The Impact of AI on Enhancing Energy Efficiency in Smart Buildings

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Abstract: The rapid urbanization of recent decades has placed immense pressure on city infrastructure, with buildings representing a substantial share of energy use and greenhouse gas emissions. Advanced technologies offer innovative solutions to these challenges by enabling dynamic and real-time optimization of energy consumption, operational efficiency, and occupant well-being. This rsearch examines various strategies, applications, and obstacles associated with incorporating modern technologies into smart building systems. Key applications include energy efficiency improvements, renewable energy integration, occupant behavior monitoring, and enhanced security measures. The role of tools such as predictive analytics and digital modeling is highlighted. The paper also addresses challenges such as data management, security risks, scalability issues, and infrastructure expenses, proposing strategies like improved training mechanisms, integrated system designs, and sustainable development practices. Future recommendations stress the importance of supportive government policies, financial incentives, and robust frameworks in achieving sustainable urban growth. This review highlights the transformative potential of modern technologies in shaping smart buildings to support a more sustainable and resilient urban environment. **Keywords**: Artificial Intelligence (AI), Machine Learning (ML), Deep Learning (DL), Internet of Things (IoT), Smart Buildings, Building Management Systems (BMS), Energy Efficiency, Predictive Analytics, Energy Management Systems, Smart Grids.

1. Introduction

The rapid urbanization of recent decades has significantly challenged our way of cohabiting. With over 60% of the global population now residing in urban areas [1], the strain on city infrastructure and resources has increased, emphasizing the urgent need for scalable technological solutions. One of the key areas for innovation is the management of building resources, as most urban residents spend the majority of their time indoors [2]. The efficient operation of buildings is essential for achieving sustainability goals, such as reducing energy consumption, minimizing pollution, and enhancing quality of life. However, conventional building management systems (BMS) often rely on fixed schedules and static processes, which do not adjust to fluctuating environmental conditions or occupant behaviors. This lack of flexibility often leads to considerable energy waste and higher operational costs.

However, a major challenge in Building Management Systems (BMSs) is the fragmentation of information, which often results in isolated subsystems like heating, lighting, or air quality, instead of integrating them into a unified system. Initially designed to centralize basic functions such as heating, BMSs have evolved to incorporate advanced technologies for the comprehensive management of lighting, air quality, and energy use. This evolution is leading to the development of more integrated systems, known as Building Operating Systems (BOSs), aimed at improving overall building efficiency. Despite these advancements, there are still gaps in fully realizing the potential of these systems, necessitating further research and development. Global concerns regarding climate change and the rapid depletion of energy resources have highlighted the urgent need for sustainable and energy-efficient solutions across all sectors. Buildings, as one of the largest contributors to energy consumption, account for roughly 40% of global energy use and 33% of greenhouse gas (GHG) emissions. These statistics emphasize the essential role of energy efficiency in urban development to reduce environmental impacts and conserve limited resources.

Smart buildings use IoT sensors to detect and analyze various factors in building parameters that can enhance the building environment and operations. These buildings, utilizing the Internet of Things (IoT) to connect building functions and monitor elements such as temperature, security, and maintenance, can be easily controlled through smartphones and tablets. The IoT is transforming buildings into smarter structures by integrating thousands of sensors and enabling real-time data collection and analysis, thus improving efficiency and user experience.

The rise of advanced technologies provides transformative solutions to these challenges, facilitating a transition from traditional, rigid systems to intelligent and adaptable frameworks. By utilizing tools such as machine learning, predictive analytics, and the Internet of Things (IoT), these technologies enable buildings to dynamically optimize energy usage in real-time. These systems can forecast energy demand by analyzing factors such as occupancy patterns, weather predictions, and historical data. They also integrate smoothly with smart devices and IoT sensors to monitor and adjust energy-intensive systems like heating, ventilation, and air conditioning (HVAC).

The idea of smart buildings represents this shift, where interconnected devices and algorithms analyze large amounts of data to apply real-time energy-saving measures.

