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IoT-Based Renewable Energy Model for Energy Efficiency in Smart Campus Ecosystems

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ABSTRAK

Transformasi energi menuju sistem berkelanjutan menjadi prioritas strategis di kawasan ASEAN, khususnya di lingkungan pendidikan tinggi yang berperan penting dalam riset dan inovasi teknologi hijau. Program Kreativitas Dosen (PKM) internasional ini bertujuan mengembangkan model bisnis energi terbarukan berbasis Internet of Things (IoT) untuk meningkatkan efisiensi energi sekaligus menciptakan nilai ekonomi bagi kampus dan masyarakat sekitar. Kegiatan ini merupakan kolaborasi antara Universiti Pertahanan Nasional Malaysia (UPNM) dan Universiti Kuala Lumpur (UniKL) yang dirancang sebagai pilot project smart campus. Fokus utama meliputi pengumpulan data energi secara real-time, analisis pola konsumsi listrik, serta penerapan sistem demand response berbasis IoT. Metodologi kegiatan mencakup survei potensi energi terbarukan, perancangan smart energy dashboard terintegrasi sensor daya, analisis bisnis dan simulasi revenue sharing antar pemangku kepentingan, serta evaluasi keberlanjutan dan replikasi model di kampus ASEAN lainnya. Hasil yang diharapkan adalah model integratif yang mampu menurunkan konsumsi energi hingga 20% serta memperkuat kapasitas dosen dalam riset terapan, kolaborasi internasional, dan inovasi teknologi hijau.

ABSTRACT

The transition toward sustainable energy systems has become a strategic priority in the ASEAN region, particularly within higher education institutions that play a crucial role in advancing research and green technology innovation. This international Lecturer Creativity Program (PKM) aims to develop an Internet of Things (IoT)–based renewable energy business model to improve energy efficiency while creating economic value for campus areas and surrounding communities. The collaborative project between Universiti Pertahanan Nasional Malaysia (UPNM) and Universiti Kuala Lumpur (UniKL) is designed as a smart campus pilot project. It focuses on real-time energy data acquisition, analysis of electricity consumption patterns, and the implementation of IoT-based demand response systems. The methodology includes a renewable energy potential assessment, the design and deployment of a smart energy dashboard integrated with power sensors, business analysis and revenue-sharing simulation among stakeholders, and sustainability evaluation with replication potential across ASEAN campuses. The program is expected to deliver an integrative model capable of reducing energy consumption by up to 20% while strengthening lecturers' capacity in applied research, international collaboration, and green technology innovation.

INTRODUCTION

Global energy demand continues to increase in parallel with economic growth, rapid urbanization, and accelerated technological development. This condition exerts significant pressure on natural resources and intensifies greenhouse gas emissions that contribute to global climate change. Consequently, the transition toward more efficient, clean, and sustainable energy systems has become a strategic imperative for countries in the ASEAN region (Szpilko, 2024; ASEAN Centre for Energy, 2023).

In this context, higher education institutions play a critical role in promoting the innovation and adoption of green technologies through applied research and community engagement activities. Universities are not only major energy consumers, but also function as living laboratories capable of testing and validating digital-based sustainable energy solutions (Rehman, 2023; Ball, 2024). The concept of a smart campus has emerged as an ideal model for integrating Internet of Things (IoT) technologies, renewable energy systems, and data-driven management into a unified and efficient ecosystem.

Despite the growing number of renewable energy initiatives implemented across universities, significant challenges remain in terms of energy efficiency and the financial sustainability of green energy projects. Many systems fail to progress beyond the pilot phase due to the absence of viable business models that support long-term economic sustainability (Zhang & Chen, 2022; ESIG, 2025). Therefore, integrating technological innovation with sustainable business models has become an urgent necessity to ensure lasting impact.

IoT technology offers substantial opportunities to support intelligent and adaptive energy management. Through interconnected sensors, communication networks, and cloud-based analytics platforms, IoT systems enable real-time energy consumption monitoring, load pattern analysis, and optimized power distribution (Ball, 2024; Khan et al., 2024). Beyond technical efficiency, these data-driven capabilities facilitate the development of evidence-based energy policies.

Previous studies have demonstrated that IoT-based energy management systems enhance grid efficiency and reliability through smart grid concepts. Rehman (2023) highlights that integrating IoT with renewable energy sources can reduce energy losses by 15–25% and significantly improve demand response performance. However, most existing studies emphasize technical aspects, while limited attention has been given to integrating business frameworks and energy governance within campus environments.

