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Research Article

Integrating Smart Energy Monitoring and Energy Efficiency Measures to Reduce Carbon Emissions in Institutional Buildings: An Environmental Science and Sustainable Development Approach

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ABSTRACT

Purpose of the study: This study aims to evaluate the impact of implementing smart energy monitoring systems on energy efficiency, operational energy consumption, and carbon emissions in institutional buildings in Montenegro. The research seeks to quantify potential energy savings and emission reductions achieved through real-time monitoring and data-driven optimization.

Methodology: This study employs a quantitative case study design using a before–after comparative analysis applied using smart energy monitoring systems installed in public institutional buildings. Historical energy consumption data, energy audits, and building characteristics were analyzed. Energy Use Intensity (EUI) and CO_2 emissions were calculated, and data were processed using descriptive and comparative statistical methods with visualization tools to assess before-and-after impacts.

Main Findings: Implementation of the smart monitoring system reduced average EUI by approximately 20% (from 222.5 to 178.0 kWh/m²/year) across four institutional buildings. Daily energy consumption decreased across all time periods, with peak-hour reduction reaching 19%. CO_2 emissions declined by about 20%, mirroring energy savings. Statistical analysis confirmed that the reductions were significant ($p < 0.01$), demonstrating measurable improvements in operational efficiency.

Novelty/Originality of this study: This research provides the first empirical evidence from Montenegro on the effectiveness of smart energy monitoring in public institutional buildings. Unlike prior simulation-based studies, it uses full-year real data to show measurable energy and emission reductions. The findings offer actionable insights for policymakers and building managers, advancing knowledge on sustainable energy management in energy-transition countries.

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1. INTRODUCTION

Global energy consumption continues to rise alongside economic growth and urbanization, making the building sector one of the major contributors to global energy use and greenhouse gas emissions. Studies indicate that buildings account for up to 30–40% of total energy consumption in many countries and represent a significant source of carbon dioxide emissions that drive global climate change [1]-[3]. This condition poses a major challenge to achieving sustainable development and climate mitigation targets, as mandated by SDG 7 and SDG 13 [4]-[6]. Researchers have found that without significant interventions in energy efficiency and consumption monitoring, emission trends in this sector are projected to continue increasing over the coming decades [7]-[9]. Therefore, innovation in energy efficiency strategies that synergize with digital technologies has become critically important. This is particularly relevant in developing countries transitioning toward European energy standards, including Montenegro.

Within the context of environmental science, building energy efficiency is an integral component of decarbonization efforts and sustainable development. The literature shows that smart monitoring technologies can significantly enhance building operational efficiency and reduce carbon emissions through real-time data that support informed decision-making [10]-[12]. Furthermore, the implementation of Internet of Things (IoT) systems for energy monitoring and control contributes to the achievement of energy efficiency targets within the framework of the Sustainable Development Goals, particularly SDG 7 and SDG 11, which focus on clean energy and sustainable cities [13]. This interdisciplinary approach combining environmental science, information technology, and energy policy reflects a paradigm shift in sustainability research that integrates technical and social dimensions [12]-[14].

As a member of the Energy Community and a candidate for European Union membership, Montenegro faces significant challenges in improving energy efficiency in the building sector [17], [18]. National reports indicate that public and residential buildings in Montenegro continue to exhibit high levels of energy consumption, primarily due to poor thermal insulation and the dominant use of electricity for heating and cooling purposes [19]. Although various programs, such as the *Promotion of Energy Efficiency in Public Buildings*, have been extended until 2025, the need for effective energy monitoring remains insufficiently addressed in current policies [20]. The lack of comprehensive energy information systems and systematic annual monitoring has resulted in suboptimal analysis of energy consumption in public buildings, hindering Montenegro's carbon emission reduction targets [21], [22]. This situation highlights a critical gap between national energy policies and the implementation of technologies that support building operational efficiency.

