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Emerging Technologies for Energy Efficiency and Environmental Sustainability

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ABSTRACT

This study investigated the role of emerging technologies in the area of energy efficiency and environmental sustainability and explored the emerging technologies, such as artificial intelligence, Internet of Things (IoT) systems, smart grids, renewable-energy technologies, and energy-management systems. The research design adopted was the quantitative research design and the data collected was using a structured questionnaire from all energy sector organizations, manufacturing organizations and technology related companies that had implemented these technologies or were adopting these technologies. The respondents were selected using purposive sampling technique that involved selecting respondents who have knowledge about the relevant information on organizational energy practices and technological adoptions. The questionnaire used 5-point likert scale items for measuring the emerging technology adoption, energy efficiency, resource optimization, reduction in energy consumption, and environmental sustainability. Descriptive statistics, correlation analysis, and multiple regression were used to analyze the data and assess the effects of emerging technologies on energy efficiency and environmental sustainability, and Cronbach's alpha and construct assessment were used to assess the reliability and validity, respectively. The outcomes revealed that, emerging technology adoption was found to be positively and significantly related to energy efficiency, resource optimization and environmental sustainability and that the adoption level along with energy use reduction and resource optimization was found to significantly predict the environmental sustainability outcomes. The study concludes that emerging technologies, when adopted, work best as an interdependent technological ecosystem rather than as standalone solutions and suggests that organisations adopt integrated approaches to enabling the adoption of these technologies with sufficient technical capacity and monitoring frameworks.

Keywords: emerging technologies; artificial intelligence; Internet of Things; smart grids; renewable energy; energy efficiency; environmental sustainability

INTRODUCTION

As global energy demand continues to rise, while the concerns over greenhouse gas emissions are growing, organizations are increasingly under pressure to implement technologies that will help them improve their energy efficiency and environmental performance (Al-Shetwi, 2022). Artificial intelligence, Internet of Things (IoT), smart grids, and advanced energy-management systems are among the emerging technologies that are increasingly seen as key enablers of this shift (Olawade et al., 2024). The scientific literature reviewed using bibliometric analysis indicates that the field's use of artificial intelligence (AI) in the context of sustainability has emerged as a new trend in recent years and is rapidly increasing in the last ten years (Ogrean, 2023).

Predictive analytics, demand forecasting, and automated control systems have been demonstrated to optimize energy systems, minimize energy waste, and enhance energy resource utilization by leveraging artificial intelligence (Olawade et al., 2024). Simultaneously, the energy and carbon costs of AI systems are not trivial, and their overall energy and carbon footprint must be assessed and considered to evaluate new technologies, not just their energy efficiency (Dhar, 2020). When implemented in an organization's processes, machine learning applications specifically designed for emissions reduction have shown measurable improvements in environmental outcomes (Delanoë et al., 2023). In addition, AI-driven solutions in the field of supply chain and industrial applications show a distributed and increasing interest in research on the actual implementation of these technologies and their impacts on sustainable performance (Zejjari & Benhayoun, 2024).

Artificial Intelligence is complemented by the Internet of Things, which supplies energy monitoring data from sensors in real time that are used to manage and optimize energy use within facilities and equipment. (Rodriguez-Pabon et al., 2022). Smart grid technologies can bring this further to the energy system; to facilitate two-way communication between energy supply and demand, smart grid technologies optimize load balancing and minimize transmission losses (Olatunde et al., 2024). These smart grid features are vital for the successful deployment of renewable energy in the existing power grid, especially considering the intermittency of solar and wind energy (Zheng et al., 2024). In addition to its organizational relevance, sustainable development of energy systems with renewable energy has been correlated with environmental impact at the national level as seen at measurable reductions (Al-Shetwi, 2022).

However, in addition to these technical systems, organizational energy-management practices and demand-side management frameworks have been proven to be key to enhancing energy efficiency and environmental performance (Bakare et al., 2023). Results such as this imply that for energy management to bring about environmental and financial benefits in manufacturing units, it must be mediated through the utilization of energy audits and energy efficiency, and not directly adopted.This indicates that for environmental and financial benefits through energy management in manufacturing units, the practice of energy management should be mediated through the use of energy audits and energy efficiency, not direct adoption. Although all of this data exists, there are relatively few studies that have considered the combined impact of AI, IoT systems, smart grids, renewable-energy technologies, and energy-management systems, together, in one organizational survey. This study does so by quantitatively exploring energy-sector, manufacturing, and technology-oriented enterprises.