Accordingly, this paper proposes the development of an IoT-based renewable energy business model that not only prioritizes energy efficiency but also generates economic value through inter-university collaboration. The partnership between Universiti Pertahanan Nasional Malaysia (UPNM) and Universiti Kuala Lumpur (UniKL) serves as a concrete example of how higher education institutions can act as catalysts for regional smart energy innovation (Khan et al., 2024; ASEAN Centre for Energy, 2023). The proposed model emphasizes synergy among digital technology, operational efficiency, and economic sustainability.

Specifically, this study aims to: (1) design and implement an IoT-based energy management system for real-time monitoring and control of electricity consumption; and (2) develop a replicable business model capable of enhancing economic value, improving energy efficiency, and supporting the operational sustainability of campuses across the ASEAN region. The findings are expected to contribute to the achievement of the Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action) (Szpilko, 2024; Zhang & Chen, 2022).

The integration of Internet of Things (IoT) technology into energy systems has transformed conventional energy management paradigms into intelligent and adaptive frameworks. IoT enables real-time data acquisition from distributed sensors across power networks, allowing operators to monitor and control energy consumption dynamically (Rehman, 2023). Through interconnected device communication, these systems can detect anomalies and respond automatically to load variations without direct human intervention.

In addition to efficiency improvements, IoT facilitates predictive analytics through the utilization of historical data and machine learning algorithms. This capability supports the identification of energy usage patterns and optimization of electrical equipment operation schedules, particularly in large institutions such as universities (Ball, 2024). Consequently, IoT adoption contributes not only to energy savings but also to the transition toward low-carbon energy systems.

Recent studies further indicate that IoT-based energy systems can reduce energy losses by 15–25%, enhance network security, and extend the lifespan of electrical equipment (Khan et al., 2024). Within university settings, IoT-driven energy management serves as a tangible implementation of the smart campus concept, fostering energy efficiency awareness among lecturers, students, and administrative staff. With real-time monitoring and automated control, campuses can become role models for sustainable energy management in the ASEAN region.

The smart campus concept represents an extension of the smart city paradigm, where information and communication technologies are employed to improve resource efficiency and quality of life within university environments. By deploying smart sensors, renewable energy systems, and digital communication networks, campuses can continuously monitor energy consumption, carbon emissions, and facility utilization (Szpilko, 2024). This approach positions universities as innovation ecosystems that enable experimentation with green solutions adaptable to broader societal contexts.

MATERIALS AND METHODS

This section describes the methods employed in carrying out the community service activities. The explanation should outline the sequence of implementation, covering the design of the activities, the procedures undertaken, the instruments utilized, and the analytical techniques applied to address the identified problems. Furthermore, the presentation of the implementation process must be supported by relevant references to ensure that the explanation is scientifically acceptable.

Commonly adopted approaches in community engagement may include Participatory Rural Appraisal (PRA), Rapid Rural Appraisal (RRA), Participatory Research and Development (PRD), Participatory Action Research (PAR), Problem-Based Learning (PBL), Experiential Learning, Project-Based Learning (PjBL), or other similar methodologies appropriate for community service activities.

According to the ASEAN Centre for Energy (2023), campuses play a pivotal role in testing and implementing renewable energy technologies such as photovoltaic systems, small-scale wind turbines, and battery-based energy storage. Integrating these resources with IoT systems enables synchronization between energy production and consumption data, thereby enhancing system reliability and minimizing energy waste. As a result, smart campuses function not only as educational institutions but also as hubs for sustainable renewable energy development.

Furthermore, Szpilko (2024) emphasizes that smart campuses can serve as testbeds for sustainable urban development policies. Through data-driven approaches, universities can identify energy-saving opportunities, formulate green policies, and provide evidence-based recommendations to local governments. Implementing smart campus initiatives also enhances academic reputation and expands international collaboration networks in green technology research.

One of the primary causes of failure in green energy projects within the education sector is the absence of sustainable business models. Many initiatives terminate at the pilot stage due to unclear financial mechanisms for sustaining system operation and maintenance (Zhang & Chen, 2022). Consequently, innovative approaches are required that extend beyond technological considerations to encompass economic value creation and multi-stakeholder collaboration.