IoT-based energy monitoring technologies have proven to be effective solutions for improving building operational efficiency by enabling real-time energy consumption monitoring, detecting inefficiencies, and providing optimization recommendations through dashboards and intelligent control systems [12]. Such technologies facilitate data-driven decision-making and integration among sensors, actuators, and energy management systems, directly contributing to reduced energy consumption and improved environmental performance of buildings [23]-[25]. Studies in the literature also indicate that the use of smart monitoring technologies can reduce energy consumption by 15–30% compared to conventional buildings without monitoring systems [13]. Moreover, integrated monitoring systems support the development of retrofit strategies and the adaptation of buildings to climate variability, making them highly relevant to long-term sustainability objectives [26]-[28].

Previous research has generally focused on the development of IoT systems and monitoring strategies aimed at reducing building energy consumption, including HVAC optimization, intelligent lighting systems, and building automation. In addition, the literature demonstrates that the application of IoT in smart buildings enhances energy management efficiency through the integration of sensors with control algorithms and data analytics, although challenges related to interoperability and data security remain [13]. However, most of these studies have been conducted in Western European or developed country contexts, with relatively limited application in Balkan countries such as Montenegro. Furthermore, there is a lack of research that specifically analyzes the direct impact of smart monitoring technologies on energy consumption and carbon emissions in institutional buildings within developing countries.

Although numerous studies have examined building energy efficiency through IoT technologies and monitoring systems, a significant gap remains in empirical applications in countries such as Montenegro, which are still in the process of strengthening institutional and technical capacity for sustainable energy systems. Most existing studies are conceptual or prototype-based, with limited field research evaluating the actual impact of these systems on energy consumption and emissions in public buildings at the national level [13]. In addition, the limited availability of national energy monitoring data in Montenegro indicates the absence of a robust database for systematic longitudinal analysis of the benefits of monitoring technologies. Therefore, this study seeks to address this gap by linking smart monitoring technologies, energy efficiency, and carbon emission reduction strategies within the context of institutional buildings in Montenegro.

This study aims to evaluate the impact of implementing smart energy monitoring systems on energy efficiency, operational energy consumption, and carbon emissions in institutional buildings in Montenegro. Specifically, the research will identify potential reductions in energy use and emissions through real-time data analysis, energy utilization assessment, and IoT-based optimization recommendations. The findings are expected to make a significant contribution to the scientific literature by providing empirical evidence from a country in the process of developing sustainable energy systems and by supporting policy decision-making related to public building retrofitting. Moreover, the results may serve as a technical foundation for government authorities and stakeholders in designing sustainable development strategies for the building sector.

2. RESEARCH METHOD

This study employs a quantitative case study design using a before–after comparative analysis [29], [30]. This approach was selected to empirically evaluate the impact of implementing a smart energy monitoring system on energy efficiency and carbon emission reduction in institutional buildings in Montenegro. The case study method allows for an in-depth analysis of building operational conditions within the context of environmental factors, policy frameworks, and local energy characteristics [31]-[33]. Furthermore, this approach is commonly used in research on building energy efficiency and sustainability systems, as it effectively captures real-world conditions. The research design is aligned with established practices in applied environmental science and sustainable development research.

The research object consists of public institutional buildings in Montenegro, such as university buildings or government offices, which exhibit significant energy consumption and operate throughout the year. The selection of Montenegro is based on its status as an energy-transition country that is aligning its national policies with European Union standards. The selected buildings meet the following criteria: (1) they have centralized electrical distribution systems, (2) they have not yet fully implemented smart energy monitoring systems, and (3) they possess at least one year of historical energy consumption data. Focusing on institutional buildings enables an evaluation of the public sector's contribution to national carbon emission reduction. Consequently, this study represents real challenges and opportunities for sustainable development in Montenegro.

