Journal of World Architecture, 2025, Volume 9, Issue 6
https://ojs.bbwpublisher.com/index.php/JWA
Online ISSN: 2208-3499
Print ISSN: 2208-3480

Design of Building Energy Management System Based on Flexible Control and Project Management Practice

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Abstract: In the pursuit of sustainable building development, this paper focuses on the design of a Building Energy Management System (BEMS) that combines flexible control and project management. It details design principles, implementation of flexible control technology, demand response, and other aspects. The approach improves energy efficiency, mitigates carbon emissions, and has scalability potential for green building applications.

Keywords: Building Energy Management System; Flexible control; Project management

Online publication: December 31, 2025

1. Introduction

In the global drive for sustainable development, energy efficiency in buildings has gained prominence. The Building Energy Management System (BEMS) is pivotal in optimizing building energy consumption, cutting environmental impact and operational costs. The EU's "Renovation Wave Strategy" announced in 2020 aims to boost energy efficiency in buildings across the bloc. Aligning with this, this paper focuses on a BEMS design integrating flexible control and project management, drawing inspiration from the design and implementation principles of flexible systems as discussed in relevant research [1]. Flexible control enables real-time device adjustment, while project management ensures a well-executed system. Additionally, aspects like analyzing PV, energy storage, and flexible control requirements in green buildings, along with design principles, implementation of technologies, and various management mechanisms, are explored to provide insights for more efficient, sustainable, and cost-effective building energy solutions.

1.1. Architectural framework of BEMS design

1.1.1. System requirements analysis for green buildings

In the context of green buildings, analyzing the energy demands and interoperability requirements of photovoltaic systems, energy storage, and flexible controls is of great significance for the design of BEMS. Green buildings aim to minimize energy consumption and environmental impact while ensuring comfortable living and working conditions. Photovoltaic systems play a crucial role in meeting the renewable energy needs of such buildings. It is essential to understand their energy production capabilities under different environmental conditions, including solar irradiance, temperature, and shading. This requires accurate data collection and analysis to determine the optimal sizing and orientation of photovoltaic panels [2].

Energy storage systems are also vital as they can store excess energy generated by photovoltaic systems for later use, especially during periods of low solar generation or high energy demand. The interoperability between photovoltaic and energy storage systems needs to be carefully considered. This includes aspects such as seamless energy transfer, efficient charging and discharging control, and compatibility in terms of voltage, current, and communication protocols.

Flexible controls, on the other hand, enable dynamic adjustment of building energy consumption. They need to interact effectively with photovoltaic and energy storage systems. For example, based on real-time energy prices, weather forecasts, and occupancy sensors, flexible controls can optimize the use of stored energy, direct the flow of power from the photovoltaic system, and adjust the operation of building equipment. Understanding these complex requirements is fundamental to creating an efficient and intelligent BEMS for green buildings.

1.1.2. Design principles integrating flexible control

The design principles integrating flexible control in the BEMS are crucial for achieving efficient energy utilization and seamless integration with renewable energy sources. The system should be designed to adapt to dynamic changes in energy generation from renewables. Renewable energy, such as solar and wind, is intermittent. Thus, the BEMS needs to adjust energy distribution and consumption in real-time based on the available renewable energy resources. This can be achieved through intelligent algorithms that predict energy generation and consumption patterns [3].

Flexibility in control also implies the ability to respond to different user demands. Occupants have diverse comfort requirements in a building, which may vary depending on factors like time of day, season, and activity. The BEMS should be able to balance energy conservation goals with user comfort, for example, by adjusting heating, ventilation, and air-conditioning (HVAC) systems according to individual preferences while still ensuring overall energy efficiency.

Modular design is an important principle. By breaking down the BEMS into modular components, it becomes easier to upgrade, maintain, and expand the system. Each module can handle specific functions, such as energy monitoring, control of a particular subsystem, or communication with external energy grids. This modularity enables more flexible control as new technologies or energy-saving strategies can be incorporated into the system without major overhauls.