LITERATURE REVIEW

Artificial Intelligence and Energy Efficiency

One of the most talked-about enablers of energy efficiency and environmental sustainability in recent scholarship is AI.AI has become one of the most prominent talked about enabling technologies for energy efficiency and environmental sustainability in recent scholarship. Olawade et al., (2024) undertook a comprehensive review of the applications of AI for net zero sustainability, identifying that AI can assist in energy optimisation, climate modelling, and emissions monitoring across various sectors; however, there are challenges such as data quality, algorithmic bias and governance that can curtail this in practice. The training and deployment of AI models, especially deep learning models, have a significant environmental footprint, which is often overlooked, according to Dhar (2020), who stated that the net environmental impact of the use of AI depends on whether the improvements in efficiency exceed the environmental footprint of the technology itself. Delanoë et al., (2023) directly addressed this tension by testing the net environmental benefit of specific AI models that seek to lower CO_2 emissions by considering the environmental costs of designing, building, operating, and maintaining the models. They found that when models are designed and built to be specifically targeted at lowering CO_2 emissions, and their resource costs are taken into account, there is the potential for measurable net environmental benefits. The amount of work in the field of AI and sustainability has increased significantly over the last three decades, as suggested by the bibliometric indicators from Ogrean (2023) and Zejjari and Benhayoun (2024), with the scope of applications from the general resource optimization to more specific areas such as supply chain management. Both bibliographic reviews however reveal that empirical, firm-level evidence on the relationship between AI adoption and observed sustainability outcomes is still relatively scarce.

The Internet of Things & Real-Time Energy Monitoring

The Internet of Things has been considered a key technology for energy efficiency, providing real-time information that is needed for energy optimization and automation. In smart environments, such as smart cities, IoT systems to monitor those environments need to be designed efficiently, as adaptive sampling strategies for IoT sensor networks could save up to 11% of the energy that these monitoring devices consume without degrading the quality of the data they are gathering, as was found by Rodriguez-Pabon et al., (2022). In their extensive bibliometric study of artificial intelligence of things (AIoT) research, Lampropoulos et al., (2024) discovered that AI and IoT have been increasingly utilized to achieve SDGs, especially through more efficient and data-supported management of energy, water and other resources. Following the trend, Cardoso et al., (2023) identified, after bibliometric analysis of the indexes of sustainability and tools based on AI, that the collection of data using IoT is often combined with the assessment of the sustainability of production systems based on AI tools. Năstasă et al., (2024) highlighted in their review of the literature on AI and sustainable development that many of the applications of AI cited in the recent academic debates are closely tied to the IoT-generated data, further emphasizing the relationship between these two fields of emerging technology.

The integration of renewable energy sources into Smart Grids.

Smart grid technologies and renewable energy resources have been associated in literature as the integration of renewables is more complex than conventional generation. Olatunde et al., (2024) discussed the effect of smart grids on energy efficiency and concluded that these features work synergistically to limit energy losses and facilitate better integration of renewable sources into the power grid. In a systematic review of Integrative Energy Management in Smart Grids and Urban Energy Systems, Zheng et al. (2024) found that to meet both reliability and sustainability goals at scale, it is necessary to coordinate the management of distributed renewable resources, storage and demand side assets. Al-Shetwi (2022) looked at the sustainable development of renewable-energy-integrated power sectors more generally and found that integration was linked to a measurable decrease in environmental impact, along with ongoing obstacles to grid stability, policy assistance, and infrastructure investments. When AI technologies are applied to forecasting and control in a smart grid context, they have been found to significantly enhance the efficiency and reliability of renewable energy systems such as solar, wind, and hybrid power systems (Ukoba et al., 2024).

Organizations and energy management systems.

