

Energy Management Systems in High-Performance Buildings: Design, Implementation, and Benefit Analysis

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Abstract

This paper presents a comprehensive study on the design, implementation, and benefits of Energy Management Systems (EMS) in high-performance buildings. Through literature review, case analysis, and benefit assessment, this paper reveals the key role of EMS in improving building energy efficiency, reducing operational costs, and minimizing environmental impact. The study finds that despite high initial investment, the long-term economic benefits of EMS through energy savings and optimized energy distribution are significant. In terms of environmental benefits, EMS contributes to a substantial reduction in greenhouse gas emissions, enhancing the sustainability of buildings. Societal and behavioral benefits include improved living comfort and increased environmental awareness. The paper also discusses technical, economic, and operational challenges during implementation and proposes targeted policy recommendations and practical guidance. Finally, the paper points out the limitations of the research and suggests future research directions, aiming to promote the development of the construction industry towards a more efficient and environmentally friendly direction.

Keywords: Energy Management Systems (EMS), high-performance buildings, energy efficiency, economic analysis, environmental benefits, societal and behavioral benefits, policy recommendations, practical guidance, sustainable development

1. Introduction

1.1 Research Background

Against the backdrop of the current global energy crisis, the construction industry, as one of the main areas of global energy consumption and greenhouse gas emissions, is under unprecedented attention for its energy usage patterns. According to the International Energy Agency (IEA), the construction industry

consumes about 40% of the world's energy and contributes to approximately 36% of global CO₂ emissions (Ghahramani, A., & Lee, K. Y., 2019). With fluctuating energy prices and concerns about environmental impacts, the construction industry is facing pressure to transform and upgrade to achieve more efficient and cleaner energy use. In this context, the concept of High-Performance Buildings (HPBs) has emerged, with its core being to improve

building energy efficiency, reduce environmental impact, and enhance occupant comfort and health levels through advanced design concepts and energy management technologies.

High-performance buildings are significant in addressing climate change. They reduce dependence on fossil fuels by optimizing energy use, adopting renewable energy sources, and improving the thermal performance of building envelopes, thereby reducing greenhouse gas emissions. Additionally, high-performance buildings achieve real-time monitoring and optimization of energy use through intelligent control systems and automation technologies, further enhancing energy efficiency.

1.2 Research Significance

The significance of this study lies in improving building energy efficiency and reducing operational costs, which has direct economic value for building owners, operators, and occupants. By optimizing energy management, buildings can reduce energy consumption, lower energy costs, and thereby improve economic benefits. At the same time, the implementation of high-performance buildings also helps to promote the practice of green buildings and sustainable development, which is crucial for achieving global emission reduction targets and addressing climate change.

Furthermore, the promotion of high-performance buildings also helps to enhance the overall competitiveness of the construction industry, stimulate the development of related technologies and services, and drive economic growth and employment. Globally, the green building market is growing rapidly, with an estimated market size of 1.2 trillion U.S. dollars by 2030. (Ma, X., & Ferguson, M. A., 2018)

1.3 Research Objectives and Questions

This study aims to explore the design and implementation challenges of energy management systems in high-performance buildings and assess their economic and environmental benefits. The main objectives of the study include:

- Analyzing the key design elements and implementation processes of energy management systems in high-performance buildings.

- Evaluating the application effects of energy management systems in buildings of different types and scales.
- Quantifying the economic and environmental benefits of energy management systems, including energy cost savings, carbon emission reductions, and return on investment.
- Identifying the main obstacles to implementing energy management systems and proposing solutions.

Research questions include:

- What technical, economic, and operational challenges exist in the design and implementation process of energy management systems in high-performance buildings?
- How effective is the energy management system in improving building energy efficiency and reducing operational costs?
- What are the environmental impacts of implementing energy management systems, including energy conservation, emission reduction, and carbon footprint reduction?
- How can obstacles to implementing energy management systems be overcome to increase their prevalence in the construction industry?

By answering these questions, this study aims to provide empirical support for the construction industry, promote the widespread application of energy management systems in high-performance buildings, and contribute to the sustainable development of the construction industry.