AI-Driven Innovations in Smart Buildings:

The integration of advanced technologies into smart buildings has transformed energy efficiency, operational management, and occupant comfort. By utilizing technologies such as machine learning (ML), predictive analytics, and Internet of Things (IoT) integration, smart buildings are becoming more adaptive, efficient, and sustainable. This combination enables real-time decision-making, resource optimization, and system automation, supporting sustainable infrastructure and effectively addressing energy efficiency challenges.

Technologies utilizing advanced methodologies process large datasets gathered through IoT devices, enabling the automation of various building functions such as lighting, heating, ventilation, and air conditioning (HVAC) systems. Predictive models, including techniques like neural networks, deep learning, and support vector machines, are fundamental to these innovations. Neural networks predict heating requirements by analyzing both external and internal environmental factors, offering more precise and efficient energy management. Deep learning models enhance system adaptability and operational intelligence by analyzing complex, hierarchical datasets, allowing for more accurate adjustments based on changing conditions. Time series analysis is used to forecast energy consumption patterns, enabling buildings to anticipate demand and optimize usage. Reinforcement learning algorithms allow systems to adjust dynamically to real-time environmental changes, further enhancing efficiency. In addition, decision trees and regression models are applied to simplify predictive tasks, optimizing energy management and ensuring that energy resources are utilized effectively in both residential and commercial settings. Furthermore, genetic algorithms are employed to improve scheduling and load balancing, optimizing the distribution of energy and improving overall system efficiency, ensuring that resources are allocated appropriately and reducing waste across various building operations.

The integration of advanced technologies into Building Management Systems (BMS) enables real-time data processing, allowing for more proactive management of inefficiencies and emergencies. These systems help optimize building operations by responding quickly to issues as they arise, ensuring smooth and efficient functioning. For example, adaptive lighting control systems play a crucial role in minimizing energy wastage by adjusting lighting levels based on occupancy or time of day, thereby reducing unnecessary energy consumption. Predictive maintenance algorithms further improve the reliability of HVAC systems by analyzing usage patterns and identifying potential failures before they occur, preventing costly breakdowns and ensuring optimal system performance.

Additionally, Demand Response Programs (DRPs) are implemented to optimize energy use during peak demand periods. These programs manage resource consumption by adjusting energy usage across various systems in real-time, helping to balance the grid and reduce strain on energy infrastructure. Hybrid algorithms, which combine predictive maintenance with optimization techniques, offer a comprehensive approach to streamlining building operations. These algorithms not only ensure that maintenance is performed before issues escalate but also optimize various operational aspects of the building, such as energy distribution and resource allocation. By incorporating such strategies, buildings can improve efficiency, reduce operational costs, and support environmental sustainability, contributing to a more energy-efficient and sustainable urban environment.

Despite these advancements, challenges remain, including cybersecurity vulnerabilities, scalability concerns, and the need for standardized IoT protocols. Addressing these issues is essential for ensuring smooth integration of advanced technologies into smart building infrastructures. However, the ability to combine data-driven insights with real-time data collection from IoT devices has been instrumental in advancing sustainable building designs. As smart buildings continue to progress, the combination of these technologies will be critical in improving energy efficiency, operational sustainability, and occupant comfort[3][4].

The extensive use of advanced technologies in smart buildings guarantees that they not only address the current need for operational efficiency but also make a significant contribution to environmental sustainability. These technologies help minimize resource wastage by optimizing energy usage, thereby reducing the overall consumption of valuable resources. Furthermore, they enhance the adaptability of building systems, allowing them to adjust dynamically to varying environmental conditions and occupant needs. This ability to respond in real-time ensures that smart buildings remain efficient and sustainable over the long term, supporting broader goals of reducing environmental impact while improving the quality of life for building occupants. As a result, these systems are a critical component in the transition towards more sustainable urban development, making it possible to achieve both operational efficiency and environmental responsibility in the built environment.

The graph illustrates the percentage distribution of different applications of advanced technologies and the Internet of Things (IoT) in improving smart building functionalities.

