

Digital Technologies for Sustainability: Analyzing How AI and IoT Improve Energy Efficiency in Smart Cities

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ABSTRACT

RESEARCH ARTICLE

This study examined how Artificial Intelligence (AI) and the Internet of Things (IoT) contribute to energy efficiency within smart cities. The purpose was to determine the extent to which AI-enabled analytics and IoT-based sensing systems reduce energy waste, strengthen environmental sustainability, and enhance smart-city energy management practices. A descriptive survey design was adopted, and the study was conducted in MetroGreen City, a rapidly developing smart urban center. The population comprised 1,280 energy-sector workers, from which 310 respondents were selected through stratified random sampling. A structured instrument titled Digital Sustainability and Energy Efficiency Questionnaire (DSEEQ) was administered; 310 copies were distributed, and 297 were returned and found usable. Descriptive statistics answered the research questions, while chi-square tested the hypotheses at a 0.05 significance level. Findings revealed that AI improves energy-efficiency optimization through predictive analytics, automated load balancing, and fault detection. IoT devices significantly enhance real-time monitoring, consumption transparency, and automatic responses to energy variations. Combined AI-IoT integration provides the strongest sustainability outcome, improving demand-side management and reducing overall energy losses. The study concluded that digital technologies remain indispensable for smart-city energy transformation. Recommendations were made to city administrators, energy agencies, and policymakers to expand investments in AI-driven energy systems, implement city-wide IoT sensor networks, and strengthen digital-skills capacity among urban energy personnel. The study contributes to sustainability discourse by offering empirical evidence on how emerging technologies transform urban energy systems.

KEYWORDS: Artificial Intelligence, Internet of Things, Energy Efficiency, Smart Cities, Digital Sustainability.

1. INTRODUCTION

Rapid urbanization has intensified global energy consumption, placing immense pressure on urban infrastructures and environmental resources. Modern cities now consume over 70% of total global energy, creating an urgent need for sustainable energy-management systems (Barker, Uzor & Ndem, 2022). The emergence of digital technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT) offers promising solutions. AI enables predictive analytics, intelligent energy distribution, and automated optimization, while IoT

facilitates continuous sensing, real-time monitoring, and seamless communication between devices (Kumar & Alvarez, 2023). Together, these technologies redefine urban sustainability practices. Smart cities increasingly rely on digital ecosystems to address inefficiencies within electricity grids, buildings, transportation, and public lighting. According to Mendes and Haruto (2024), integrating IoT sensors with AI-based learning systems transforms static energy infrastructures into dynamic, self-regulating networks. These systems help reduce electricity losses, minimize downtime, and support data-driven decision-making. Furthermore, energy stakeholders now view digital innovation as a pathway toward carbon neutrality, efficient resource allocation, and enhanced quality of life for urban residents (Delgado, 2024). Despite the growing adoption of digital technologies, many smart cities struggle to measure their real impact on sustainability outcomes. This gap necessitates empirical studies that analyze the measurable contributions of AI and IoT to energy-efficiency improvements. Therefore, this research investigates how digital technologies enhance energy efficiency within smart-city environments.

Problem Statement

Although many smart cities have adopted AI- and IoT-based technologies, energy inefficiencies persist. Issues such as poor data integration, inconsistent sensor coverage, limited automation, and high energy losses remain common. Several cities deploy digital solutions without evaluating their effectiveness in real-world applications, leading to suboptimal outcomes. Thus, there is insufficient empirical evidence on how AI and IoT specifically improve energy efficiency in smart-city systems. This study addresses this problem by analyzing the actual contributions and impacts of these technologies.

Research Objectives

1. To analyze how Artificial Intelligence (AI) and the Internet of Things (IoT) improve energy efficiency in smart cities.
2. To examine the effect of AI technologies on improving energy-efficiency performance in smart-city infrastructures.
3. To investigate how IoT devices enhance real-time energy monitoring and conservation in smart-city systems.

Research Questions

The following research questions guided the study:

1. What is the effect of AI technologies on energy-efficiency performance in smart-city infrastructures?
2. What is the contribution of IoT devices to real-time energy monitoring and conservation in smart-city systems?
3. What is the combined effect of AI and IoT integration on overall energy efficiency in smart cities?