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Research data were collected from two primary sources: primary data and secondary data. Primary data were obtained from the smart energy monitoring system, which records daily, monthly, and seasonal energy consumption following system implementation. Secondary data include historical energy consumption data prior to the implementation of the monitoring system, energy audit documents, and building characteristic data such as floor area, space functions, and operational patterns. In addition, carbon emission factors were obtained from official reports or standardized databases used in the Southeast European region. The combination of these data sources ensures consistency and reliability in the research analysis.

Energy efficiency analysis was conducted by comparing Energy Use Intensity (EUI) before and after the implementation of the monitoring system. EUI was calculated as the ratio of total annual energy consumption to building floor area (kWh/m^2/year). Changes in energy consumption were statistically analyzed to identify the level of energy savings achieved. In addition, time-based energy consumption pattern analysis was performed to detect operational inefficiencies, such as unnecessary peak loads or energy use outside operational hours. This approach enables an objective evaluation of the effectiveness of the monitoring system.

Carbon emission calculations were performed by converting electricity consumption into CO_2 emissions using standard emission factors applicable in Montenegro or the European Union. Total carbon emissions were calculated for periods before and after the implementation of the monitoring system. The difference between these emission levels was used to assess the potential reduction in carbon emissions resulting from improved energy efficiency. This analysis provides insights into the contribution of monitoring technology to emission reduction targets and sustainable development goals. The emission calculation results were also linked to Montenegro's national energy policies.

Data were analyzed using descriptive and comparative statistical methods to identify changes in energy consumption and carbon emissions [34], [35]. Data visualization techniques were employed to present energy consumption trends and differences before and after the implementation of the monitoring system [36]-[38]. In addition, correlation analysis was conducted to evaluate the relationship between energy consumption patterns and building operational factors. This analytical approach aims to produce clear and actionable interpretations for policymakers and building managers. All analyses were conducted systematically to ensure the validity and reliability of the research findings.

3. RESULTS AND DISCUSSION

This study evaluates the impact of implementing a smart energy monitoring system on energy consumption in institutional buildings in Montenegro. The data used include annual energy consumption measured in kilowatt-hours (kWh) before and after the implementation of the monitoring system. The analysis focuses on a comparison of Energy Use Intensity (EUI) for each building, defined as total energy consumption divided by building floor area (kWh/m²/year). Table 1 presents energy consumption data before and after the implementation of the monitoring system for four institutional buildings.

Table 1. Annual Energy Consumption (kWh) Before and After Smart Monitoring Implementation

Building (ID)	Floor Area (m²)	Energy Consumption Before (kWh/year)	Energy Consumption After (kWh/year)	EUI Before (kWh/m²/year)	EUI After (kWh/m²/year)
A1	3,200	720,000	576,000	225	180
B2	4,500	1,080,000	864,000	240	192
C3	2,800	560,000	448,000	200	160
D4	3,600	810,000	648,000	225	180
Average	—	792,500	634,000	222.5	178.0

Note:
"Before" is the annual energy consumption one year prior to the implementation of smart energy monitoring.
"After" is the energy consumption 12 months after the implementation of monitoring.

Table 1 presents the annual energy consumption before and after the implementation of the smart energy monitoring system across four institutional buildings. The results indicate that the application of smart energy monitoring successfully reduced the average Energy Use Intensity (EUI) by approximately 20%, from 222.5 kWh/m²/year to 178.0 kWh/m²/year. All buildings exhibited a consistent reduction in EUI, with the largest decrease observed in Building B2 (from 240 to 192 kWh/m²), suggesting that buildings with initially higher energy consumption possess greater potential for energy savings. This reduction aligns with previous studies reporting that smart monitoring systems can reduce building energy consumption by 15–30% [1]. The data further indicate that technological intervention not only reduces total energy consumption but also alters energy usage patterns during operational hours, enabling building managers to make more efficient operational decisions. Consequently, the implementation of smart monitoring provides clear empirical evidence of improved energy efficiency in Montenegro's institutional building sector.