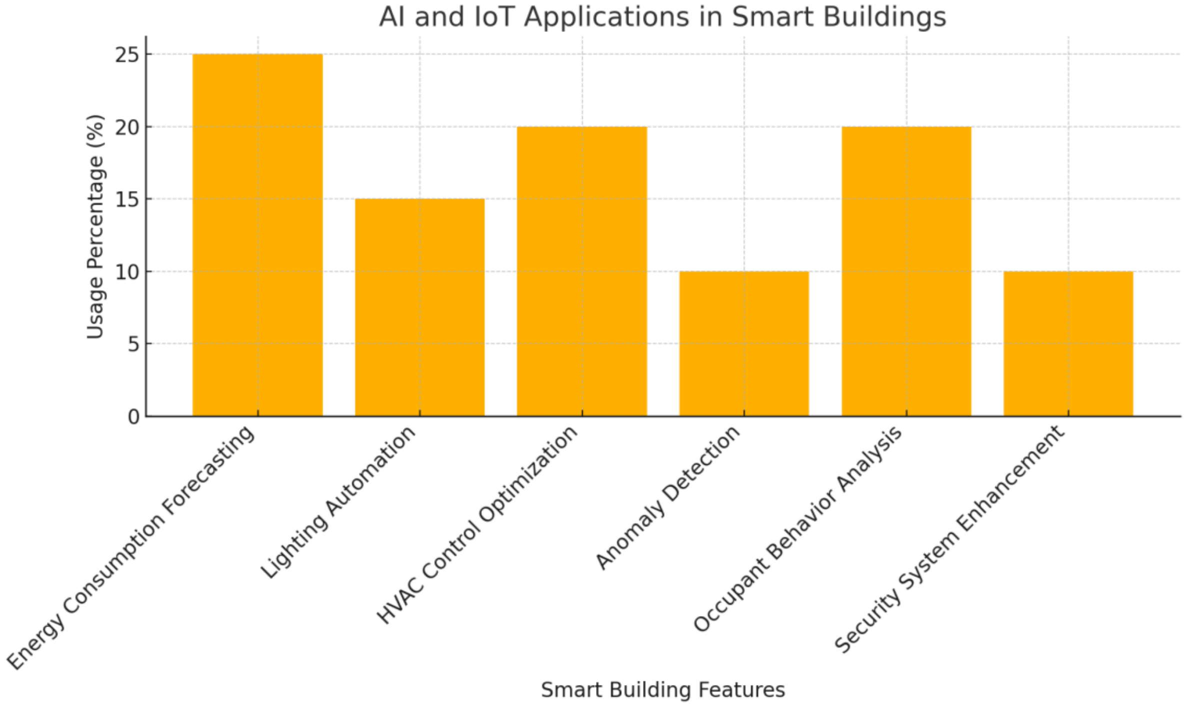

Figure 1: AI and IoT Applications in Smart Buildings

The methodology outlined in [5] focuses on improving energy efficiency in smart buildings through the integration of IoT-based systems and innovative energy management practices. At the core of this approach is a sensor-based architecture that gathers real-time data on environmental factors such as temperature, humidity, and air quality using wireless sensor networks. This data is processed and stored in cloud-based systems, allowing for smooth communication and analysis. A proposed smart building template, overseen by a Building Energy Management System (BEMS), continuously monitors and adjusts systems like HVAC, lighting, and domestic hot water based on occupancy and environmental conditions. The methodology also incorporates renewable energy sources such as solar photovoltaic systems and thermal energy storage, decreasing reliance on conventional energy sources and fostering sustainability.

To optimize energy usage and ensure occupant comfort, the BEMS utilizes predictive algorithms and infrared sensors to detect room occupancy, intelligently controlling energy-consuming systems to reduce wastage. The methodology also facilitates remote and automated building certification and ensures compliance with European energy efficiency regulations, making it scalable and adaptable to various building types. However, the approach recognizes challenges, including data security, integration difficulties, and the need for a strong IoT infrastructure. Overall, the methodology effectively combines IoT and energy management strategies to offer a comprehensive, sustainable, and scalable solution for enhancing energy efficiency in smart buildings.