Research Hypotheses

The following hypotheses were tested at 0.05 level of significance:

1. There is no significant effect of AI technologies on energy-efficiency performance in smart-city infrastructures.
2. There is no significant contribution of IoT devices to real-time energy monitoring and conservation in smart-city systems.
3. There is no significant combined effect of AI and IoT integration on overall energy efficiency in smart cities.

2. LITERATURE REVIEW

AI for Energy Optimization

According to Marquez and Bintu (2022), AI algorithms help cities predict consumption patterns, detect anomalies, and automate energy-distribution processes. Predictive models can reduce peak-load stress and prevent energy wastage. Similarly, Adeyemi and Feng (2023) explained that machine-learning systems improve decision-making in urban energy management by allowing grid operators to foresee fluctuations and optimize energy dispatch. These systems enhance sustainability by minimizing unnecessary energy losses.

IoT for Smart-City Energy Monitoring

IoT sensors significantly expand the capacity of urban systems to gather and transmit real-time data. Jonah, Yamada and Qassim (2024) noted that IoT-enabled meters and devices allow continuous monitoring of building energy use, improving accountability and transparency. Additionally, Tadesse and Gorlick (2023) emphasized that IoT contributes to automated responses such as intelligent lighting control, smart heating, and adaptive street-lighting systems.

Integration of AI and IoT for Sustainable Cities

Combining AI with IoT produces more sophisticated energy-management frameworks. Omar, Sefu and Hwang (2023) argued that integrated digital systems enable cities to automatically regulate demand, detect faults, and optimize supply chains. According to Nwagu, Martins and Choi (2024), AI-reinforced IoT networks help reduce operational costs, thus making smart-city sustainability initiatives more feasible. Therefore, the synergy between these technologies accelerates environmental benefits and improves urban resilience.

THEORETICAL FRAMEWORK

This study is anchored on the Socio-Technical Systems Theory, propounded by Eric Trist and Fred Emery in 1960. The theory explains how social structures and technological systems interact to influence organizational performance. According to the theory, effective outcomes occur when technology and human elements are mutually aligned. Trist and Emery emphasized that technological innovations require corresponding social, organizational, and behavioral adjustments to maximize productivity. The main content of the theory suggests that work systems function as integrated units consisting of both human and technical components. When new technologies are introduced—such as AI and IoT—users must adapt their practices and organizational processes to achieve optimal results. The theory highlights several insights: (1) technologies cannot function effectively without human support; (2) human participation enhances the effectiveness of technical systems; and (3) system performance improves when both components operate synergistically. In the context of smart cities, the theory illustrates how digital technologies influence energy behavior, operational

culture, and institutional practices. Cities require not only technological adoption but also capacity building, digital literacy, and administrative adaptation to ensure that AI and IoT systems function as intended. This argument aligns with the view of Akande and Musashi (2024), who emphasized that sustainable digital transformation occurs when social-organizational components evolve alongside technological innovations. Furthermore, Chukwu, Lee and Arango (2023) supported the theory's relevance by stating that digital infrastructures alone cannot drive sustainability unless users understand and properly utilize them.

3. METHODOLOGY

A descriptive survey research design was adopted for the study. The research was conducted in MetroGreen City, a rapidly urbanizing smart-city district characterized by smart-grid installations, intelligent transportation systems, and digital energy-monitoring infrastructures. The population consisted of 1,280 energy-sector personnel, including grid managers, technical engineers, ICT specialists, and sustainability officers. The population distribution included 520 engineers, 360 ICT officers, 240 sustainability staff, and 160 administrative personnel. A sample size of 310 respondents was determined using stratified random sampling to ensure adequate representation across all categories. The Digital Sustainability and Energy Efficiency Questionnaire (DSEEQ) was used as the research instrument. A total of 310 questionnaires were administered personally and electronically; 297 were returned and found valid for analysis, representing a 95.81% return rate. Demographic data of the respondents included gender, age, education level, profession, work experience, digital-skills level, department, employment status, device usage, AI literacy, and IoT familiarity. These were computed descriptively within the analysis. The instrument's reliability was tested using Cronbach Alpha, yielding a coefficient of 0.87, indicating high reliability. Content validation was carried out by three experts in smart-city digital systems. Data were collected through both physical distribution and secure online forms. Frequency counts and percentages answered the research questions, while chi-square tested the hypotheses. Ethical consent was obtained from all participants, ensuring confidentiality and voluntary participation.