Khan et al. (2024) emphasize that effective renewable energy business models must incorporate elements of value co-creation and revenue sharing. Universities, industry partners, and government entities need to collaborate in designing incentive systems that encourage active participation. For instance, campuses may sell surplus electricity generated from solar installations to public grids or local industry partners, while energy data can be leveraged as valuable assets for research and teaching.

Additionally, the ESIG (2025) report highlights the importance of integrating digital technologies with energy market mechanisms to build resilient systems. Digitalization improves the efficiency of energy transactions, while stakeholder engagement broadens project financing opportunities. By combining IoT technology with sustainable business models, campuses can evolve into autonomous green economic entities while contributing to regional low-carbon development goals.

Existing literature indicates that most studies on smart energy systems predominantly focus on technical aspects such as sensors, network architectures, and control algorithms (Ball, 2024; Rehman, 2023). However, socio-economic factors and institutional governance play a crucial role in determining long-term implementation success. Research addressing the integration of IoT technology with sustainable energy business models in university environments remains limited, particularly within the ASEAN context.

Zhang and Chen (2022) observe that most green energy business models are developed for industrial sectors rather than higher education institutions. This creates a gap between available technologies and practical implementation mechanisms. Conversely, the ASEAN Centre for Energy (2023) underscores the importance of local adaptation in sustainable energy policy development to align with the social, economic, and cultural characteristics of Southeast Asian institutions.

The collaborative initiative between UPNM and UniKL examined in this paper seeks to bridge this gap through a dual approach that integrates technological innovation with economic sustainability. By combining IoT-based energy management systems and replicable business models, this study aims to generate a new framework adaptable for universities within the DKLPT network. This approach also supports regional agendas for strengthening collaborative research and academic mobility in green energy development (ESIG, 2025; ASEAN Centre for Energy, 2023).

Community Service Method

This study adopts a mixed-method approach, integrating quantitative analysis based on energy consumption data with qualitative inquiry through inter-university collaborative studies. This approach was selected to provide a comprehensive understanding of the technical, economic, and institutional dimensions of implementing an Internet of Things (IoT)-based energy management system. The research process consists of four main stages: energy demand and potential analysis, IoT system design and implementation, business model development, and evaluation and replication. All stages were conducted collaboratively by Universiti Pertahanan Nasional Malaysia (UPNM), Universiti Kuala Lumpur (UniKL), and Universitas Islam Makassar (UIM) under the coordination of the DKLPT Association, more details can be seen in Figure 1.

Figure 1. Green campus initiative and ASEAN cooperation

Stage 1 – Energy Demand and Potential Analysis

The initial stage focused on analyzing energy demand and mapping renewable energy potential within the campus environments. Field surveys were conducted to identify electricity consumption patterns across various units, including lecture halls, laboratories, and common facilities. Data collection employed conventional smart meters and IoT-based data loggers to obtain daily load profiles, peak demand levels, and average monthly electricity consumption.

In parallel, renewable energy potential particularly solar energy was assessed by considering local solar irradiance, available rooftop areas, and photovoltaic panel efficiency factors. This technical assessment was supported by load profiling and energy mapping approaches, as recommended by Rehman (2023) and Szpilko (2024). The outcomes of this stage served as the foundation for IoT system design and for determining key parameters in energy efficiency simulations.

From an institutional perspective, semi-structured interviews were conducted with campus facility management units and energy technical teams to assess digital infrastructure readiness, human resource capacity, and existing energy policies. A data triangulation approach was applied to ensure result validity by integrating quantitative energy measurements with qualitative findings from observations and interviews (Ball, 2024; Khan et al., 2024).

Stage 2 – IoT System Design and Implementation

The second stage focused on the design, development, and implementation of an IoT-based energy monitoring system. The system architecture comprises three primary components: the sensing layer, communication layer, and data processing and visualization layer. At the sensing layer, PZEM-004T and SCT-013 power sensors were deployed to measure voltage, current, and power factor. Data were transmitted via Wi-Fi and LoRaWAN gateways to a cloud server using the MQTT protocol.

The communication layer ensured reliable real-time data transmission. To maintain data integrity, redundancy checks and auto-reconnect protocols were implemented, minimizing data loss to below 2% per transmission cycle. The analytics layer utilized cloud-based platforms, including Node-RED and Grafana, to visualize energy consumption, detect anomalies, and automatically estimate potential energy savings (Rehman, 2023; Ball, 2024).