Another researcher examines the application of advanced technologies and Big Data (BD) to energy-efficient buildings, emphasizing their combined role in optimizing energy usage and improving indoor comfort. The approach uses data-driven platforms consisting of sophisticated algorithms, simulation tools, and data visualization systems. These platforms analyze data from IoT sensors, weather databases, and historical building performance records to make dynamic, real-time adjustments to building systems such as HVAC, lighting, and insulation. Key techniques include machine learning (ML) and deep learning (DL) for predictive modeling of energy consumption and environmental factors. Algorithms such as Support Vector Regression (SVR), Neural Networks (NNs), and Genetic Algorithms (GA) are used to improve decision-making processes. For example, predictive models calculate optimal settings for heating and cooling loads based on occupancy and weather data. Additionally, energy dashboards and simulation tools like EnergyPlus are integrated to monitor performance and validate building energy consumption forecasts.

The methodology also incorporates Big Data (BD) to support advanced systems in real-time data mining and decision-making. Databases such as weather repositories and Building Information Models (BIMs) play a crucial role in providing context-specific data that improves operational efficiency. This approach is enhanced by innovative building technologies, such as smart windows with adjustable opacity and thermal diodes for dynamic heat flow management, which further contribute to energy efficiency.

Overall, the methodology offers a robust and scalable framework for utilizing advanced data systems in sustainable architecture. However, challenges related to data integration, scalability, and the computational demands of these systems remain important areas for further research and development[6].

Another approach uses bibliometric analysis to evaluate the application of advanced technologies in green and smart buildings. The methodology is structured into five systematic steps: defining the research field, selecting relevant databases, adjusting research criteria, codifying retrieved material, and analyzing the information. Key databases, including Web of Science (WoS) and Scopus, were utilized. Data was codified using tools like Excel and VOSviewer, enabling visualization of keyword co-occurrences and network relationships among authors, institutions, and countries. The methodology further emphasizes temporal and content analysis, highlighting trends in applications for sustainability, energy efficiency, and user comfort in building management systems. Additionally, keywords like machine learning, deep learning, and Internet of Things (IoT) were analyzed to identify evolving research areas[7].

The approach offers a strong framework for understanding the interdisciplinary applications of advanced technologies in sustainable architecture. However, it also highlights challenges such as gaps in global collaborations, limited integration of Industry 4.0 concepts, and the need for more practical implementations of these technologies in real-world buildings. This bibliometric review not only evaluates past trends but also lays the groundwork for future research directions in technology-driven sustainable building advancements.

Another research develops a comprehensive methodology to explore the integration of advanced technologies into the renewable energy (RE) sector within the context of European smart cities. The research employs a multidimensional approach to assess macroeconomic and technological factors influencing RE adoption and performance. Key aspects of the methodology include the use of macroeconomic data, advanced algorithms, and sector-specific performance indicators.

The study uses data from international organizations such as Eurostat, the European Commission, and the United Nations to evaluate Gross Inland Consumption, transformation efficiency, and labor productivity in the RE sector. The methodology also incorporates advanced technologies, including machine learning and computational neural networks, to model energy consumption patterns, optimize grid performance, and predict renewable energy supply fluctuations.

Further, the research introduces the concept of "Smart Energy Infrastructure as a Service (SEIaaS)" to propose a scalable model for integrating advanced technologies into RE systems. This includes exploring centralized control systems, intelligent storage solutions, and predictive algorithms to manage supply-demand fluctuations effectively. The integration of these technologies with IoT and 5G is also highlighted as a transformative approach to modernizing energy grids.

While the methodology emphasizes the benefits of advanced technologies in enhancing energy efficiency and sustainability, it also addresses challenges such as data integration, infrastructure costs, and labor market shifts. The research model sets the foundation for future studies on technology-driven smart energy systems and their role in achieving sustainable urban development[8].

Applications of AI and IoT in Smart Buildings

Energy Optimization

IoT technologies play a transformative role in optimizing energy use within smart buildings. Advanced predictive models are deployed to analyze and control energy-intensive systems such as HVAC and lighting. These models not only forecast energy demands but also identify inefficiencies and recommend real-time adjustments to reduce consumption. Additionally, IoT sensors provide continuous monitoring of energy usage across building systems. By enabling real-time data collection and adaptive control mechanisms, these sensors ensure optimal resource utilization, significantly minimizing energy wastage and operational costs[5].