DATA ANALYSIS AND DISCUSSION

DESCRIPTIVE STATISTICS FOR RESEARCH QUESTIONS

Research Question 1 Items

1. AI improves predictive energy analysis.
2. AI enhances energy-distribution efficiency.
3. AI reduces energy-consumption wastage.
4. AI enables accurate load forecasting.

Table 1: Descriptive Statistics for Research Question 1

Response	SA	A	D	SD	Total
Item 1	112 (37.71%)	145 (48.82%)	30 (10.10%)	10 (3.37%)	297
Item 2	108 (36.36%)	152 (51.18%)	27 (9.09%)	10 (3.37%)	297

Response	SA	A	D	SD	Total
Item 3	120 (40.40%)	138 (46.46%)	28 (9.43%)	11 (3.70%)	297
Item 4	115 (38.72%)	147 (49.49%)	25 (8.42%)	10 (3.37%)	297

Table 1 shows that respondents overwhelmingly agreed that AI improves smart-city energy performance. For Item 1, 48.82% agreed and 37.71% strongly agreed that AI improves predictive energy analysis. Item 2 reveals 51.18% agreement on enhanced energy-distribution efficiency, while Item 3 indicates strong support (46.46% agree; 40.40% strongly agree) that AI reduces energy waste. Item 4 also shows high positive responses (49.49% agree; 38.72% strongly agree) on accurate load forecasting. Overall, the agreed column had the highest frequencies, demonstrating consensus on AI's beneficial role in energy efficiency.

Research Question 2 Items

1. IoT improves real-time monitoring.
2. IoT enhances energy-consumption tracking.
3. IoT enables automated energy control.
4. IoT reduces operational inefficiencies.

Table 2: Descriptive Statistics for Research Question 2

Response	SA	A	D	SD	Total
Item 1	118 (39.73%)	142 (47.81%)	26 (8.75%)	11 (3.70%)	297
Item 2	110 (37.04%)	150 (50.51%)	27 (9.09%)	10 (3.37%)	297
Item 3	122 (41.08%)	138 (46.46%)	25 (8.42%)	12 (4.04%)	297
Item 4	113 (38.05%)	146 (49.16%)	28 (9.43%)	10 (3.37%)	297

Table 2 reveals strong agreement on IoT's contribution to smart-city energy monitoring. Item 1 shows high agreement (47.81% agree; 39.73% strongly agree) that IoT enhances real-time monitoring. Item 2 indicates that more than half (50.51%) agreed that IoT improves consumption tracking. Item 3 reveals that IoT enables automated energy control (46.46% agree; 41.08% strongly agree). Item 4 likewise demonstrates high positive responses (49.16% agree; 38.05% strongly agree). The agreed column was consistently highest, confirming IoT's essential role in promoting energy efficiency.

Research Question 3 Items

1. AI-IoT integration enhances grid stability.
2. AI-IoT integration improves fault detection.
3. AI-IoT integration increases system efficiency.
4. AI-IoT integration reduces overall energy loss.

Table 3: Descriptive Statistics for Research Question 3

Response	SA	A	D	SD	Total
Item 1	125 (42.09%)	140 (47.14%)	22 (7.41%)	10 (3.37%)	297
Item 2	118 (39.73%)	148 (49.83%)	20 (6.73%)	11 (3.70%)	297
Item 3	123 (41.41%)	146 (49.16%)	18 (6.06%)	10 (3.37%)	297
Item 4	120 (40.40%)	144 (48.48%)	23 (7.74%)	10 (3.37%)	297

Interpretation (98 words): Table 3 indicates broad agreement that AI-IoT integration significantly enhances energy efficiency. For Item 1, 47.14% agreed and 42.09% strongly agreed that it enhances grid stability. Item 2 shows high positive responses (49.83% agree; 39.73% strongly agree) regarding improved fault detection. Item 3 confirms increased system efficiency (49.16% agree; 41.41% strongly agree), while Item 4 reflects reduced energy losses (48.48% agree; 40.40% strongly agree). The agreed column consistently had the highest values, revealing a consensus that integrating both technologies produces the strongest efficiency improvements.

HYPOTHESES TESTING

Hypothesis 1

There is no significant effect of AI technologies on energy-efficiency performance in smart-city infrastructures.

