to modern electricity transitions, although it raises issues of intermittency, voltage regulation, and inverter coordination. More recent work broadens the discussion from grid connection to urban system design. McCarty et al. (2025), in their data-driven review of urban photovoltaics, show that urban PV research spans multiple scales from cells and modules to communities and energy systems, but remains fragmented in methods and lacks standardization, especially in life-cycle and systems-level analysis. This is important for urban-transition research because it suggests that solar studies are abundant, but often weakly connected to broader city-scale planning questions (Nwaigwe et al., 2019; McCarty et al., 2025).

The integration of solar specifically with smart grids is receiving more explicit attention in the newer literature. *A Comprehensive Review of Solar PV Integration with Smart-Grids* (2025) identifies AC and DC grid architectures, cost optimization, AI, IoT, and blockchain as important dimensions of future PV integration. The review argues that solar's intermittency makes intelligent grid coordination indispensable for stable and economical operation. Complementing this, *Comparative Analysis of Smart Grid Solar Integration in Urban and Rural Power Distribution Networks* (2023) highlights practical challenges such as voltage fluctuation, power-quality deterioration, and network imbalance under higher PV penetration. Taken together, these studies suggest that solar is the most immediate renewable pathway for cities, but one whose benefits depend heavily on smart-grid control, forecasting, and network management (*A Comprehensive Review of Solar PV Integration with Smart-Grids*, 2025; *Comparative Analysis of Smart Grid Solar Integration in Urban and Rural Power Distribution Networks*, 2023).

2.4 Biomass in Hybrid and Smart-Grid Energy Systems

Compared with solar, biomass appears less dominant in the urban-transition literature, but reviews increasingly emphasize its dispatchability and hybrid-system value. Ahmadipour et al. (2025) review biomass system optimization and find that operational efficiency, feedstock management, emissions reduction, and public perception are persistent challenges. Their analysis shows that biomass system planning is increasingly shaped by optimization methods seeking to minimize cost while improving reliability and sustainability. This matters for smart-grid research because dispatchable biomass can complement variable renewables in ways that purely intermittent sources cannot (Ahmadipour et al., 2025).

Hybrid-system reviews make this complementary role even clearer. *Sustainable Solar/Biomass/Energy Storage Hybridization for Enhanced Renewable Energy Integration in Multi-Generation Systems* (2025) concludes that biomass gasification, PV, and storage can be combined to produce more resilient hybrid systems, though synchronization, cost, feedstock variability, and context-specific sustainability assessment remain major barriers. Likewise, *An Integrated Photovoltaic/Wind/Biomass and Hybrid Energy Storage System* (2021) reports that combining multiple renewable resources and storage improves reliability and demand-supply matching. These studies are particularly relevant to the present paper because they show why biomass deserves inclusion alongside solar in a smart-grid-based urban framework: not simply as another renewable source, but as a stabilizing and dispatchable complement to variable generation (*Sustainable Solar/Biomass/Energy Storage Hybridization*, 2025; *An Integrated Photovoltaic/Wind/Biomass and Hybrid Energy Storage System*, 2021).

2.5 Hydrogen and Sector-Coupled Smart Grids

Hydrogen has emerged in the literature as a strategic flexibility resource rather than just another energy carrier. Balta-Ozkan et al.'s line of work, reflected in *Toward a Hydrogen Society: Hydrogen and Smart Grid Integration* (2020), argues that hydrogen can be a key storage and management element in smart grids, especially under ambitious low-carbon scenarios. More recent reviews deepen that perspective. Zhang et al. (2025) systematically review modeling methods for hydrogen integration and identify cross-sector interaction, model formulation, and infrastructure sequencing as major research gaps. Jia et al. (2026) synthesize key technologies, planning methods, scheduling strategies, and market mechanisms across the green-hydrogen supply chain, concluding that hydrogen can increase reliability and flexibility in renewable power systems but remains constrained by cost and system complexity (*Toward a Hydrogen Society*, 2020; Zhang et al., 2025; Jia et al., 2026).

Hydrogen is also increasingly studied in relation to sector coupling and city-scale decarbonization. *Hydrogen-Incorporated Sector-Coupled Smart Grids: A Systematic Review* (2024) presents hydrogen as a complementary solution for enhancing the reliability, stability, and scalability of solar-dominated smart grids. The review by Kaur et al. (2025) similarly finds that hydrogen, biomass, biogas, and solar PV improve the efficiency and stability of hybrid renewable systems when combined with AI-driven energy management and hybrid storage. At the urban scale, *Decarbonizing Urban Residential Communities with Green Hydrogen Systems* (2024) shows that hydrogen is becoming relevant to community-level decarbonization pathways, even if deployment remains emergent. Overall, the literature positions hydrogen as especially valuable in advanced transition stages where longer-duration storage, balancing, and sector coupling become critical (*Hydrogen-Incorporated Sector-Coupled Smart Grids*, 2024; Kaur et al., 2025; *Decarbonizing Urban Residential Communities with Green Hydrogen Systems*, 2024).

2.6 Hybrid Renewable Systems and Multi-Disciplinary Frameworks

One of the strongest developments in recent literature is the shift from single-technology studies to hybrid renewable energy systems. Kaur et al. (2025) review 174 articles and identify seven major themes around hydrogen, biomass, biogas, solar PV, optimization, and energy-system management. Their review concludes that hybrid renewable systems can improve grid stability and energy efficiency while reducing emissions, but that policy support and cost reductions remain necessary for scale-up. A related 2026 review on green hydrogen integration also reinforces the need for integrated planning across production, storage, transport, and utilization stages, while the 2025 solar-biomass-storage hybridization review calls for region-specific sustainability assessment and stronger smart-grid integration. These works collectively strengthen the case for studying solar, biomass, and hydrogen together rather than in isolation (Kaur et al., 2025; Jia et al., 2026; *Sustainable Solar/Biomass/Energy Storage Hybridization*, 2025).