Renewable Energy Integration

Advanced technologies enhance the integration and management of renewable energy systems, such as solar panels and wind turbines, within smart buildings. By leveraging IoT, these energy systems are linked to smart grids that dynamically balance energy supply and demand, ensuring efficient storage and distribution. Predictive algorithms forecast renewable energy generation patterns based on weather data and consumption trends, further improving system reliability and sustainability. This integration supports the global transition towards low-carbon energy solutions and aligns with the objectives of future smart cities.[8].

Occupant Comfort and Behavior Analysis

Advanced models are increasingly being used to enhance occupant comfort by analyzing behavior patterns and environmental preferences. These models optimize parameters such as thermal comfort, lighting levels, and air quality by adjusting building systems in real time[6][7]. Reinforcement learning, a technique enabling autonomous systems, allows these systems to learn and adapt to individual occupant needs, ensuring personalized comfort while maintaining energy efficiency[8]. These technologies create intelligent environments that respond dynamically to occupants' preferences, leading to greater satisfaction and productivity.

Security and Safety Enhancements

IoT and advanced technologies significantly bolster the security and safety of smart buildings. IoT-enabled fire alarms, surveillance systems, and access controls provide real-time monitoring and rapid response capabilities. Algorithms enhance these systems by detecting anomalies, such as unauthorized access or unusual activity patterns, and predicting potential threats[1][9]. These proactive measures not only improve safety but also reduce risks associated with emergencies, ensuring a secure environment for occupants.

Smart Energy Infrastructures

The development of smart energy infrastructures is vital to the progress of smart buildings, with advanced tools driving their implementation. Digital twins, for instance, simulate building operations, allowing for predictive maintenance and optimization of systems. These simulations help facility managers predict potential problems, reducing downtime and maintenance costs[8]. Integrating these infrastructures with IoT improves data-driven decision-making, ensuring efficient energy management and operational resilience. Combined, these technologies form a strong basis for scalable and sustainable smart building ecosystems.

Challenges in AI and IoT Integration for Smart Buildings

Data Management

The vast amount of data produced by IoT sensors in smart buildings presents considerable challenges related to storage, processing, and integration. IoT devices continually gather high-resolution data on various factors, such as energy consumption, environmental conditions, and occupant activities. Handling such large-scale, diverse data demands advanced analytics platforms that can process the information in real-time. Furthermore, the integration of data from different building systems adds complexity, requiring strong frameworks for interoperability and scalability[3][5].

Cybersecurity Risks

The interconnected nature of IoT devices in smart buildings introduces vulnerabilities to cyber threats. These systems often lack sufficient protection against hacking, data breaches, and other malicious activities. Advanced encryption techniques, such as CoAP with DTLS protocols, are necessary to ensure secure communication between devices and prevent unauthorized access[9]. Despite these security measures, the complexity of safeguarding IoT networks remains a significant challenge, especially in large-scale implementations where the potential for attacks increases.

Scalability and Standardization

Expanding IoT networks to support different building types is challenging due to the absence of standardized protocols, data formats, and system architectures. This lack of uniformity obstructs smooth integration and restricts the scalability of smart building systems. Additionally, applying consistent frameworks across diverse building designs, locations, and usage scenarios requires substantial customization and expertise, which can slow down the widespread adoption[7][8].

Infrastructure Costs

The high initial costs of deploying smart technologies present a significant barrier, particularly in developing regions. Investment in sensors, gateways, cloud infrastructure, and advanced platforms is substantial, making these systems inaccessible for many organizations. Furthermore, ongoing costs related to maintenance, upgrades, and energy consumption add to the financial burden. These economic challenges require policy incentives and funding support to accelerate adoption.