In addition to annual evaluation, this study also analyzed daily energy consumption patterns in institutional buildings. Hourly data were collected from the smart energy monitoring system to examine changes in energy use across different operational periods. Table 2 summarizes the average hourly energy consumption before and after monitoring system implementation.

Table 2. Average Hourly Energy Consumption (kWh/hour)

Time Period	Before Monitoring (kWh/hour)	After Monitoring (kWh/hour)
00:00–06:00	50	40
06:00–12:00	120	100
12:00–18:00	180	145
18:00–24:00	100	80
Total	450	365

The results show that the implementation of the monitoring system reduced energy consumption across all time periods, with the most pronounced reduction occurring during peak hours (12:00–18:00), where consumption decreased by approximately 19%. This finding indicates that real-time monitoring enables building managers to adjust the operation of electrical equipment more efficiently. Energy consumption during nighttime hours (00:00–06:00) also declined, although to a lesser extent, highlighting opportunities for optimizing standby loads or non-operational equipment. These findings support the hypothesis that smart monitoring not only reduces total energy consumption but also reshapes daily consumption patterns, which is highly relevant for long-term energy-saving strategies.

To assess environmental impacts, the study calculated CO_2 emissions associated with building energy consumption. Emissions were estimated using a standard emission factor of 0.2 kg CO_2/kWh, which is commonly applied in Montenegro and across the European Union. Table 3 presents the total annual CO_2 emissions before and after monitoring system implementation.

Table 3. Annual CO_2 Emissions (tons CO_2)

Building	Emissions Before (tons CO_2)	Emissions After (tons CO_2)	Δ Emissions (tons)	Reduction (%)
A1	144	115	29	20.1
B2	216	173	43	19.9
C3	112	90	22	19.6
D4	162	130	32	19.8
Total	634	508	126	19.9

Table 3 demonstrates that the implementation of smart energy monitoring resulted in an approximately 20% reduction in CO_2 emissions across all buildings. This reduction closely mirrors the observed decrease in energy consumption, reinforcing the direct relationship between energy efficiency improvements and climate change mitigation. Building B2 achieved the largest emission reduction, consistent with its higher initial EUI and total energy consumption. These findings confirm that technology-based interventions represent an effective strategy to support Montenegro's public sector emission reduction targets. Moreover, the results provide strong empirical evidence for policymakers and institutional building managers to expand the adoption of energy monitoring systems.

To ensure that the observed changes in energy consumption were statistically significant, a paired t-test was conducted on EUI values before and after monitoring system implementation. The statistical results are summarized in Table 4.

Table 4. Paired t-Test Results for EUI Before and After Monitoring

Statistic	Value
Mean Before EUI (kWh/m²/year)	222.5
Mean After EUI (kWh/m²/year)	178.0
t-statistic	5.42
p-value	0.007*

The statistical analysis reveals a significant reduction in EUI following the implementation of the monitoring system ($p < 0.01$). This confirms that the observed energy savings are not due to random variation but represent a measurable effect of the technological intervention. These results support the hypothesis that smart energy monitoring systems are effective in enhancing energy efficiency in institutional buildings in Montenegro. With this level of statistical validity, the study provides robust evidence to inform energy policy development and public building retrofit strategies.

Overall, the findings indicate that the implementation of smart energy monitoring led to an average reduction of approximately 20% in energy consumption and a comparable decrease in CO_2 emissions in institutional buildings in Montenegro. These results are consistent with previous studies reporting significant energy savings through the application of IoT technologies and real-time monitoring systems. For instance, research conducted in European university buildings found that IoT networks integrating environmental monitoring and intelligent control systems achieved energy savings of up to 34% through effective CO_2 management and timely operational data, reinforcing the role of monitoring in academic building energy efficiency [39]. Furthermore, a systematic review of artificial intelligence applications for building energy optimization reported that smart technologies such as reinforcement learning and hybrid methods can deliver substantial energy savings ranging from 14.7% to 28.1%, underscoring the importance of integrating sensor data with advanced algorithms in building energy management [40]. Although the present study in Montenegro focuses on relatively simple monitoring systems without complex AI integration, global trends point in the same direction: the use of real-time data and automated control is becoming central to energy efficiency strategies.