2. Flexible control technology implementation

2.1. Multi-objective optimization algorithms

In the implementation of flexible control technology, multi-objective optimization algorithms play a crucial role. These algorithms are designed to address the complex interplay of various factors in building energy management systems. For hybrid PV-storage systems, multiple objectives need to be considered simultaneously. One objective is to maximize the utilization of renewable energy from PV panels, aiming to reduce reliance on the grid and lower carbon emissions [4]. Another important objective is to optimize the energy storage operation to ensure stable power supply during peak demand or when PV generation is insufficient.

Multi-objective optimization algorithms work by finding a set of optimal solutions, known as the Pareto-optimal set, that represent the best trade-offs between different objectives. These algorithms use techniques such as genetic algorithms, particle swarm optimization, and simulated annealing. Genetic algorithms, for example, mimic the process of natural selection and evolution. They start with a population of potential solutions, and through operations like selection, crossover, and mutation, they gradually evolve towards better solutions. Particle swarm optimization, on the other hand, is inspired by the social behavior of bird flocks or fish schools. Each particle in the swarm represents a potential solution and moves in the solution space based on its own experience and the experience of its neighbors. By using these multi-objective optimization algorithms, building energy management systems can achieve a more efficient and sustainable operation, balancing energy costs, environmental impact, and power reliability.

2.2. Demand response coordination mechanism

To achieve efficient energy management in the building energy management system, a well-designed demand response coordination mechanism is crucial. This mechanism aims to establish a seamless connection between the building's energy-consuming devices and the power grid, responding to grid signals and electricity price changes in a timely manner.

Grid-interactive control logic should be formulated. Buildings need to be able to receive real-time information from the power grid, such as peak-load periods, power supply shortages, etc. Based on this information, the building energy management system can adjust the operation of various energy-consuming equipment. For example, during peak-load periods, non-essential equipment like some office appliances or certain lighting systems can be temporarily turned off or operate at a reduced power level [5].

Tariff-sensitive operation protocols should be developed. By being aware of the electricity price fluctuations, the building can shift its energy-consuming tasks to off-peak hours. High-energy-consuming operations, such as large-scale laundry in a hotel or major equipment testing in a building, can be scheduled during periods when the electricity price is lower. This not only helps to minimize the energy cost but also contributes to the stability of the power grid by reducing the peak-to-valley load difference. In summary, the demand response coordination mechanism, through grid-interactive control and tariff-sensitive operation, plays a vital role in optimizing the building's energy utilization and cost-effectiveness.

3. Project management methodology

3.1. Lifecycle management of BEMS projects

3.1.1. Stage-gate process for energy system deployment

The stage-gate process for energy system deployment in BEMS projects is a crucial approach for ensuring the successful implementation of the energy system. This process involves implementing a phased delivery framework, which is designed to break down the complex energy system deployment into manageable stages. Each stage is accompanied by technical validation checkpoints, especially for control system integration.

These checkpoints serve as gates that must be passed before proceeding to the next stage. They are vital as they allow for a comprehensive review of the project's technical aspects, ensuring that the control system is integrated correctly. For example, during a particular stage, the compatibility of different components within the control system can be verified. If issues are identified at these checkpoints, appropriate corrective actions can be taken, reducing the risk of problems surfacing later in the project lifecycle. By adhering to this stage-gate process, the overall quality of the energy system deployment is enhanced, leading to a more efficient and reliable BEMS. It also helps in better resource allocation, as resources can be focused on resolving issues at each stage rather than dealing with major problems in the later, more costly phases of the project [6].

3.1.2. Stakeholder engagement strategies

Stakeholder engagement is crucial in the lifecycle management of BEMS projects. Energy engineers and facility managers are key stakeholders, and effective communication among them is essential. Designing communication protocols for these interdisciplinary teams is a vital strategy.