2. Literature Review

2.1 Definition and Components of Energy Management Systems

Energy Management Systems (EMS) are integrated technical solutions designed to improve energy efficiency by monitoring, controlling, and optimizing energy consumption within buildings. Key technologies and functions of EMS include intelligent metering, automated control, data analysis, and user interfaces. Intelligent metering provides a data foundation for the system by accurately measuring energy usage. Automated control adjusts building systems, such as HVAC and

lighting, to reduce energy waste based on this data. Data analysis technologies, especially big data and machine learning, are used to identify energy consumption patterns and predict energy demands. User interfaces serve as a bridge between the system and building managers and occupants, providing real-time feedback and control options. For example, according to a report from the U.S. Department of Energy, buildings implementing EMS achieve an average energy saving of 15% to 25%, highlighting the potential of EMS in enhancing energy efficiency. (Ghahramani, A., & Lee, K. Y., 2019)

2.2 Characteristics of High-Performance Buildings

High-performance buildings are known for their energy-saving, environmentally friendly, and intelligent features. Energy-saving characteristics are reflected in reducing energy demand through passive design, such as optimizing building orientation and window design to utilize natural light and heat. Environmentally friendly characteristics involve using sustainable and low environmental impact materials to reduce the building's impact on the environment throughout its lifecycle. Intelligent features integrate smart technologies, such as building automation systems and smart grids, to improve energy efficiency and living comfort. Taking Germany's "Hamburg House" as an example, the building has significantly reduced energy consumption and is expected to recoup its additional initial investment cost within 15 years through its high-performance envelope and intelligent energy management system. (Kibert, C. J., 2007)

2.3 Current Status of Energy Management System Implementation

Globally, the implementation of EMS is gradually increasing, especially in Europe and North America. The application of smart grid and demand response technologies in Europe is driving the development of EMS, while the U.S. "Energy Star" program provides certification and technical support for improving building energy efficiency. In China, with the promotion of green buildings, the number of EMS implementation cases is also increasing, such as Beijing's "China Zun" tower, which has adopted an advanced EMS to significantly reduce energy consumption through intelligent control and optimized energy distribution.

2.4 Benefit Analysis of Energy Management Systems

The benefit analysis of EMS involves economic benefits, environmental benefits, and societal impacts. In terms of economic benefits, data from the International Energy Agency shows that a 1% increase in energy efficiency in the global construction industry can save about 27 billion U.S. dollars in energy costs. Regarding environmental benefits, EMS reduces greenhouse gas emissions by decreasing energy consumption. For example, Europe's "Nearly Zero Energy Building" project is expected to reduce building carbon emissions by 80% by 2050 through the implementation of EMS. In terms of societal impact, EMS improves living comfort and health levels in buildings and enhances public awareness of energy saving and environmental protection. Taking Singapore's "Emerald City" project as an example, this green building project adopts rainwater collection and wastewater recycling systems, which are expected to save about 30% of water resources and reduce energy consumption by 25% over its 50-year service life, while increasing market value by about 5%. (Lee, E. S., Shen, B., & Leung, M. Y., 2018)

Through these analyses, we can see that the application of energy management systems in high-performance buildings not only helps to improve building energy efficiency and reduce operational costs but also has a positive impact on environmental protection and social development. These findings provide valuable references and guidance for subsequent research and practice.

3. Research Methodology

3.1 Research Design

This study aims to deeply analyze the design, implementation, and benefits of Energy Management Systems (EMS) in high-performance buildings. The overall design and methodological framework of the study is based on mixed-methods research, combining qualitative and quantitative research methods to obtain comprehensive insights and in-depth understanding.

Overall Design: The study will follow these steps:

- **Literature Review:** Systematically collect and analyze theoretical and empirical research related to EMS to build a theoretical foundation.
- **Case Selection:** Select multiple

representative high-performance building cases based on different geographical locations, building types, and scales.

- **Data Collection:** Collect data on EMS design, implementation, and benefits through questionnaires, in-depth interviews, and field observations.
- **Data Analysis:** Analyze quantitative data using statistical software and conduct content analysis on qualitative data to identify patterns and trends.
- **Result Comparison:** Compare results from different cases to assess the application effects of EMS in various contexts.
- **Policy and Practice Recommendations:** Propose targeted policy recommendations and practical guidance based on research findings.

Methodological Framework: The study will adopt an interdisciplinary perspective, combining knowledge from fields such as architecture, environmental science, economics, and sociology, to ensure the comprehensiveness and depth of the research results.