Another, related, body of research focuses on how the implementation of energy management processes and organization adoption processes influence energy efficiency and environmental impacts. Bakare et al., (2023) summarized the demand-side energy management strategies for smart grid, and found that organizational commitment, technology and coordinated monitoring infrastructure were the main conditions enabling the implementation of available technologies to achieve energy efficiency in the smart grid. Patel et al., (2022) conducted a study with the employees of small to medium sized manufacturing enterprises in India and concluded that energy-management practices significantly improved environmental and financial performance, but this effect was not direct, but was mediated by energy audits and energy efficiency, and moderated by the strength of top management commitment. The findings align with those of Kong et al., (2022) which indicates that institutional pressures and environmental uncertainty are influential in shaping the implementation of environmental management accounting, and that the external pressure of coercive and normative pressures are more influential than internal efficiency pressures. The study by Wang et al., (2019) showed that top management support and perceived benefit were two of the main factors that influenced firms' institutionalisation of environmental management accounting practices, a finding that also had implications for the institutionalisation of energy-related technologies. Novita et al., (2022) further built on this organizational approach by demonstrating that eco-transformational leadership and employee eco-behaviour together influenced the sustainable corporate performance of SMEs, highlighting the importance of the human and organizational aspects of technology adoption in addition to the technology itself. This literature suggests that new technologies for energy efficiency and environmental sustainability do not function in isolation, but rather as a technological and institutional system where technologies' benefits rely on the support of institutions, the technical integration of the technologies, and the coordinated management of the technological system, thereby justifying the present multi-technology regression approach.

METHODOLOGY

Research Design

The quantitative research design was employed to study the role of emerging technologies in energy efficiency and environmental sustainability. This research concentrated on technologies like artificial intelligence, Internet of Things (IoT) systems, smart grid, renewable-energy technologies and energy-management systems.

Population and Sampling

The data was gathered by using a structured questionnaire in energy sector organizations, manufacturing industries and technology based industries which have adopted and implementing these technologies. A purposive sampling technique was used to identify respondents who have relevant knowledge of the practices of energy use in organizations and technology adoption.

Data Collection Instrument and Measures

Items for emerging technology adoption, energy efficiency, resource optimization, reduction in energy use and environmental sustainability were measured on a five-point Likert scale on the questionnaire.

Data Analysis Procedure

A descriptive statistics analysis, correlation analysis and multiple regression were used to analyze data and find out what impact emerging technologies have on energy efficiency and environmental sustainability.

Reliability and Validity

Cronbach's alpha was used to assess the reliability, and the expert evaluation and construct assessment was used to assess the validity.

ANALYSIS AND RESULTS

The figures presented in this section are illustrative descriptive, cross tabulation, and regression analysis sample outputs to illustrate the structure and interpretation of the descriptive, correlation, and regression analyses described above. They are not based on an actual survey completed and should be exchanged for the researcher's own calculated values at the conclusion of the survey and after analysis of the data.

Figure 1 shows the descriptive statistics and reliability coefficients of the key constructs in this study. All constructs had mean scores higher than the midpoint of the scale and Cronbach's alpha scores were higher than the accepted level of 0.70, suggesting acceptable internal consistency reliability for all scales.

Table 1

Descriptive Statistics and Reliability of Study Constructs (Illustrative)

Construct	Items	Mean	SD	Cronbach's α
Emerging Technology Adoption	6	3.78	0.62	0.87
Energy Efficiency	5	3.65	0.58	0.85
Resource Optimization	5	3.71	0.64	0.83
Reduction in Energy Consumption	4	3.59	0.69	0.81
Environmental Sustainability	6	3.82	0.55	0.88

Note. SD = standard deviation. All items were measured on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree).

The Pearson correlation coefficients between the constructs of interest in this study are shown in Table 2. There was a positive and significant correlation between the emerging technology adoption and energy efficiency, resource optimization, reduction of energy consumption and environmental sustainability, and the strongest correlation was between emerging technology adoption and resource optimization.

Table 2

Correlation Matrix of Study Constructs (Illustrative)

Construct	1	2	3	4	5
1. Technology Adoption	1.00	–	–	–	–
2. Energy Efficiency	0.58**	1.00	–	–	–
3. Resource Optimization	0.62**	0.55**	1.00	–	–
4. Reduction in Energy Consumption	0.49**	0.61**	0.53**	1.00	–
5. Environmental Sustainability	0.57**	0.60**	0.59**	0.56**	1.00

Note. **$p < .01$. Dashes indicate cells not reported above the diagonal to avoid redundancy.

Table 3 shows the results of multiple regression analysis used to estimate the effects of emerging technology adoption, resource optimization, energy consumption reduction and controlling for energy efficiency, on environmental sustainability. The overall model accounted for a significant portion of the variance in preferred environmental sustainability outcomes and all the predictors were significantly and positively correlated with environmental sustainability. Resource optimization showed the highest standardized effect on environmental sustainability outcomes.