At the framework level, Zheng et al. (2023) argue that both smart grids and smart urban energy systems should be treated as cyber-physical-social systems. Their review is especially relevant because it identifies a lack of general design guidelines for integrating smart energy technologies across scales. Sharma et al. (2025) similarly emphasize the need to connect sustainability, air quality, economics, and digital transformation in urban energy-transition studies. These findings suggest that a multi-disciplinary framework is not merely desirable but necessary if urban renewable integration is to be analyzed in a way that captures engineering, economics, environment, and governance together (Zheng et al., 2023; Sharma et al., 2025).

2.7 Research Gaps and Positioning of the Present Study

The reviewed literature provides strong evidence on smart grids, solar integration, biomass optimization, hydrogen flexibility, and urban energy transition, but several gaps remain. First, much of the literature is still segmented by technology, with solar often treated separately from biomass and hydrogen. Second, many reviews are rich in technical analysis but relatively weaker in linking technical integration to policy readiness, urban governance, and sustainability trade-offs. Third, even when urban systems are discussed, the studies often stop short of proposing integrated comparative frameworks for scenario analysis at city level. Zheng et al. (2023) explicitly note the siloed nature of smart-grid and urban-energy-system research, while McCarty et al. (2025) identify scale disconnects in urban PV studies and Kaur et al. (2025) highlight regulatory and cost barriers in hybrid renewable systems (Zheng et al., 2023; McCarty et al., 2025; Kaur et al., 2025).

This study addresses those gaps by examining solar, biomass, and hydrogen.

3. Methodology

3.1 Research Design

This study adopts a quantitative case study design combined with scenario-based techno-economic and environmental analysis to examine how smart grid technologies can enhance the integration of renewable energy systems in urban areas. The focus is on the coordinated use of solar photovoltaic, biomass, and hydrogen technologies within a smart grid environment to support sustainable urban energy transition. The methodological approach is multidisciplinary because it brings together engineering, economics, environmental assessment, and policy analysis within a single analytical framework. The study is structured around the assumption that efficient urban energy transition cannot be achieved through renewable energy deployment alone, but requires enabling grid intelligence, system flexibility, and supportive policy conditions. For this reason, smart grid technologies such as energy storage support, demand response, intelligent monitoring, and grid loss reduction measures are incorporated into the analytical design. The research therefore evaluates not only the contribution of renewable energy technologies, but also the broader system conditions that influence their successful integration.

3.2 Study Area and Case Selection

Lagos, Nigeria, is selected as the case study area for this research. The choice of Lagos is based on its large and rapidly growing population, high electricity demand, recurring grid supply challenges, and increasing relevance in discussions of sustainable urban energy planning. As one of the most prominent urban centers in Africa, Lagos provides an appropriate context for examining the role of renewable energy and smart grid technologies in addressing the pressures of urbanization, energy insecurity, and environmental sustainability. The city also represents a useful case for exploring energy transition in developing economies where existing infrastructure constraints coexist with strong demand for cleaner and more reliable electricity supply. The urban characteristics of Lagos make it possible to assess the technical and strategic value of integrating distributed renewable energy systems into a complex and evolving power environment.

3.3 Data Sources and Dataset Construction

The study is based on a literature-based sample dataset compiled from secondary sources and organized into a structured Excel workbook for analysis. The dataset covers monthly observations for the 2025 study period and includes technical, economic, environmental, and policy-related variables relevant to renewable energy integration and smart grid performance. The workbook is arranged into multiple sheets containing raw data for solar, biomass, hydrogen, grid conditions, economic indicators, and policy variables, as well as a consolidated master sheet for analysis. Each observation in the master dataset represents a city-scenario-technology-month combination. This structure makes it possible to compare technologies across different scenarios and across time. The technical variables include installed capacity, energy output, conversion efficiency, storage capacity, grid losses, and a reliability indicator. The economic variables include capital expenditure, operating expenditure, maintenance cost, and levelized cost-related indicators. The environmental variables include carbon dioxide emissions reduction, renewable energy share, and fossil fuel displacement. The policy and institutional variables include policy support score, feasibility score, and related proxies for implementation readiness.

All variables were carefully documented in a codebook to ensure consistency, transparency, and reproducibility. The data structure was designed to support scenario comparison, performance assessment, and cross-dimensional evaluation of energy transition outcomes.

3.4 Scenario Development

To analyze possible pathways for sustainable urban energy transition, four scenarios were developed in this study. The first scenario is the base scenario, which represents the conventional grid-dominated electricity supply system with minimal renewable integration. This scenario provides the reference point against which all other scenarios are compared. The second scenario introduces solar photovoltaic systems supported by smart grid technologies. In this configuration, solar energy is combined with basic grid intelligence measures such as smart metering, limited storage support, and demand-side management. This scenario reflects an early stage of smart renewable integration in an urban setting. The third scenario expands the system by combining solar photovoltaic and biomass technologies within the smart grid environment. Biomass is introduced to improve generation diversity and dispatchability, thereby complementing the variability of solar output. This scenario captures a broader renewable mix with enhanced system resilience. The fourth scenario represents the most advanced transition pathway considered in the study. It integrates solar photovoltaic, biomass, and hydrogen technologies with advanced smart grid functions. In this scenario, hydrogen serves as an additional flexibility and storage vector, while the smart grid enables improved balancing, monitoring, and system coordination. Together, the four scenarios provide a progressive framework for comparing increasingly complex urban energy transition strategies.