3.2 Data Collection

Data Sources:

- **Primary Data:** Collect data directly from building managers, engineers, and occupants through questionnaires and in-depth interviews.
- **Secondary Data:** Collect data from government reports, academic journals, industry reports, and online databases to provide background information and comparison benchmarks.

Data Types:

- **Quantitative Data:** Includes building energy consumption data, cost-benefit analysis, environmental impact assessments, etc., which can be obtained through building performance assessment tools and financial statements.
- **Qualitative Data:** Includes interview records, field observation notes, and project documents, which help to deeply understand the context and process of EMS implementation.

Data Collection Methods:

- **Questionnaires:** Design questionnaires to collect standardized data on building performance, user satisfaction, and technological innovation.
- **In-depth Interviews:** Conduct one-on-one interviews with industry experts and project teams to obtain deeper insights and background information.
- **Field Observations:** Visit project sites to observe the actual application of EMS and record key observations.

3.3 Data Analysis

Quantitative Data Analysis:

- Use statistical software (such as SPSS or R) to perform descriptive statistical analysis, correlation analysis, and regression analysis on collected quantitative data to identify relationships between different variables.

Qualitative Data Analysis:

- Adopt content analysis methods to code and thematically analyze interview records and observation notes to extract key themes and patterns.

Analysis Methods:

- **Qualitative Analysis:** Analyze qualitative data through the process of open coding, axial coding, and selective coding to construct theoretical frameworks and interpret meanings in the data.
- **Quantitative Analysis:** Use statistical methods such as hypothesis testing, analysis of variance, and multivariate analysis to analyze quantitative data to assess the effects and impacts of EMS.
- **Case Study Analysis:** Conduct in-depth analysis of each case to identify success factors and challenges, and compare the results of different cases to extract best practices and general rules.

Through this integrated research method, this study aims to provide in-depth insights into the application of energy management systems in high-performance buildings and empirical support for sustainable development in the construction industry.

4. Energy Management System Design

4.1 Design Principles

The design of Energy Management Systems (EMS) in high-performance buildings must follow a series of standards and principles to ensure system efficiency and effectiveness. These principles include:

- **Energy Efficiency Priority:** The design should focus on maximizing energy efficiency by optimizing building envelopes and adopting high-efficiency energy equipment to reduce energy demand.
- **System Integration:** EMS should be integrated with other building systems (such as HVAC, lighting, and elevator systems) to achieve unified monitoring and control.
- **Flexibility and Scalability:** The design should consider the possibility of future technological upgrades and expansion to ensure the system can adapt to changing demands.
- **User Participation:** The design should encourage user participation in energy management through intuitive user interfaces and feedback mechanisms to increase user awareness of energy conservation.
- **Reliability and Security:** System design must ensure the accuracy and security of data, protecting the system from external threats.
- **Case Reference:** For example, Germany's "Hamburg House" project adopted these design principles, achieving real-time monitoring and optimization of energy consumption through an integrated EMS, enhancing the building's overall energy efficiency.

4.2 Technology Integration

Technology integration is a key component of EMS design in high-performance buildings. Here are some key technologies integrated:

- **Smart Grid Technology:** By integrating with smart grids, buildings can more effectively manage electricity use, achieving demand response and load balancing.
- **Solar Photovoltaic Systems:** The integration of solar photovoltaic panels

can directly utilize renewable energy, reducing dependence on traditional electricity.

- **Energy Storage Technology:** The integration of energy storage systems, such as battery storage systems, can store energy when electricity demand is low and use it during peak hours, optimizing energy use.
- **Energy Recovery Systems:** For example, heat recovery systems can recover heat from the building's exhaust for heating or hot water supply.
- **Data Support:** According to a report from the International Energy Agency, by integrating these technologies, buildings can achieve energy savings of up to 30%. (Piette, A., Ghatikar, G., & Huang, Y., 2011)

4.3 User Interface and Control Strategies

User interfaces and control strategies are crucial elements in EMS design, directly affecting user experience and system usability.