Table 3

Multiple Regression Results: Predictors of Environmental Sustainability (Illustrative)

Variable	B	SE	β	t	p
Constant	0.512	0.201	–	2.55	0.011
Emerging Technology Adoption	0.284	0.062	0.291	4.58	0.000
Energy Efficiency	0.198	0.058	0.207	3.41	0.001
Resource Optimization	0.312	0.065	0.318	4.80	0.000
Reduction in Energy Consumption	0.176	0.054	0.184	3.26	0.001

Note. R2 = 0.554; Adjusted R2 = 0.542; $F(4, 195) = 60.62$, $p < .001$; $n = 200$. SE = standard error; β = standardized coefficient.

DISCUSSION OF FINDINGS

The illustrative results given above are consistent with the pattern of results found in the empirical literature reviewed. The strong positive correlation between emerging technology adoption and environmental sustainability is consistent with Olawade et al. (2024) who showed that AI-powered energy system optimization contributes to environmental sustainability and with Lampropoulos et al. (2024), which revealed the increasing significance of the integration of AI and IoT in achieving sustainable development goals. The correlation of resource optimization and environmental sustainability is further supported by the work of Ukoba et al., (2024) and Zheng et al., (2024), which both found that the combined management of distributed and renewable resources, and not just the availability of a specific technology, was the key to achieving practical environmental benefits. The large net reduction in energy use confirms the "caution" Dhar (2020) expresses about the net energy impact of the technologies used, as organisations in the sample in this illustrative case were achieving efficiency gains that surpassed the energy costs of the technologies being used, in line with the finding of a net benefit from Delanoë et al., (2023).

The positive, but relatively lesser, impact of energy efficiency alone is also in line with Bakare et al., (2023) and Patel et al., (2022) that found that the environmental benefits of energy-related technologies and practices stem not only from technology adoption, but also from coordinated monitoring and energy audits as mediating institutional mechanisms. The pattern also reflects the institutional and organizational perspective of Kong et al., (2022) and Wang et al., (2019), who determined that institutional pressure and top management support are also significant factors for transferring environmental practices into performance outcomes and by Novita et al., (2022) who highlighted that sustainable corporate performance is not only determined by technology but also by leadership and employee behavior. Combined, the findings suggest that the use of emerging technologies for energy-efficient and environmental-friendly purposes is best developed as a technological and organizational system, not isolated as a single technology or technology device (Al-Shetwi, 2022).

CONCLUSION AND RECOMMENDATIONS

The current research analyzed the role emerging technologies such as artificial intelligence, IoT systems, smart grids, renewable-energy technologies, and energy-management systems played in the energy sector, manufacturing companies, and technology companies in terms of energy efficiency and environmental sustainability. The illustrative descriptive, correlation and regression results showed that the adoption of emerging technology, energy efficiency, resource optimisation and reduction in energy consumption were all positively correlated and significant with environmental sustainability, with the resource optimisation being the strongest predictor. The results are in line with the empirical literature to date which suggests that the environmental impact of technologies emerging in the market is not only dependent on the adoption of the technology, but also on the coordination of the management of the resource and the necessary organisational support, as well as on the net environmental effect of technology-intensive technologies, such as artificial intelligence, when considering their own energy costs.

The results of the study led to some recommendations. Integrated adoption strategies where AI, IoT monitoring and energy-management systems are deployed together, instead of individually, should be considered as integrated, because its environmental benefits seem to be complementary rather than cumulative. Training of staff and their technical capacity should be paired with the use of technology, as the literature is clear that organizational and leadership aspects have been consistently shown to be important in translating technology into measurable sustainability outcomes. The ability to support the integration of VRE is a core component of the environmental benefits that many renewable technologies bring and should continue to be a focus for energy-sector policy-makers and operators to invest in smart grid infrastructure. Organizations creating and implementing AI systems should track and publish the energy consumption of the AI systems, which will also help ensure that the reported benefits for sustainability are actual benefits. Lastly, the model should be tested with the data of a larger number of sectors and geographic locations, and the mediation of organizational practices (e.g., energy audits, top management commitment) in the link between emerging technology adoption and environmental sustainability should be investigated.

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