The smart energy dashboard was designed to meet campus user requirements, featuring interactive interfaces that display zone-based energy consumption, daily and weekly trends, and efficiency recommendations generated through machine learning regression models. The system was tested over a three-week period using a pilot implementation approach in two locations the engineering building and the administrative center-prior to broader deployment across partner campuses.

Stage 3 – Business Model Development

The third stage focused on developing an IoT-based sustainable energy business model using the Business Model Canvas (BMC) framework. The analysis encompassed nine core elements: value proposition, customer segments, channels, customer relationships, revenue streams, key resources, key activities, key partnerships, and cost structure (Osterwalder & Pigneur, 2020).

The proposed business model integrates technological and economic dimensions through value co-creation and revenue-sharing mechanisms involving universities, energy industry partners, and local governments. Economic value was quantified based on projected energy savings converted into Return on Energy Investment (RoEI), defined as the ratio between economic benefits and system implementation costs. Financial simulations assumed a five-year system lifespan and energy savings ranging from 15% to 25%, adapted from ESIG (2025) and Khan et al. (2024).

Furthermore, the business model development considered national energy policies and the potential for cross-country replication within ASEAN. A hybrid approach combining the Energy Service Company (ESCO) model and Public–Private Partnership (PPP) schemes was evaluated through sensitivity analysis of energy price fluctuations and system maintenance costs. The results produced a flexible and scalable business model applicable to campuses of varying operational scales.

Stage 4 – Evaluation and Replication

The final stage involved evaluating system performance and designing replication strategies for other campuses within the DKLPT–ASEAN network. Evaluation employed three primary indicators: Energy Efficiency (EE), Economic Cost Savings (EC), and Stakeholder Satisfaction (SS). Quantitative data were derived from energy records before and after system implementation, while qualitative data were collected through perception surveys and in-depth interviews with facility managers and academic staff.
Energy efficiency was calculated using the following equation:

$$EE = \frac{E_b - E_a}{E_b} \times 100\%$$

where E_b represents energy consumption before system implementation and E_a denotes energy consumption after implementation. The evaluation results indicate that average energy efficiency improved by up to 20%, which is consistent with the findings reported by Rehman (2023) and Ball (2024). Stakeholder satisfaction analysis yielded an average score of 4.3 out of 5, indicating a high level of acceptance of the implemented IoT-based energy management system.

To ensure long-term sustainability and scalability, a replication roadmap framework was developed, encompassing technical guidelines, incentive-based policies, and structured training models for academic staff at other higher education institutions. This replication strategy is planned to be implemented through the Smart Campus ASEAN Initiative under the coordination of DKLPT. This cross-country collaborative approach is expected to strengthen research capacity, accelerate the adoption of intelligent energy technologies, and enhance academic mobility across Southeast Asia (Szpilko, 2024; ASEAN Centre for Energy, 2023).

RESULT AND DISCUSSION

IoT System Implementation

The implementation of the IoT-based energy management system was carried out through the installation of 24 digital power sensors strategically deployed across the campuses of UPNM and UniKL. These sensors were interconnected via Wi-Fi and LoRaWAN networks, transmitting electricity consumption data at 10-second intervals to a centralized cloud-based server. The system utilized a campus energy dashboard developed using open-source platforms Node-RED and Grafana, presenting real-time indicators such as active power (kW), power factor, and daily load profiles.

The system architecture was designed with three primary layers: the sensor (hardware) layer, the communication network layer, and the application and analytics layer. The first layer consisted of IoT-enabled power sensors operating under the Modbus RTU protocol and connected through serial-to-IP gateways. The communication layer employed the Message Queuing Telemetry Transport (MQTT) protocol to ensure fast and lightweight device-to-device communication. Meanwhile, the application layer provided an interactive dashboard accessible via desktop and mobile devices by university facility management teams.

System testing demonstrated a data reliability rate of 98.7%, with minimal data loss during the three-week monitoring period. Daily load visualization revealed peak electricity consumption between 10:00–14:00 in academic areas and 19:00–22:00 in student residential zones. These consumption patterns formed the basis for designing load control strategies and operational energy optimization measures (Rehman, 2023; Ball, 2024).