3.5 Data Processing and Harmonization

Before analysis, the dataset was cleaned, standardized, and harmonized to ensure comparability across technologies and scenarios. All energy values were converted to megawatt-hours, installed capacities were standardized in megawatts, cost variables were expressed in United States dollars, and emissions were recorded in tons of carbon dioxide. Monthly observations were aligned across all technologies to maintain a consistent time basis for comparison. The data cleaning process involved checking for duplicate entries, correcting inconsistent labels, and resolving unit differences across source materials. Where direct values were unavailable, literature-informed assumptions were applied in a transparent manner. These assumptions were clearly separated from directly reported values to maintain methodological clarity. Some indicators were also normalized to support cross-scenario comparison and interpretation. The processed raw data were then consolidated into a single master dataset that served as the basis for descriptive, comparative, and evaluative analysis. This harmonization process was essential for ensuring that the analytical results were internally consistent and suitable for journal-level presentation.

3.6 Analytical Framework

The analytical framework for this study integrates four major dimensions, namely technical performance, economic feasibility, environmental sustainability, and policy readiness. These dimensions were selected because the integration of renewable energy systems into smart urban grids is not purely a technical issue, but a systems challenge involving cost, emissions, governance, and implementation capacity. The technical dimension focuses on the operational contribution of each renewable technology and the role of smart grid systems in improving efficiency, flexibility, and reliability. The economic dimension examines the financial implications of renewable integration through cost-related indicators such as capital and operating expenditure. The environmental dimension evaluates the sustainability contribution of each scenario through emissions reduction and renewable energy penetration. The policy dimension reflects the institutional and regulatory conditions that can either support or hinder urban energy transition. By combining these four dimensions, the framework provides a multidimensional basis for evaluating the comparative suitability of different renewable integration pathways. This makes the approach especially appropriate for a study that seeks to develop a multi-disciplinary framework for sustainable urban energy transition.

3.7 Methods of Data Analysis

The study applies descriptive statistics, comparative scenario analysis, and multi-criteria evaluation to examine the performance of the different scenarios. Descriptive statistics are used to summarize monthly and scenario-level patterns in energy generation, renewable energy share, grid losses, emissions reduction, and cost variables. These summaries provide an overall picture of how each renewable technology and scenario performs within the urban energy system. Comparative scenario analysis is then used to assess the relative strengths and weaknesses of the four scenarios. The base scenario is used as the benchmark, while the renewable integration scenarios are evaluated in terms of improvements in technical performance, economic viability, environmental benefit, and smart grid compatibility. Tables, charts, and percentage changes are employed to identify how each scenario differs from the baseline and from the other alternative pathways. Because the study is explicitly multidisciplinary, a multi-criteria perspective is also incorporated into the analysis. The scenarios are evaluated across key criteria such as efficiency, cost, emissions reduction, renewable share, grid reliability, and policy support. This allows the study to move beyond single-variable comparison and identify the most balanced pathway for sustainable urban energy transition. In addition, monthly trend analysis is applied to observe temporal variation in the performance of the technologies and scenarios. Where necessary, sensitivity analysis may also be carried out by adjusting important assumptions such as solar output, biomass availability, hydrogen system efficiency, grid loss rate, and policy support score. This helps to test the robustness of the framework and improve confidence in the interpretation of results.

3.8 Model Variables

The dependent outcomes in this study include renewable energy output, carbon emissions reduction, grid performance improvement, and the overall sustainability ranking of each scenario. These outcomes capture the principal objectives of the study, which are to determine how effectively smart grid technologies can support renewable integration and to identify the most suitable transition pathway for an urban context. The independent variables include technology type, installed capacity, smart grid features, storage integration, policy support, and scenario composition. These variables influence the observed outcomes and form the basis for scenario comparison. Their interaction helps explain differences in performance across the various renewable integration pathways examined in the study.

3.9 Validity and Reliability

Validity in this study is supported through the use of structured secondary data, transparent scenario assumptions, and consistent observation periods across all technologies and scenarios. The selection of variables was guided by the objectives of the study and by the need to capture technical, economic, environmental, and policy dimensions in an integrated manner. This strengthens the extent to which the methodology measures what it is intended to measure. Reliability is enhanced through the use of a reproducible Excel-based dataset structure with clearly named sheets, standardized units, and documented variables in the codebook. The use of a harmonized monthly dataset also improves consistency in the analytical process. By maintaining a clear record of assumptions, sources, and variable definitions, the study ensures that the methodology can be replicated or adapted by future researchers.

3.10 Ethical Considerations

This study relies exclusively on secondary and modeled data and does not involve human participants, personal information, or confidential institutional records. As a result, the research does not raise direct ethical concerns relating to consent, privacy, or participant protection. The main ethical responsibility lies in ensuring transparency in data handling, proper acknowledgment of source materials, and accurate distinction between directly obtained values and modeled assumptions.

Figure 3: *Scenario Architecture for Integrating Solar, Biomass, and Hydrogen within a Smart Grid for Urban Energy System*