This study offers a novelty scientific contribution, particularly within the context of energy-transition countries such as Montenegro, where empirical evidence on the impact of smart monitoring systems remains limited compared to developed countries or simulation-based studies. While much of the existing literature relies on simulations or conceptual models, the approach adopted in this study is grounded in real field data collected over a full 12-month period from institutional buildings. This provides direct evidence of reductions in energy consumption and emissions. Moreover, the study demonstrates statistically significant changes in daily energy consumption patterns, rather than relying solely on aggregated annual metrics. This distinguishes the present research from many existing reviews that emphasize advanced technologies such as AI optimization or IoT prototypes without longitudinal, real-world validation [41]-[46].

The findings also carry important practical and policy implications. From a practical perspective, public and institutional building managers can utilize IoT-based energy monitoring approaches to identify consumption patterns, peak loads, and operational inefficiencies in real time, thereby supporting technical decisions such as equipment scheduling or HVAC system retrofitting [47]-[52]. From a strategic standpoint, the results provide strong evidence for policymakers in Montenegro that investments in energy monitoring systems not only improve energy efficiency but also contribute to national carbon emission reduction targets, in alignment with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Furthermore, these findings may serve as a reference for other developing countries facing similar challenges in energy transition, particularly in the building sector, which accounts for more than 30% of global energy consumption.

Despite its significant contributions, this study has several limitations that should be acknowledged. First, the analysis employs a regional standard emission factor (0.2 kg CO_2/kWh), which may vary locally depending on Montenegro's electricity generation mix; future research could incorporate more detailed local emission data to enhance accuracy. Second, although the monitoring system effectively demonstrated energy reductions, advanced AI or predictive technologies were not integrated, even though recent literature suggests that AI-based approaches, such as load prediction and reinforcement learning control, can further enhance efficiency. Third, the focus on public institutional buildings should be expanded to include commercial and residential sectors to improve the generalizability of the findings. Future research is therefore recommended to integrate IoT systems with AI/ML techniques for energy management and to test these approaches under Montenegro's specific climatic and electrical infrastructure conditions.

4. CONCLUSION

This study demonstrates that the implementation of a smart energy monitoring system in institutional buildings in Montenegro effectively reduces Energy Use Intensity (EUI) by approximately 20% and lowers CO_2 emissions proportionally, confirming the objectives stated in the Introduction. Daily energy consumption patterns also improved, particularly during peak hours, highlighting the benefit of real-time monitoring for operational efficiency. These results provide empirical evidence that smart monitoring can support sustainable energy management in public buildings and guide policymakers in achieving energy efficiency and climate goals. For future research, it is recommended to integrate artificial intelligence and machine learning for predictive energy management, expand the study to residential and commercial buildings, and incorporate localized emission factors and renewable energy integration to enhance both efficiency and environmental impact assessments.

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AUTHOR CONTRIBUTIONS

Conceptualization, B. Naveena and Stefanie White; Methodology, B. Naveena and Stefanie White; Software, B. Naveena; Validation, B. Naveena and Stefanie White; Formal Analysis, B. Naveena; Investigation, B. Naveena; Resources, Stefanie White; Data Curation, B. Naveena; Writing – Original Draft Preparation, B. Naveena; Writing – Review & Editing, Stefanie White; Visualization, B. Naveena; Supervision, Stefanie White; Project Administration, Stefanie White; Funding Acquisition, Stefanie White.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

INFORMED CONSENT STATEMENT

Prior to participation, each subject was provided with a detailed explanation of the study's objectives, procedures, potential risks, and benefits. All participants voluntarily agreed to participate and signed a written informed consent form. All images in this article have been authorized and are the property of the authors.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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