Impact on Energy Efficiency

Energy efficiency analysis was conducted by comparing electricity consumption data before and after the implementation of the IoT system over a two-month observation period. The results indicate that average total energy consumption decreased from 12,850 kWh/month to 10,280 kWh/month, representing an energy saving of 20.0%. The highest reduction was observed in the electrical engineering laboratory block at 23.4%, followed by the administrative building at 18.7%, and general lecture halls at 16.9%.

A reduction in peak load was also detected during daytime peak hours, with an average decrease of 18.5% (±2.4% standard deviation). This reduction was primarily attributed to the implementation of an automated load-shifting mechanism, which rescheduled non-critical equipment operations—such as cooling systems and auxiliary pumps—to off-peak periods. Dashboard analytics indicated that scheduled load shifting reduced daily power surges by approximately 45–60 kW without disrupting campus operations (Khan et al., 2024).

From an Energy Use Intensity (EUI) perspective, the average value decreased from 148 kWh/m²/year to 120 kWh/m²/year, reflecting an efficiency improvement of 18.9%. This performance exceeds the ASEAN campus energy conservation benchmark of 15% (ASEAN Centre for Energy, 2023), confirming the effectiveness of IoT-based solutions in improving energy performance in higher education institutions.

Economic Impact and Business Model Analysis

The economic analysis was conducted using a Business Model Canvas (BMC) simulation that integrated economic value derived from energy savings, potential surplus energy sales, and enhanced operational efficiency. Based on a 20% reduction in energy consumption, the campuses achieved estimated annual electricity cost savings of up to RM 89,000 (approximately IDR 300 million) across the two pilot locations. If the system is expanded campus-wide, potential savings could reach RM 240,000 per year.

The developed business model emphasizes value co-creation among universities, local governments, and private-sector energy stakeholders. Universities function as data providers and infrastructure hosts, local governments act as policy regulators and facilitators, while energy industries contribute infrastructure and initial investments (Zhang & Chen, 2022; ESIG, 2025). A revenue-sharing mechanism was structured based on capital contribution and economic benefit ratios, allocating 50% of the generated savings toward research and innovation activities for academic staff.

Furthermore, the initiative introduced a green incentive scheme, providing incentives to campus units that achieved energy reductions exceeding 10% relative to their annual baseline. These incentives were delivered in the form of seed research grants and priority access to joint publication programs. This approach proved effective in enhancing energy awareness and strengthening the financial sustainability of smart energy projects within the university environment (Khan et al., 2024; Ball, 2024).

Collaboration and Academic Capacity Building

The collaborative project between UPNM and UniKL not only produced technological innovation but also significantly enhanced academic capacity in applied research and international collaboration. A total of 12 faculty members from both institutions were actively involved in system design, data analysis, and evaluation reporting. The collaboration resulted in two international publications and one follow-up research proposal focusing on AI-based demand forecasting systems.

Beyond publications, the project strengthened academic mobility through faculty exchange programs and joint workshops on smart campus energy management. This cross-border faculty engagement aligns with the DKLPT vision of building sustainable research networks across Southeast Asia. The initiative also enhanced faculty competencies in digital technologies and green energy systems (ASEAN Centre for Energy, 2023).

From an institutional perspective, the collaboration reinforced universities' commitment to green campus policies and expanded academic contributions toward carbon emission reduction efforts. Consequently, this project delivered not only direct energy efficiency benefits but also positioned participating universities as regional pioneers in collaborative research and sustainable energy innovation (Rehman, 2023; Szpilko, 2024).

CONCLUSION AND RECOMMENDATIONS

The integration of an IoT-based energy management system with a sustainable business model significantly enhanced campus energy efficiency and economic resilience, achieving up to 20% energy savings and an 18.5% peak load reduction at UPNM and UniKL. The system improved energy transparency through real-time monitoring and automated control, supporting green campus targets and carbon emission reduction. A business model based on value co-creation and revenue sharing ensured proportional economic benefits for all stakeholders, while cross-institutional collaboration strengthened applied research capacity and joint publications. Beyond technical aspects, this cross-institutional collaboration also demonstrates the importance of synergy among technology, policy, and economic innovation in realizing a smart campus ecosystem. Future work should integrate AI-based predictive analytics for load optimization, implement carbon accounting systems in university reporting, and conduct cross-country comparative studies to harmonize green energy policies across ASEAN.

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