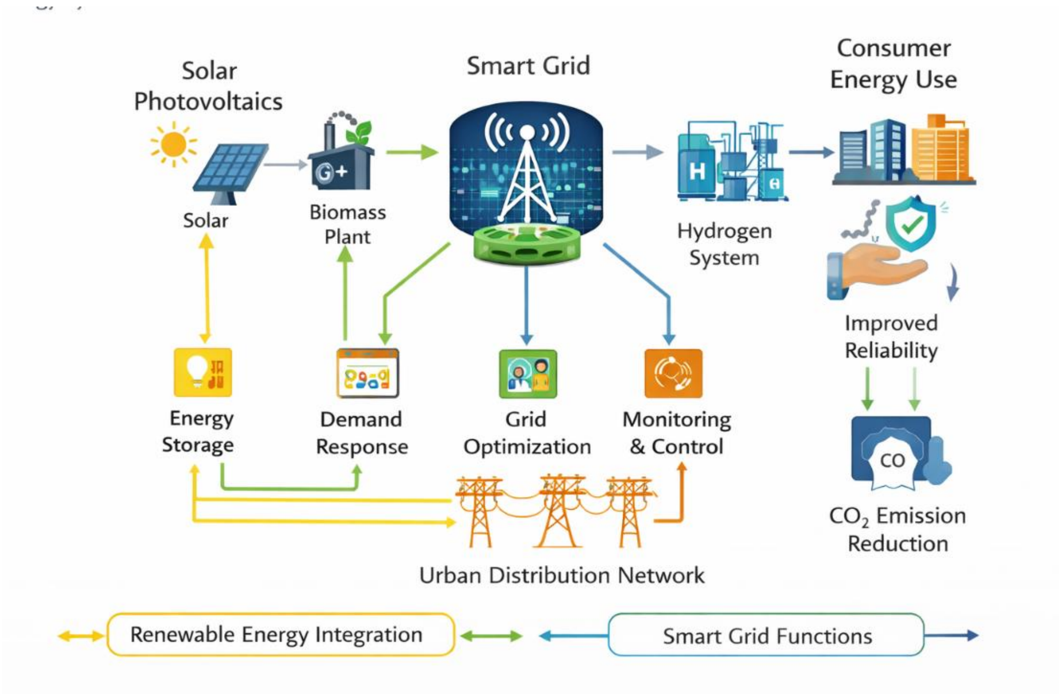

Figure 3 illustrates the methodological system architecture used in this study for analyzing the integration of solar, biomass, and hydrogen within a smart-grid-enabled urban energy system. It shows how the selected renewable energy sources are connected through the smart grid to urban electricity demand, while incorporating key operational components such as storage, monitoring, control, and demand management. The figure supports the methodology by visually explaining the structural basis of the scenario design and the interaction among the major variables considered in the analysis.

4. Results

4.1 Scenario Performance Overview

This section presents the results of the scenario analysis for Lagos under four energy transition pathways, namely the conventional grid-dominated baseline, a solar-smart-grid pathway, a solar-biomass-smart-grid pathway, and a solar-biomass-hydrogen-smart-grid pathway. The results show that the integration of renewable energy systems through smart grid technologies improves the technical, environmental, and operational performance of the urban electricity system.

Across all scenarios, annual electricity supply remains constant at 3,500,204.0 MWh because the model assumes that the city's annual demand is fully met in each case. However, the composition of the energy supply changes significantly as renewable technologies are introduced and smart grid functions become more advanced. The baseline scenario records the weakest overall performance, while the most integrated scenario records the strongest outcomes in renewable penetration, emissions reduction, grid efficiency, and reliability. The overall comparative results are presented in Table 1, while the change in renewable share across scenarios is illustrated in Figure 4.

Table 1: Scenario Summary Results

Scenario	**Annual Energy Supply (MWh)**	**Annual CAPEX (USD)**	**Annual OPEX (USD)**	**Annual CO2 Reduction (tons)**	**Avg. Renewable Share (%)**	**Avg. Grid Loss (%)**	**Avg. Reliability**	**Avg. Policy Score**
BASE	3,500,204.0	0	0	0.0	10.0	18.0	0.62	62.0
S1	3,500,204.0	648,000,000	12,960,000	62,474.7	24.0	15.0	0.74	70.0
S2	3,500,204.0	1,624,800,000	63,120,000	144,662.9	38.0	13.0	0.82	76.0
S3	3,500,204.0	2,490,000,000	101,400,000	199,442.3	53.0	11.0	0.89	82.0

As shown in Table 1, renewable share increases steadily from 10.0 percent in the baseline to 53.0 percent in Scenario 3. At the same time, grid loss declines from 18.0 percent to 11.0 percent, while the reliability index rises from 0.62 to 0.89. This indicates that deeper renewable integration, when coordinated through smart grid technologies, produces clear improvements in the performance of the urban electricity system.

Figure 4. Renewable Energy Share by Scenario

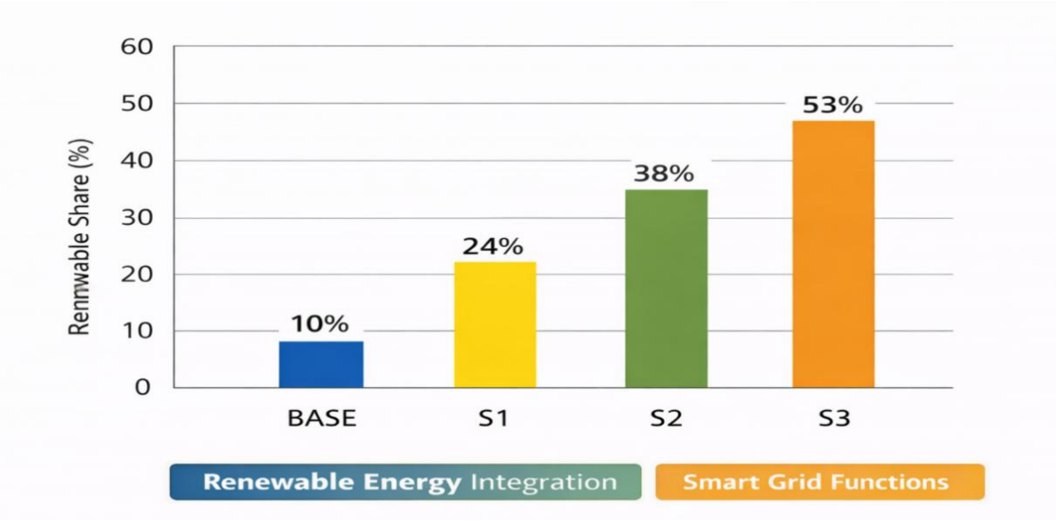

Figure 4 shows the progressive increase in renewable energy penetration across the four scenarios, with Scenario 3 recording the highest renewable share.