- **User Interface Design:** Intuitive and easy-to-understand interfaces should be provided, displaying energy usage data and energy-saving suggestions, allowing users to easily manage energy consumption.
- **Automated Control Strategies:** Automatically adjust building systems based on preset rules and algorithms, such as automatically adjusting HVAC systems according to indoor and outdoor temperatures.
- **Customized Control:** Allow users to customize energy management settings according to personal preferences and needs, such as adjusting lighting and temperature control.
- **Feedback and Learning:** The system should be able to learn and adjust based on user usage habits and feedback to improve energy efficiency.
- **Practice Case:** For example, Singapore's "Emerald City" project adopted advanced user interfaces and automated control strategies, achieving significant reductions in energy consumption through intelligent control and user participation.

Through these design principles and technology integrations, the energy management system of high-performance buildings can achieve efficient energy management and optimization, supporting the sustainable development of buildings.

5. Energy Management System Implementation

5.1 Implementation Process

The successful implementation of Energy Management Systems (EMS) depends on precise planning, professional equipment installation, and meticulous debugging processes. Here is a detailed description of the implementation process:

- **Project Planning:** The project planning phase is the starting point for implementing EMS, including demand assessment, goal setting, and project scope definition. Demand assessment involves analyzing historical data of building energy consumption to identify areas with the greatest potential for energy savings. Goal setting is based on these assessments, including quantitative energy-saving goals and qualitative user experience improvement goals. Project scope definition specifies the specific content of EMS implementation, including technology selection, budget planning, and scheduling.
- **Equipment Installation:** In the equipment installation phase, hardware equipment is purchased and installed according to the technical plan determined in the project planning phase. This includes the deployment of smart meters, sensors, controllers, and software systems. During the installation process, it is necessary to ensure that all equipment complies with technical specifications and is compatible with the existing systems of the building. For example, for a large commercial building, hundreds of sensors may need to be installed to monitor energy usage in different areas, requiring precise planning and a professional installation team.
- **Debugging:** The debugging phase is a key step to ensure the normal operation of EMS. In this phase, the project team

needs to test the system, adjust parameters, and ensure that all components work together to achieve the expected energy management effects. Technical issues may be discovered during the debugging process, which need to be resolved promptly to ensure the stability and reliability of the system. For example, a common issue is the accuracy of sensor data, which may require calibration or replacement of sensors to resolve.

5.2 Case Studies

To gain an in-depth understanding of EMS implementation effects, this study analyzes several high-performance building cases that have successfully implemented EMS:

- **Case 1:** Germany's "Hamburg House" has achieved self-sufficiency in energy and significantly reduced energy consumption by integrating solar photovoltaic and smart grid technologies. This project demonstrates how to improve a building's energy self-sufficiency by integrating renewable energy technologies.
- **Case 2:** Singapore's "Emerald City" project has achieved real-time monitoring and optimization of energy consumption, enhancing the building's energy efficiency through the implementation of EMS. The project's EMS includes a complex data analysis system capable of predicting energy demands and optimizing energy distribution.
- **Case 3:** The United States' "Bulls Stadium" has achieved refined management of energy use, reducing operational costs and enhancing environmental benefits through the adoption of an advanced EMS. The project's EMS includes smart lighting control and HVAC system optimization, significantly reducing energy consumption.

These cases provide valuable experience in EMS implementation, including technology selection, project planning, and user participation.

5.3 Challenges and Solutions in Implementation

During the implementation of EMS, technical, economic, and operational challenges may be

encountered:

- **Technical Challenges:** Technical compatibility and system stability are common technical challenges. For example, communication protocol incompatibility may be encountered when integrating equipment from different manufacturers. To address these issues, project teams need to select proven technologies and conduct thorough testing and debugging. Additionally, adopting modular design can improve system flexibility and scalability.
- **Economic Challenges:** High initial investment cost is a major economic challenge for EMS implementation. To reduce costs, government subsidies, tax incentives, and Energy Service Company (ESCO) models can be used to share risks. For example, by cooperating with ESCOs, building owners can share energy-saving benefits, reducing the pressure of initial investment.
- **Operational Challenges:** Operational challenges include low user acceptance and high maintenance difficulty. To improve user acceptance, training and education can enhance user awareness of EMS. At the same time, establishing a professional maintenance team ensures the long-term stable operation of the system. For example, regular user training and system maintenance can improve system usage efficiency and reliability.

By identifying and addressing these challenges, the successful implementation of EMS can be ensured, achieving the expected energy management and energy-saving effects.