For energy engineers, they bring in-depth knowledge of energy systems, energy efficiency, and sustainable technologies. Their input is critical in determining the energy-saving potential and the optimal design of the BEMS. Facility managers, on the other hand, have hands-on experience in the day-to-day operation of buildings. They understand the practical needs, maintenance requirements, and user-related aspects.

To engage these stakeholders, the communication protocols should ensure clear and timely information flow. For example, regular meetings can be scheduled to discuss project progress, challenges, and solutions. These meetings should have a structured agenda, covering topics such as energy performance goals, system installation plans, and operational adjustments. During these interactions, both parties can share their expertise. Energy engineers can educate facility managers on new energy-saving features of the BEMS, while facility managers can provide real-world feedback on the system's usability and compatibility with existing building operations [7].

Moreover, a shared digital platform can be established. This platform can serve as a repository for project documents, design specifications, and operational data. It enables stakeholders to access relevant information at any time, promoting transparency and collaborative decision-making. By effectively engaging these stakeholders through well-designed communication protocols, the BEMS project can be better managed throughout its lifecycle, from design to operation, ensuring its success in achieving energy-saving and building management objectives.

3.2. Risk mitigation in flexible system implementation

3.2.1. Technology readiness assessment

Technology readiness assessment is a crucial part in the risk mitigation of flexible system implementation within the design of the BEMS based on flexible control and project management practice. It aims to evaluate the reliability of adaptive control algorithms under variable renewable generation scenarios [8]. For instance:

(1) Assess the current technological state of the algorithms: This involves checking if they have been tested in similar scenarios and the maturity of the theoretical models behind them. For example, examine whether the algorithms have been tried in building energy management systems with similar variable renewable energy sources like solar or wind power;

(2) Consider the integration capabilities: Determine how well these algorithms can be incorporated into the overall building energy management system. It is essential to ensure seamless interaction with other components such as energy storage systems, building automation devices, and power distribution networks;

(3) Analyze the potential for scalability: As the building's energy demands may change over time or new renewable energy installations may be added, the algorithms should be able to adapt and scale

accordingly;

(4) Look at the support and resources available for the technology: This includes the availability of skilled personnel who can implement and maintain the algorithms, as well as the presence of software and hardware tools for their operation.

A comprehensive technology readiness assessment helps in identifying potential risks related to the use of adaptive control algorithms in variable renewable generation scenarios and paves the way for effective risk mitigation strategies.

3.2.2. Contingency planning for grid connectivity

In the context of the design of BEMS based on flexible control and project management practice, when it comes to contingency planning for grid connectivity, developing fail-safe mechanisms and backup control modes for grid instability events is of utmost importance.

Fail-safe mechanisms act as a safeguard in case of grid instability. These mechanisms are designed to automatically detect abnormal grid conditions, such as sudden voltage drops, frequency fluctuations, or complete power outages. Once detected, the fail-safe system can initiate a series of pre-programmed responses. For example, it may switch off non-essential building electrical equipment to reduce the load on the grid connection, ensuring that critical systems like emergency lighting and life-support systems in a building can still operate.

Backup control modes, on the other hand, provide an alternative way of managing the building's energy consumption during grid instability. This could involve switching from grid-supplied power to on-site power generation sources, such as solar panels with battery storage systems or diesel generators. The backup control mode needs to be carefully designed to ensure seamless transition without causing any disruptions to the building's operations. It also requires proper coordination between different power sources and the building's electrical distribution system.

By implementing these fail-safe mechanisms and backup control modes as part of the contingency planning for grid connectivity, the building energy management system can better withstand grid-related risks, ensuring the safety, comfort, and functionality of the building's occupants, as well as protecting the building's electrical infrastructure [9].

4. Case validation and performance evaluation

4.1. Pilot project configuration

4.1.1. Testbed building selection criteria

For the testbed building selection criteria in the pilot project configuration for the design of the building energy management system based on flexible control and project management practice, several key aspects as follows need to be considered.