4.2 Technology Contribution to Urban Electricity Supply

The results further show that solar, biomass, and hydrogen contribute differently to the electricity system and perform complementary roles within the smart-grid-enabled transition pathway. Solar provides the dominant early renewable contribution, biomass strengthens dispatchability, and hydrogen adds additional flexibility in the most advanced scenario. The technology-specific contribution of each energy source is presented in Table 2.

Table 2: *Technology Contribution by Scenario*

Scenario	Grid Energy (MWh)	Solar Energy (MWh)	Biomass Energy (MWh)	Hydrogen Energy (MWh)	Total Renewable Energy (MWh)
BASE	3,500,204.0	0.0	0.0	0.0	0.0
S1	3,401,192.7	99,011.3	0.0	0.0	99,011.3
S2	3,201,748.9	132,015.1	166,440.0	0.0	298,455.1
S3	3,080,239.2	165,018.7	248,346.0	6,600.1	419,964.8

The baseline scenario depends entirely on conventional grid electricity. In Scenario 1, solar contributes 99,011.3 MWh annually, reducing dependence on the grid. In Scenario 2, the addition of biomass significantly expands total renewable supply to 298,455.1 MWh. In Scenario 3, the combined contribution of solar, biomass, and hydrogen reaches 419,964.8 MWh, resulting in the lowest level of conventional grid dependence among all scenarios. These findings confirm that a diversified renewable portfolio supported by smart grid functions improves system flexibility and reduces reliance on conventional electricity sources.

4.3 Economic Results

The economic results reveal a clear trade-off between system advancement and investment requirement. As the system moves from the baseline toward more integrated renewable-smart-grid configurations, capital and operating costs increase. However, the comparative cost-performance outcomes differ across scenarios. The economic comparison is shown in Table 3.

Table 3: *Economic Comparison of Scenarios*

Scenario	CAPEX (USD)	OPEX (USD)	Average LCOE (USD/MWh)	Interpretation
BASE	0	0	113.42	Grid-dominated reference case
S1	648,000,000	12,960,000	73.82	Lower cost transition entry point
S2	1,624,800,000	63,120,000	63.96	Best cost-performance balance
S3	2,490,000,000	101,400,000	166.22	Highest cost, strongest system performance

Scenario 1 represents a relatively affordable transition option because it introduces solar and smart grid functions at moderate cost while producing noticeable improvements in renewable share and system performance. Scenario 2 records the lowest average LCOE at USD 63.96/MWh, indicating that the combination of solar, biomass, and smart grid technologies provides the most favorable cost-performance balance. Scenario 3, although technically superior, has the highest CAPEX, OPEX, and average LCOE, reflecting the high cost associated with hydrogen deployment and more advanced infrastructure. These results suggest that the most technically advanced system is not necessarily the most economically attractive in the short term. From a medium-term planning perspective, Scenario 2 appears to be the most economically viable transition pathway.

4.4 Environmental Results

The environmental results show that renewable-smart-grid integration produces substantial gains in carbon emissions reduction. As renewable share increases across the scenarios, dependence on conventional electricity supply declines and annual carbon dioxide reduction improves. The environmental performance of the scenarios is summarized in Table 4 and illustrated in Figure 5.

Table 4: *Environmental Performance by Scenario*

Scenario	Annual CO2 Reduction (tons)	Renewable Share (%)	Environmental Interpretation
BASE	0.0	10.0	No modeled renewable-driven reduction
S1	62,474.7	24.0	Moderate emissions improvement
S2	144,662.9	38.0	Strong environmental benefit
S3	199,442.3	53.0	Highest environmental performance

The baseline scenario does not produce any modeled emissions reduction because it serves as the reference case. Scenario 1 records an annual reduction of 62,474.7 tons of CO2, while Scenario 2 increases this to 144,662.9 tons. Scenario 3 produces the highest environmental benefit, with 199,442.3 tons of annual CO2 reduction. This pattern confirms that smart-grid-enabled renewable integration contributes directly to urban decarbonization.