Energy Efficiency Challenges

While smart buildings aim to achieve near-zero energy buildings (NZEB), optimizing renewable energy sources and integrating them with existing infrastructures remain complex. Balancing the intermittent nature of renewable energy, such as solar and wind, with consistent energy demand is challenging. Advanced algorithms play a critical role in addressing this issue, but their effectiveness is often limited by the quality and availability of data. Achieving energy efficiency goals requires innovative approaches and advanced control systems to overcome these hurdles.

Limited Adaptability

Current models in smart buildings face difficulties in adapting to unpredictable changes in user behavior, occupancy patterns, and environmental conditions. For instance, sudden shifts in energy demand or unusual weather conditions can disrupt system performance. Adaptive algorithms and learning techniques are being explored to address these challenges, but their development and implementation remain in early stages. Enhanced adaptability in these systems is crucial for building resilience and ensuring optimal performance under dynamic conditions.

Below is a comparison table summarizing the methodologies, applications, and challenges discussed across the reviewed articles:

Table 1 : Advancements, Applications, and Challenges in Machine Learning and IoT for Smart and Energy-Efficient Buildings

Paper Title	**Methodology**	**Applications**	**Challenges**
The Role of ML and IoT in Smart Buildings	Integration of IoT sensors for real-time monitoring, combined with models for predictive analytics. Focus on energy efficiency, occupant comfort, and safety systems.	Smart energy management, HVAC optimization, and occupant behavior analysis.	Data management, cybersecurity, and scalability issues.
Evolution of Smart Buildings for Energy	Machine learning-driven Building Management Systems (BMS) for demand-response programs and real-time energy optimization. Evaluation of models for energy prediction and efficiency improvements.	Demand forecasting, adaptive energy systems, and indoor climate control.	High infrastructure costs and limited adaptability to unpredictable conditions.
Energy Efficiency in Smart Buildings: IoT	IoT-based architecture integrating renewable energy sources with smart grids. Cloud-based systems for energy monitoring and compliance with regulatory frameworks.	Renewable energy integration, automated certification, and compliance.	Complexity of achieving NZEB and challenges in energy regulation compliance.
Big Data and Building Energy Efficiency	Use of big data analytics and machine learning for energy forecasting, occupant comfort optimization, and intelligent control systems. Integration of building information models (BIM).	Sustainable building design, energy forecasting, and environmental impact reduction.	Data integration, lack of standardization, and computational resource requirements.
Review of Green/Smart Buildings	Bibliometric analysis and keyword co-occurrence to assess applications in sustainable buildings. Adaptive control systems and embedded	Enhanced indoor comfort, energy efficiency, and user-driven system	Scalability of solutions and cost-effectiveness of implementation.

	agents for user interaction.	adaptability.	
Applications for Smart Buildings	Deep reinforcement learning for autonomous energy management. Digital twins as training environments to improve adaptability to dynamic changes.	Autonomous building systems, energy market participation, and predictive maintenance.	Limited availability of training data and adaptability to abrupt changes.
Secure and Energy Smart IoT for Buildings	IoT architecture employing CoAP with DTLS protocols for secure communication. Use of SHA-256 for data encryption and lightweight energy monitoring systems.	Secure energy systems, latency reduction, and scalable IoT applications.	Cybersecurity risks, data encryption challenges, and system latency in large-scale deployments.
Smart Renewable Energy in Europe	Framework for renewable energy systems integration, with a focus on energy chain optimization and smart grid performance. Incorporation of cognitive computing for better decision-making.	Smart grids, renewable energy forecasting, and optimization of energy infrastructure.	High cost of infrastructure deployment and the complexity of aligning systems across different socio-economic areas.

This table outlines the comparative methodologies, their practical uses, and the inherent challenges, offering a concise overview for future research or documentation.

Future Directions

Enhanced Training Environments

The implementation of digital twins and sophisticated simulation platforms marks a substantial advancement in refining AI training for smart buildings. Digital twins replicate physical systems virtually, enabling AI models to train and adapt without causing real-world disruptions. These platforms facilitate the simulation of intricate scenarios, such as shifts in occupancy trends, weather variability, and fluctuating energy demands, enabling AI systems to anticipate and optimize performance across diverse conditions. Additionally, simulation platforms offer a controlled environment for testing and enhancing reinforcement learning algorithms, improving the flexibility and dependability of autonomous systems. By incorporating detailed data inputs and real-time feedback mechanisms, these training tools significantly lower the costs and duration of AI development while boosting decision-making precision.