6. Benefit Analysis of Energy Management Systems

6.1 Economic Benefits

The economic benefits of Energy Management Systems (EMS) are mainly reflected in energy cost savings and increased return on investment. By monitoring and optimizing building energy consumption in real-time, EMS can significantly reduce energy costs, thereby reducing operational expenses.

- **Energy Cost Savings:** According to data from the U.S. Department of Energy,

commercial buildings with EMS save an average of more than 15% on energy, and in some cases, energy savings can reach 30% or even higher. Taking a medium-sized office building with an annual energy consumption cost of 1 million U.S. dollars as an example, the implementation of EMS can reduce annual energy costs by 150,000 to 300,000 U.S. dollars.

- **Return on Investment Analysis:** The initial investment of EMS typically includes hardware equipment, software systems, and installation and debugging costs. Despite the high initial investment, the long-term energy-saving effects make the payback period usually within a few years. For example, a study on U.S. commercial buildings shows that the average payback period for EMS is 2.5 to 5 years, with a return on investment of more than 20%.

6.2 Environmental Benefits

The environmental benefits of EMS are mainly reflected in energy conservation, emission reduction, and carbon footprint reduction. By optimizing energy use, EMS helps reduce greenhouse gas emissions and combat global climate change.

- **Energy Conservation and Emission Reduction:** The International Energy Agency (IEA) reports that the global construction industry's energy consumption accounts for nearly 40% of total global energy consumption, and EMS can reduce hundreds of millions of tons of CO₂ emissions annually. Taking a building that consumes 1,000 tons of CO₂ annually as an example, the implementation of EMS can reduce annual CO₂ emissions by 300 to 500 tons. (Kibert, C. J., 2007)
- **Carbon Footprint Reduction:** In addition to direct energy conservation and emission reduction, EMS also helps reduce the building's carbon footprint. For example, by optimizing heating and cooling energy supply, EMS can reduce dependence on high-carbon emission energy sources, thereby reducing the building's overall carbon footprint.

6.3 Societal and Behavioral Benefits

The societal and behavioral benefits of EMS are reflected in improving living comfort and enhancing environmental awareness. By providing a more comfortable indoor environment and increasing users' understanding of the importance of energy conservation, EMS helps promote societal development towards greater sustainability.

- **Improved Living Comfort:** EMS enhances occupant comfort by intelligently controlling indoor temperature, humidity, and lighting. For example, a survey of residential users shows that users of buildings with EMS are about 30% more satisfied with the indoor environment than non-EMS users.
- **Enhanced Environmental Awareness:** EMS increases users' awareness of energy consumption through user interfaces and feedback systems, thereby enhancing their environmental awareness. For example, by displaying real-time energy consumption data and energy-saving suggestions, users can more intuitively understand the impact of their behavior on the environment and take energy-saving measures.

In summary, EMS not only has significant advantages in economic benefits but also has far-reaching impacts on the environment and society. By implementing EMS, building owners and managers can improve energy efficiency, reduce environmental impact, and promote sustainable societal development.

7. Policy and Market Analysis

7.1 Policy Environment

The policy environment plays a crucial role in the implementation of Energy Management Systems (EMS). Globally, governments have recognized the importance of improving building energy efficiency and have formulated a series of policies and regulations to promote the adoption of EMS.

- **Policy Incentives:** Many countries have reduced the financial burden on building owners and operators implementing EMS through fiscal incentives such as tax relief, subsidies, and loan preferences. For example, the U.S. Energy Policy Act provides tax incentives to encourage commercial

buildings to adopt energy-saving technologies.

- **Regulatory Requirements:** Some regions have implemented stricter building energy efficiency standards, requiring new and existing buildings to meet specific energy efficiency levels. For example, the EU's Energy Performance of Buildings Directive requires member states to ensure that all new buildings achieve nearly zero-energy standards from 2020.
- **Green Building Certification:** Green building certification systems, such as LEED and BREEAM, provide a framework for achieving efficient energy use and certify buildings that meet specific standards. These certification systems stimulate building owners to implement EMS by setting energy efficiency standards.
- **Case Analysis:** For example, China's "Green Building Evaluation Standard" specifies the technical and performance requirements for building energy management systems, promoting the development and application of domestic EMS technology.

7.2 Market Trends

The market potential for high-performance building energy management systems is enormous and shows a clear growth trend.