Figure 5: *Annual CO2 Reduction by Scenario*

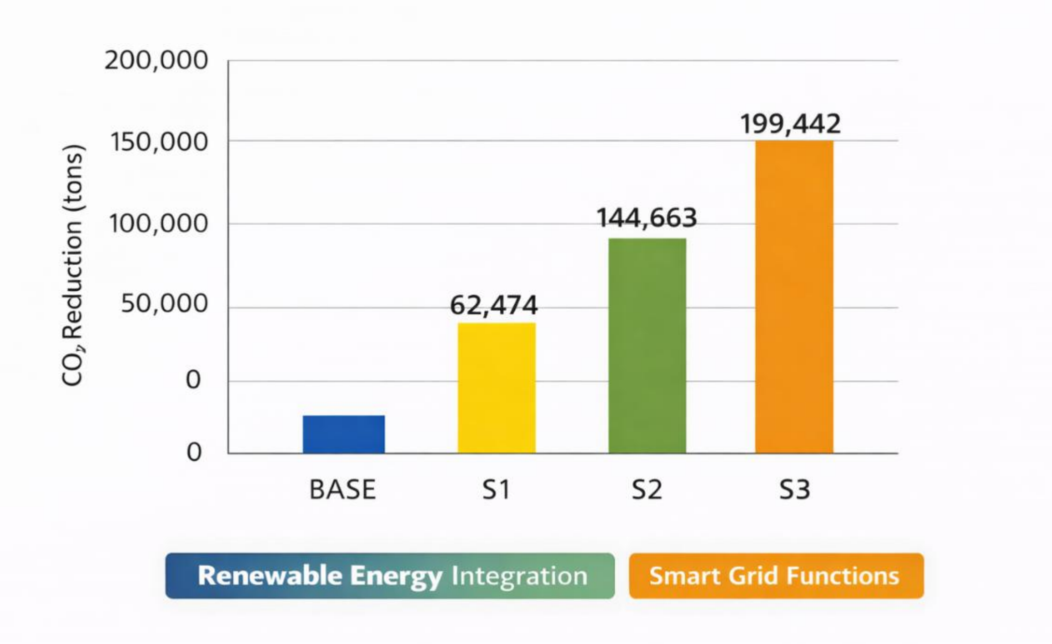

Figure 5 presents the steady increase in annual carbon dioxide reduction as the system moves from the baseline to more advanced renewable-smart-grid scenarios.

4.5 Grid Efficiency and Reliability

A major finding of this study is that smart grid technologies improve both grid efficiency and reliability. As renewable integration becomes more advanced, average grid losses decline consistently while the reliability index improves across all scenarios. The detailed results are presented in Table 5. The trends is shown graphically using Figure 6 for grid loss and Figure 7 for reliability.

Table 5: Grid Efficiency and Reliability Results

Scenario	Avg. Grid Loss (%)	Reduction in Grid Loss from BASE (%)	Avg. Reliability	Improvement in Reliability from BASE (%)
BASE	18.0	0.0	0.62	0.0
S1	15.0	16.7	0.74	19.4
S2	13.0	27.8	0.82	32.3
S3	11.0	38.9	0.89	43.5

Compared with the baseline, Scenario 1 reduces grid losses by 16.7 percent and improves reliability by 19.4 percent. Scenario 2 performs better, with a 27.8 percent reduction in grid loss and a 32.3 percent improvement in reliability. Scenario 3 records the strongest operational outcome, with grid loss reduced by 38.9 percent and reliability improved by 43.5 percent relative to the baseline. These results indicate that smart grid functions such as monitoring, storage coordination, demand response, and system control significantly strengthen the performance of the urban electricity network.

Figure 6. *Average Grid Loss by Scenario*

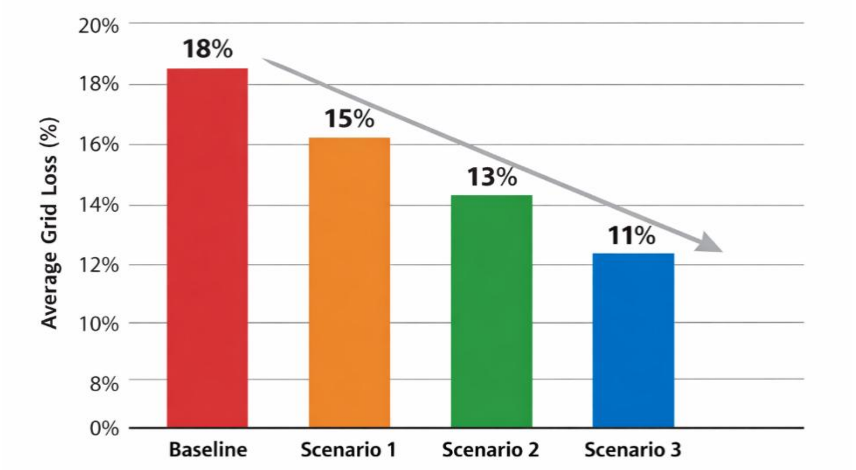

Figure 6 shows the progressive decline in average grid loss as smart grid functions and renewable integration increase across scenarios.

Figure 7. *Average Reliability by Scenario*

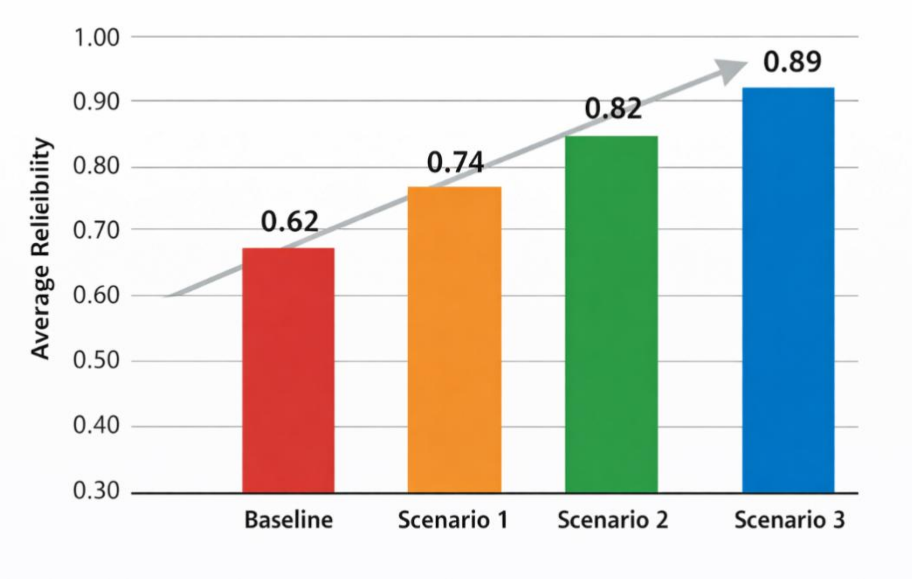

Figure 7 illustrates the steady increase in the reliability index from the baseline to Scenario 3.

4.6 Policy Support and Transition Readiness

The analysis also indicates that stronger renewable integration requires stronger policy and institutional support. The policy support score rises consistently across the scenarios, suggesting that technical progress is accompanied by greater governance and implementation demands.