Holistic AI Models

Creating integrated models is critical for tackling the diverse challenges associated with managing smart buildings. These models unify key functions like occupant behavior assessment, energy management, and security within a single framework. For instance, machine learning techniques can study behavioral trends to adjust HVAC and lighting systems while simultaneously identifying irregularities to improve safety. By merging these functionalities, integrated models ensure buildings are both energy-efficient and secure while prioritizing user experience. Furthermore, the inclusion of cross-sector data, such as weather patterns and energy market rates, enables predictive maintenance and economical energy usage. These systems have the potential to evolve smart buildings into adaptive, self-sustaining environments that dynamically adjust to operational and environmental variations.

Policy and Incentives

Government policies and support are crucial in promoting the implementation of advanced technologies in renewable energy and modern building systems. Authorities can accelerate this shift by offering financial benefits, such as tax reductions and grants, to boost investments in IoT and related infrastructures. Additionally, formulating comprehensive guidelines for data security, interoperability, and system privacy can mitigate several obstacles linked to widespread adoption. Collaborations between public and private sectors can drive advancements by funding research in innovative solutions for smart buildings. Furthermore, programs like eco-friendly building certifications can encourage the use of sustainable technologies, aiding global environmental objectives and minimizing urban carbon emissions.

Sustainable Design Integration

Integrating advanced technologies into the initial phases of designing sustainable buildings is essential for achieving long-term energy and ecological advantages. These tools can process historical data and model prospective scenarios to guide material selection, structural layout, and energy systems. For instance, advanced algorithms can determine the ideal orientation and insulation strategies to reduce heating and cooling demands. Additionally, such tools facilitate the seamless incorporation of renewable energy systems, like solar arrays and wind turbines, by forecasting energy output and synchronizing it with expected usage. Embedding smart solutions into the architectural planning process ensures that sustainable buildings achieve optimal energy performance, occupant well-being, and resilience to environmental shifts. This anticipatory approach reflects the core values of eco-friendly design, enabling buildings to positively impact both society and the planet.

These future direction collectively underscore the revolutionary potential of advanced technologies in shaping intelligent, eco-friendly, and resource-efficient building systems. By overcoming existing obstacles and promoting forward-thinking solutions, these developments lay the groundwork for a more advanced and sustainable architectural landscape.

Conclusion:

The growing urbanization of contemporary society has significantly strained city infrastructures, calling for innovative technological measures to tackle resource allocation and sustainability concerns. Intelligent buildings, supported by cutting-edge technologies and interconnected systems, offer transformative potential to improve energy use, operational oversight, and occupant well-being. Through the use of advanced computational models, predictive techniques, and sensor-equipped devices, these frameworks adaptively enhance building performance, minimize resource wastage, and promote environmental responsibility.

This analysis emphasized crucial techniques, practical uses, and obstacles related to the incorporation of advanced technologies in intelligent buildings. Uses such as energy management, sustainable energy incorporation, user behavior evaluation, and safety improvements demonstrate the diverse advantages of these systems. Nonetheless, hurdles like handling large datasets, security vulnerabilities, scalability limitations, and substantial implementation costs need to be resolved to fully harness the capabilities of such innovations.

Upcoming strategies highlight the utilization of virtual replicas and simulated settings for improved system training, the creation of comprehensive models for unified management, and the importance of policy support to boost technology uptake. Incorporating sustainable designs and active governmental backing will be critical in addressing present obstacles and promoting the extensive adoption of intelligent infrastructure solutions.

As cities aim for sustainability and resilience, the integration of advanced technologies offers a pathway to achieving energy-efficient, adaptive, and user-centric building ecosystems. Addressing current challenges through research, innovation, and collaboration will unlock the transformative potential of smart buildings, contributing significantly to global sustainability goals and enhancing quality of life in urban environments.

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