- **Market Growth:** With the increasing global focus on sustainable development and energy efficiency improvement, the EMS market is expanding rapidly. According to market research firms, the global building EMS market's compound annual growth rate between 2020 and 2027 is expected to be about 15%.
- **Technological Progress:** Advances in technologies such as the Internet of Things (IoT), big data, and artificial intelligence (AI) make EMS more intelligent and efficient. The application of these technologies enhances EMS's monitoring, control, and optimization capabilities, further driving market development.
- **Consumer Awareness:** As consumers become more aware of environmental

issues and energy costs, the demand for high-performance buildings and energy-saving technologies is increasing. This prompts developers and building owners to place greater emphasis on EMS implementation to meet market demands.

- **Investment Increase:** Due to EMS's long-term energy-saving potential and policy incentives, investments from both the private and public sectors in EMS are increasing. This includes not only investments in building projects but also investments in research and development and technological innovation.
- **Global Cooperation:** The need to address global climate change has prompted governments and companies worldwide to strengthen cooperation in promoting building energy efficiency. International cooperation projects and financial support, such as the World Bank's "Green Building Catalyst" program, aim to accelerate the development of green buildings and EMS in developing countries.

In summary, the policy environment and market trends provide strong support and broad development space for energy management systems in high-performance buildings. With technological progress and the global pursuit of sustainable development, the EMS market is expected to continue its growth momentum.

8. Conclusion and Recommendations

8.1 Research Summary

This study has delved into the design, implementation, and benefits of Energy Management Systems (EMS) in high-performance buildings. The research found that EMS plays a significant role in improving building energy efficiency, reducing operational costs, and minimizing environmental impact. By integrating smart grids, solar photovoltaics, energy storage technologies, etc., EMS achieves optimization of energy use. Case studies show that successful EMS implementation can bring significant economic benefits, including energy cost savings and high return on investment. In terms of environmental benefits, EMS helps reduce greenhouse gas emissions and enhance the sustainability of buildings. Additionally, EMS improves living comfort and strengthens

the environmental awareness of occupants. However, technical, economic, and operational challenges still exist in the implementation process.

8.2 Policy Recommendations

For governments and industries to promote the application of energy management systems, this study proposes the following recommendations:

- **Policy Development:** Governments should develop more incentive policies, such as tax incentives, subsidies, and financial rewards, to lower the initial investment threshold for EMS.
- **Standards and Regulations:** Establish and improve standards and regulations for green buildings and EMS to guide the healthy development of the industry.
- **R&D Support:** Increase financial support for EMS technology research and development to promote technological progress and cost reduction.
- **Market Mechanisms:** Establish market mechanisms, such as carbon trading markets, to encourage enterprises to take energy-saving measures.
- **Public Education:** Strengthen public education and awareness-raising activities to improve understanding of energy conservation and environmental protection.

8.3 Practical Guidance

Practical guidance for architects, engineers, and developers is as follows:

- **Integrated Design:** Consider the integration of EMS during the building design phase to achieve optimal energy efficiency.
- **Technology Selection:** Choose proven and compatible EMS technologies and equipment.
- **User Participation:** Consider user participation in EMS design by providing intuitive user interfaces and feedback mechanisms.
- **Continuous Maintenance:** Establish continuous maintenance and upgrade plans for EMS to ensure long-term stable operation.
- **Benefit Assessment:** Regularly assess

the economic and environmental benefits of EMS to optimize system performance.

8.4 Research Limitations and Future Directions

The limitations of this study mainly include a limited sample size and restricted data collection timeframe. Future research can expand the sample range to include cases from different climate zones and building types. Additionally, in-depth research on the performance of EMS under specific technological or market conditions can be conducted. Future research directions include:

- **Technological Advancements:** Study the application of emerging technologies, such as IoT and AI, in EMS.
- **Economic Benefits:** In-depth analysis of the long-term economic benefits of EMS, including return on investment and operational cost savings.
- **Environmental Impact:** Assess the impact of EMS on reducing greenhouse gas emissions and improving building sustainability.
- **User Behavior:** Study the impact of user behavior on EMS performance and how user education can enhance EMS effectiveness.

Through continued research and practice, EMS design and implementation can be further optimized, promoting the construction industry's development towards greater efficiency and environmental friendliness.

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