The policy results are shown in **Table 4.6**.

Table 4.6 Policy Support and Transition Readiness

Scenario	**Policy Score**	**Transition Readiness Interpretation**
BASE	62.0	Limited renewable transition readiness
S1	70.0	Moderate readiness with basic smart grid support
S2	76.0	Stronger policy alignment for integrated renewables
S3	82.0	Highest policy and institutional readiness requirement

The baseline scenario records the lowest policy score, indicating limited transition readiness. Scenario 1 reflects moderate readiness, while Scenarios 2 and 3 require stronger regulatory coordination, investment support, and institutional capacity. This result highlights that sustainable urban energy transition depends not only on technology performance, but also on the quality of the policy and governance environment.

4.7 Comparative Ranking of Scenarios

To provide an overall interpretation of the scenario outcomes, the results were comparatively ranked across technical, economic, environmental, and operational dimensions. The summary ranking is presented in Table 7.

Table 7. *Comparative Ranking of Scenarios*

Criterion	**BASE**	**S1**	**S2**	**S3**
Technical Performance	Low	Moderate	High	Very High
Economic Attractiveness	Low	High	Very High	Moderate
Environmental Benefit	Low	Moderate	High	Very High
Grid Reliability	Low	Moderate	High	Very High
Policy Readiness Demand	Low	Moderate	High	Very High
Overall Assessment	Weakest	Good entry pathway	Best balanced option	Best overall performance

The baseline scenario is clearly the weakest pathway across all major indicators. Scenario 1 serves as a practical entry pathway because it delivers moderate gains at lower cost. Scenario 2 emerges as the most balanced scenario because it combines strong technical and environmental performance with the best economic outcome. Scenario 3 delivers the highest technical and environmental performance, but it is also the most expensive and policy-demanding option.

4.8 Monthly Pattern of Results

The monthly results indicate that the benefits of renewable-smart-grid integration are sustained across the entire study period. Although total electricity supply remains fixed each month because demand is assumed to be fully met, the composition of generation and the quality of system performance vary across scenarios. Carbon reduction, renewable penetration, and reliability improvement remain higher in the renewable-smart-grid scenarios throughout the year, showing that the gains from system integration are not confined to a particular season. The monthly pattern further suggests that solar contributes variable output across the year, while biomass and hydrogen help stabilize system performance in the more advanced scenarios. This confirms the value of combining variable and dispatchable renewable sources within one smart-grid-enabled framework.

5. Discussion

5.1 Interpretation of the Main Findings

The findings of this study demonstrate that smart grid technologies play a critical enabling role in the efficient integration of renewable energy systems for sustainable urban energy transition. Although total annual electricity supply remains constant across the scenarios, the composition of that supply changes significantly as solar, biomass, and hydrogen are progressively introduced. This indicates that the real value of the transition pathways examined in this study lies not in increasing total electricity demand served, but in improving how that demand is met through cleaner, more reliable, and more flexible energy sources.

The results show that the shift from the base scenario to the advanced renewable-smart-grid scenarios leads to higher renewable energy share, lower grid losses, improved reliability, and greater carbon emissions reduction. This confirms that urban energy transition is not simply a matter of adding renewable technologies into an existing grid structure. Rather, it requires an intelligent grid system capable of coordinating generation diversity, managing intermittency, reducing operational inefficiencies, and supporting system-wide optimization. In this regard, the smart grid emerges as the central integrating platform through which renewable energy technologies can function effectively in an urban environment.

5.2 Smart Grid as the Core Enabler of Renewable Integration

One of the most important contributions of this study is the demonstration that smart grid technologies are not merely supportive add-ons, but foundational elements of renewable energy integration. The observed decline in grid loss and rise in reliability across the scenarios strongly suggests that improvements in system intelligence, monitoring, demand response, and operational control significantly enhance the performance of renewable energy systems. In practical terms, this means that solar, biomass, and hydrogen technologies are more effective when embedded in a grid architecture that can dynamically manage supply and demand conditions.

This finding is especially important for rapidly urbanizing cities such as Lagos, where grid instability and demand pressure often undermine the performance of both conventional and renewable systems. The study shows that as smart grid functions become more advanced, the system is better able to accommodate higher levels of renewable penetration without compromising reliability. This supports the argument that energy transition in urban areas should be approached as a systems transformation rather than a technology substitution exercise.

5.3 Role of Solar, Biomass, and Hydrogen in the Transition Pathway

The discussion of technology roles reveals that the three renewable energy sources examined in this study do not perform identical functions. Solar photovoltaic systems provide the strongest early contribution to renewable integration and appear to be the most accessible entry point for urban renewable deployment. This is consistent with the relatively strong solar contribution recorded in the renewable scenarios and with the common view that solar energy is often the first large-scale distributed renewable option adopted in urban settings.

However, the results also show that solar alone is not sufficient for a robust urban transition pathway. Biomass contributes significantly to dispatchability and system stability because it can provide a more controllable renewable energy source than solar. Its inclusion in Scenario 2 and Scenario 3 improves the overall technical and environmental performance of the system, indicating that a diversified renewable portfolio is more resilient than a single-technology strategy. Hydrogen, although contributing less direct energy output in the modeled system, appears to perform a strategic flexibility role. Its value lies less in volumetric supply and more in long-term storage, balancing, and future system adaptability. This suggests that hydrogen may become increasingly relevant in advanced stages of urban energy transition, particularly where renewable penetration and system complexity are high.

5.4 Economic Implications of the Transition Scenarios

The economic results reveal a key trade-off between system advancement and affordability. While Scenario 3 delivers the strongest technical and environmental outcomes, it also has the highest capital and operating cost burden. This means that the most sustainable scenario in performance terms is not necessarily the most immediately feasible from an investment perspective. The high cost associated with hydrogen deployment and advanced grid integration implies that long-term transition planning must consider financing structures, policy incentives, and phased implementation strategies.