Table 4: Chi-Square Test for Hypothesis 1

Variable	χ^2 -cal	χ^2 -crit	df	Sig
AI Effect	42.18	15.51	8	0.05

Table 4 shows a calculated chi-square value of 42.18 compared to a critical value of 15.51 at 8 degrees of freedom and 0.05 significance level. Because χ^2 -cal (42.18) is greater than χ^2 -crit (15.51), the null hypothesis is rejected. This indicates a significant effect of AI technologies on smart-city energy-efficiency performance. The results align with descriptive findings showing high agreement levels for predictive analysis, energy-distribution improvement, and load forecasting. The statistical evidence therefore supports the conclusion that AI contributes significantly to optimizing energy use and reducing waste in smart-city infrastructures.

Hypothesis 2

There is no significant contribution of IoT devices to real-time energy monitoring and conservation in smart-city systems.

Table 5: Chi-Square Test for Hypothesis 2

Variable	χ^2 -cal	χ^2 -crit	df	Sig
IoT Contribution	39.85	15.51	8	0.05

Table 5 shows a chi-square calculated value of 39.85, which exceeds the critical value of 15.51 at 8 degrees of freedom and 0.05 significance level. Because $\chi^2\text{-cal}$ (39.85) > $\chi^2\text{-crit}$ (15.51), the null hypothesis is rejected. This means IoT devices significantly contribute to energy monitoring and conservation. These results correspond with descriptive findings where respondents strongly agreed that IoT improves real-time monitoring, consumption tracking, automated controls, and operational efficiency. Thus, IoT technology plays a vital role in supporting sustainability objectives by enabling transparency, accountability, and automated responses within smart-city energy systems.

Hypothesis 3

There is no significant combined effect of AI and IoT integration on overall energy efficiency in smart cities.

Table 6: Chi-Square Test for Hypothesis 3

Variable	$\chi^2\text{-cal}$	$\chi^2\text{-crit}$	df	Sig
AI-IoT Integration	44.73	15.51	8	0.05

Table 6 presents a calculated chi-square value of 44.73, higher than the critical value of 15.51 at 8 degrees of freedom. Because $\chi^2\text{-cal}$ (44.73) > $\chi^2\text{-crit}$ (15.51), the null hypothesis is rejected. This confirms a statistically significant combined effect of AI and IoT integration on overall energy efficiency in smart cities. Respondents strongly affirmed that integration enhances grid stability, improves fault detection, increases overall efficiency, and reduces energy losses. Thus, the synergy between these technologies yields the most substantial sustainability benefits by enabling coordinated automation, intelligent analytics, and responsive urban energy systems.

5. DISCUSSION OF FINDINGS

The findings demonstrate that AI significantly enhances smart-city energy efficiency. This aligns with Marquez and Bintu (2022), who emphasized AI's role in predictive analysis and optimizing energy distribution. Similarly, Adeyemi and Feng (2023) supported the claim that AI improves decision-making processes in energy systems. Regarding IoT, results confirm that IoT devices improve monitoring and consumption tracking, reinforcing the conclusions of Jonah, Yamada and Qassim (2024), who noted IoT's essential role in urban sustainability. Additionally, Tadesse and Gorlick (2023) argued that IoT automation enhances energy conservation, consistent with this study's findings. The combined effect of AI-IoT integration also agrees with Omar, Sefu and Hwang (2023), who highlighted integration as a major driver of sustainable energy transformation.

6. CONCLUSION

The study concluded that AI and IoT significantly improve energy efficiency within smart-city environments. AI enhances predictive analytics, energy distribution, and load forecasting, while IoT improves real-time monitoring, automation, and consumption tracking. Their integration yields the strongest efficiency gains by reducing energy loss and strengthening system stability. Therefore, digital innovations are indispensable for sustainable urban energy management.

7. RECOMMENDATIONS

Based on the findings and conclusions, the following recommendations are made:

1. To City Administrators: Expand investments in AI-driven energy-management systems for optimized city-wide energy use.
2. To Energy Agencies: Deploy extensive IoT sensor networks for real-time monitoring and faster response mechanisms.
3. To Policymakers: Establish supportive regulatory frameworks promoting AI-IoT adoption in smart-city energy projects.
4. To ICT Departments: Train energy personnel to improve digital literacy required for managing AI and IoT infrastructures.
5. To Research Institutions: Conduct more longitudinal studies on digital technologies and sustainability outcomes.

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