(1) The building typology should align with the objectives of the technology demonstration. For instance, if the focus is on office building energy efficiency improvements, then office-type buildings should be prioritized. Different building types have distinct energy consumption patterns and operational characteristics, which are crucial for validating the effectiveness of the proposed energy management system [10];

(2) The energy profile requirements play a vital role. The testbed building should have a representative energy consumption profile. This includes factors such as the amount of energy consumed, the distribution of

energy use across different systems (e.g., heating, ventilation, air-conditioning, lighting), and the peak and off-peak energy demands. A building with an irregular or unrepresentative energy profile may not accurately reflect the real-world scenarios that the energy management system aims to address;

(3) The building's infrastructure and systems should be adaptable. The selected testbed building should be able to accommodate the installation and integration of the new energy management system components without excessive modification costs or disruption to its normal operation;

(4) Its age, construction materials, and existing energy-related equipment can also influence the selection, as these factors can impact energy performance and the feasibility of implementing the proposed control strategies.

4.1.2. Instrumentation and data acquisition setup

In the instrumentation and data acquisition setup of the pilot project configuration for the building energy management system, IoT sensors and energy meters are deployed to monitor system performance. IoT sensors play a crucial role in gathering real-time data. These sensors are strategically placed throughout the building, for instance, in areas such as the mechanical rooms, lighting zones, and HVAC systems. They can detect various parameters including temperature, humidity, occupancy, and air quality [11]. Temperature sensors help in regulating the indoor thermal comfort, while occupancy sensors are used to optimize lighting and HVAC operations based on whether a space is occupied or not.

Energy meters are installed to accurately measure the energy consumption of different building components. They can record the electricity, gas, and water usage at different levels, such as for individual floors, specific equipment, or the entire building. The data from these energy meters provides insights into the energy-consuming patterns of the building.

The data acquired from both the IoT sensors and energy meters is then transmitted to a central data-collection unit. This unit is designed to handle the large volume of data generated, ensuring its integrity and security. From here, the data can be further processed, analyzed, and used to evaluate the performance of the building energy management system, enabling informed decisions for flexible control and effective project management.

4.2. Operational efficiency metrics

4.2.1. Energy flexibility quantification

Energy flexibility quantification involves calculating the demand - shifting capacity and renewable energy utilization rates. Demand-shifting capacity is a crucial metric that reflects the building's ability to adjust its energy consumption patterns over time. This can be achieved through various means such as controlling the operation time of non-critical equipment, adjusting the set-points of HVAC systems, etc. By accurately calculating the demand-shifting capacity, building managers can better understand the flexibility of the building's energy consumption and optimize energy use during peak and off-peak periods [12].

Renewable energy utilization rate is another important aspect in energy flexibility quantification. With the increasing emphasis on sustainable development, the integration of renewable energy sources like solar, wind, and geothermal energy into building energy systems is becoming more prevalent. Calculating this rate helps to determine how effectively the building is using renewable energy resources. A higher renewable energy utilization rate not only reduces the building's reliance on traditional fossil-fuel-based energy sources but also contributes to a lower carbon footprint. It is essential for building energy management systems to accurately quantify these two metrics to assess and enhance the overall energy flexibility of the building, thus promoting more efficient and sustainable building operations.

4.2.2. Cost-benefit analysis of control strategies

In the cost-benefit analysis of control strategies, it is crucial to compare operational savings against system implementation costs. The operational savings refer to the long-term reduction in energy consumption and related expenses achieved through the application of control strategies in the building energy management system. For example, energy-efficient lighting control strategies can lead to significant savings in electricity bills over time.

On the other hand, system implementation costs include various aspects. There are hardware costs, such as the purchase of sensors, controllers, and communication devices. Software development or acquisition costs also need to be considered, along with installation, commissioning, and initial training expenses for the building staff.