At the same time, the results indicate that Scenario 2 offers the most balanced economic outcome. Its lower average levelized cost of electricity relative to the other renewable scenarios suggests that the combination of solar, biomass, and smart grid functionality may represent the most practical medium-term pathway for cities seeking both performance and affordability. This is a particularly relevant finding for developing urban economies where investment constraints often limit the pace of technology transition. The implication is that urban energy planning may need to proceed incrementally, beginning with relatively cost-effective renewable-smart-grid combinations before moving toward more capital-intensive options such as hydrogen-based flexibility systems.

5.5 Environmental Significance of Smart-Grid-Enabled Renewable Transition

The environmental findings of this study reinforce the importance of coordinated renewable integration for urban sustainability. The progressive rise in carbon dioxide reduction across the scenarios demonstrates that each additional layer of renewable integration contributes to lower emissions intensity in the city’s electricity system. This result confirms that urban energy transition has direct climate and environmental value when cleaner technologies are systematically integrated into the power mix.

More importantly, the results suggest that emissions reduction is most effective when renewable deployment is accompanied by smart grid optimization. This is because environmental benefit is not determined solely by renewable capacity, but also by how efficiently the system absorbs and manages renewable generation. A poorly coordinated grid can weaken the environmental value of renewable integration through losses, curtailment, and instability. In contrast, a smart-grid-enabled system supports higher renewable utilization and therefore improves the environmental return on renewable investment.

5.6 Policy and Governance Implications

The discussion also highlights the central importance of policy and governance in urban energy transition. The increasing policy support score across the scenarios reflects the reality that more advanced renewable integration requires stronger institutional readiness. This means that technological improvement alone is insufficient. Effective urban transition depends on regulation, incentives, financing frameworks, implementation planning, and administrative coordination.

This has major implications for policymakers. If cities are to move beyond small-scale renewable deployment toward integrated smart-grid systems, then public policy must evolve accordingly. Regulatory structures should encourage distributed generation, support smart metering and storage investment, reduce barriers to grid modernization, and create stable conditions for private and public investment. The results therefore support the multidisciplinary logic of the study by showing that successful renewable integration depends on technical systems and governance systems working together.

5.7 Comparison of Scenarios and Preferred Transition Pathway

The comparison of the four scenarios suggests that no single pathway is superior under all conditions. The base scenario performs weakest and clearly does not support long-term urban sustainability. Scenario 1 provides a useful entry-level pathway, especially where cities seek moderate improvement at relatively manageable cost. Scenario 2 emerges as the most balanced scenario because it combines strong technical, environmental, and economic performance. Scenario 3 provides the strongest long-term sustainability outcome, but it is also the most capital-intensive and institutionally demanding.

This comparison implies that transition planning should be phased and context-sensitive. For cities with severe fiscal or regulatory constraints, beginning with a solar-smart-grid or solar-biomass-smart-grid strategy may be more realistic than attempting full hydrogen integration immediately. Over time, as institutional and financial readiness improves, more advanced flexibility options can be introduced. In this sense, the scenarios should not necessarily be viewed as mutually exclusive alternatives, but as stages along a broader transition continuum.

5.8 Implications for Sustainable Urban Energy Transition

The broader implication of this study is that sustainable urban energy transition requires more than renewable resource availability. It requires integration capacity. Cities need a framework in which renewable technologies, smart grid infrastructure, economic planning, and policy support are developed together rather than in isolation. The results show that when this integrated approach is followed, urban electricity systems can become more reliable, less carbon intensive, and more adaptable to future energy challenges.

For rapidly growing cities in developing economies, this finding is especially significant. Such cities often face the dual challenge of expanding energy access while reducing environmental and system vulnerability. The study suggests that smart-grid-enabled renewable integration provides a pathway for meeting both objectives simultaneously. It therefore contributes to the wider debate on how urban centers can pursue economic development without deepening fossil-fuel dependence and grid inefficiency.

5.9 Relation of the Findings to the Study Objective

The objective of this study was to develop a multi-disciplinary framework for the efficient integration of solar, biomass, and hydrogen systems through smart grid technologies in support of sustainable urban energy transition. The discussion confirms that this objective has been achieved. The results demonstrate that the framework is capable of capturing the interconnections between technical performance, economic feasibility, environmental sustainability, and policy readiness.

The findings show that the smart grid is the central coordinating mechanism through which these dimensions are linked. Technical efficiency improves because renewable generation is better managed. Economic outcomes become more interpretable because scenario costs can be compared with performance gains. Environmental benefits become more substantial because renewable energy is utilized more effectively. Policy significance becomes clearer because higher-performing scenarios require stronger governance conditions. In this way, the multidisciplinary framework developed in the study provides a coherent structure for analyzing urban renewable integration.

6. Conclusion

This study concludes that smart grid technologies are essential for the efficient integration of solar, biomass, and hydrogen systems in support of sustainable urban energy transition. The results show that as renewable integration increases, renewable energy share rises, carbon emissions decline, grid losses reduce, and system reliability improves.

The findings also reveal that the three renewable technologies play complementary roles within the urban energy system. Solar provides the main early contribution to renewable penetration, biomass improves dispatchability and system stability, while hydrogen offers strategic long-term flexibility and storage support.

Economically, the study finds that the solar-biomass-smart-grid scenario provides the best balance between cost and performance, while the solar-biomass-hydrogen-smart-grid scenario delivers the strongest long-term sustainability outcome despite its higher investment requirement.

Overall, the study confirms that sustainable urban energy transition depends not only on renewable energy deployment, but also on intelligent grid management, supportive policy frameworks, and coordinated system planning.

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