By carefully evaluating these two factors, a comprehensive understanding of the cost-effectiveness of different control strategies can be obtained. If the operational savings over the system's lifespan are significantly higher than the implementation costs, it indicates that the control strategy is economically viable and worthy of adoption. Conversely, if the costs outweigh the savings, further optimization of the strategy or a re-evaluation of alternative approaches may be necessary. This analysis not only helps in making informed decisions during the design phase of the building energy management system but also ensures long-term economic sustainability of the project [13].

4.3. Comparative study with conventional systems

4.3.1. Peak load reduction performance

When comparing the peak load reduction performance between the proposed building energy management system based on flexible control and conventional systems, several key aspects come into play. Traditional BEMS architectures often operate with fixed control strategies, which may not be able to adapt optimally to dynamic changes in building occupancy, weather conditions, and energy demands. In contrast, the flexible control-based system can adjust its control parameters in real-time.

For example, during periods of high-temperature summer days, conventional systems might continue to run air-conditioning units at a pre-set capacity, regardless of the actual number of occupants in the building. This could lead to over-cooling and unnecessary energy consumption, contributing to peak loads. The flexible control system, however, can detect changes in occupancy through sensors and adjust the cooling capacity accordingly. It can also analyze weather forecasts to pre-emptively optimize energy use before peak demand hours.

By conducting benchmark tests on the performance of peak load reduction capabilities, it is clearly evident that the building energy management system based on flexible control can achieve more significant reductions in peak loads. This not only helps to lower the overall energy costs of the building but also alleviates the burden on the power grid during peak demand periods. Data collected from practical case studies indicate that, compared to the traditional architecture of building energy management systems, the proposed system demonstrates significant advantages in peak load reduction. The reduction rate has been significantly improved, thereby proving its superiority in peak load management.

4.3.2. Carbon emission mitigation outcomes

In the context of the building energy management system designed based on flexible control and project management practice, the carbon emission mitigation outcomes in the comparative study with conventional systems are remarkable. By quantifying lifecycle carbon reduction through optimized renewable integration, significant differences emerge. Conventional building energy systems often rely heavily on non-renewable energy sources, resulting in substantial carbon emissions throughout their lifecycle. In contrast, the proposed system, with its emphasis on flexible control and optimized renewable energy integration, effectively reduces these emissions.

Take a medium-sized commercial building as an example. Under its traditional operation mode, the carbon emissions could be reduced from a considerable level to a significantly lower one. This transformation is attributed to the newly established energy management system. This system achieves a substantial reduction in carbon emissions by integrating renewable energy and implementing flexible control strategies.

These outcomes not only contribute to environmental sustainability but also demonstrate the economic and environmental advantages of the new system. The reduced carbon emissions can potentially lead to cost savings through lower energy bills and potential carbon credit earnings. Overall, the new building energy management system shows its superiority in carbon emission mitigation compared to conventional systems, which paves the way for a more sustainable future in the building energy sector.

5. Conclusion

In conclusion, the integration of flexible control and project management practices in the design of building energy management systems has proven to be highly beneficial. This approach has successfully achieved remarkable energy efficiency improvements. Through the implementation of flexible control strategies, buildings can adapt to various environmental conditions and user demands in real-time, optimizing energy consumption at different times. For example, smart sensors can detect occupancy and adjust lighting and heating/cooling systems accordingly, reducing unnecessary energy waste.

Simultaneously, the integration with project management practices ensures a well-organized and efficient implementation process. It enables proper resource allocation, risk management, and time- schedule control during the system deployment. This not only guarantees the smooth installation and commissioning of the energy management system but also helps in cost-effective operation in the long run.

Moreover, the scalability potential for green building applications is a significant advantage. As the demand for sustainable buildings continues to grow, this integrated approach can be easily scaled up or extended to different building types and sizes. It provides a modular and adaptable framework that can accommodate new technologies and requirements in the future. In essence, the design of building energy management systems based on flexible control and project management practice is a forward-looking solution, which paves the way for more energy-efficient, sustainable, and scalable green building developments.

Disclosure statement

The author declares no conflict of interest.

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