Recent Research Progress on Sustainable Energy Management System Based on Energy Efficiency and Renewable Energy

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Abstract. Energy Management Systems (EMS) have become increasingly important in efforts to address global energy challenges, such as increasing energy demand and climate change. EMS can be used to improve energy efficiency; reduce greenhouse gas emissions; and increase energy security. The purpose of the research is to review the latest research progress which focuses on EMS from various sectors based on energy efficiency and renewable energy. This research method involves four steps: selecting the EMS topic, searching for related papers using keywords on Google Scholar; summarizing and categorizing the obtained papers, and creating a table for easy understanding of the collected research; followed by analysis and discussion. As a result, recent research progress on sustainable EMS has been discussed, emphasizing categories like IoT; cloud data; controllers; reinforcement learning; renewable energy sources; energy storage; energy trading; and dashboards. The focus in EMS studies lies on IoT devices; controllers; reinforcement learning; and renewable energy; with less emphasis on energy trading and dashboards. The primary objective is to facilitate energy use tracking for users in various sectors, enabling them to assess efficiency and cost-effectiveness. This review facilitates energy tracking across diverse sectors for users, enabling evaluation of efficiency and cost-effectiveness.

Keywords: Green energy system, home energy storage, IoT, smart grid, smart home

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1 Introduction

In the contemporary era, the role of Energy Management Systems (EMS) is becoming increasingly important. EMS is expected to address the complex challenges posed by increasing energy demand and the importance of sustainable resource utilization [1]. It is predicted that total final energy consumption will increase by 29 % by 2030 and 49 % by 2050 [2], indicating that environmental issues will be a major concern for effective EMS in the future. Balancing development with ecological preservation, it's crucial to adopt advanced EMS solutions. EMS aims for immediate efficiency gains and serves as a foundation for a resilient, eco-conscious energy landscape in the future. A robust EMS not only facilitates the optimization of energy utilization but also plays a pivotal role in mitigating carbon emissions and fostering environmental stewardship.

When embarking on a deeper exploration of the critical role of EMS, it is important to contextualize our understanding of the current research landscape and scientific discourse. The existing literature on EMS reflects a growing awareness of its importance, with research exploring various aspects, such as technological advancements, policy implications, and socio-economic dynamics of energy consumption. Recent research has begun to examine the effectiveness of different EMS strategies in diverse contexts, with associated implementation nuances and challenges. However, according to the International Renewable Energy Agency (IRENA), global energy-related CO_2 emissions in the Renewable Energy map (Re-map) scenario are projected to fall by 70 % from current levels. This estimate suggests that 75 % of the reduction can be achieved through renewable energy and electrification technologies. If energy efficiency is included, this share increases to more than 90 % [2]. Energy efficiency and renewable energy are two important pillars in the transition to clean energy. Energy efficiency can help reduce demand for fossil energy, while renewable energy can help meet that demand in a sustainable way.

Many researchers have studied the application of EMS, which is considered to have an important role in improving energy efficiency and facilitating the integration of renewable energy sources in various sectors. The sectors include industrial, urban, residential, grid interactive building and data center environments. In the industrial sector, Bagdadee *et al.* [3] described using smart technology in industries to boost equipment power through efficient energy planning and wireless power transfer from IoT devices. Found that smart industrial facilities, when studied in specific cases, show a balance in meeting energy demands. Wang *et al.* [4] conducted study for smart cities and industrial parks, analyzing pilot projects, technical progress, incentives, and policies. Explored how smart solutions could improve decision-making in urban planning and low-carbon sectors. Tabaa *et al.* [5] developed a Green Industrial Internet of Things (GIIoT) and various applications and perspectives following a discussion on how the Internet of Things (IoT) impacts industry. The results indicate that IoT plays a crucial role in the success of the industrial revolution.

Zonta *et al.* [6] created an Internet of Things (IoT)-based system for monitoring, operating, and maintaining Predictive Maintenance (PdM) in Industry 4.0. The results achieved decreased downtime, minimized energy losses, and improved efficiency. Kychkin *et al.* [7] described in an EMS, established an IoT-based energy planning and monitoring system, allowing real-time reading of all parameters. Gohel *et al.* [8] described Machine Learning has been applied to analyze PdM, enabling the identification of speech, management of IoT equipment, and even control of unmanned vehicles for forecasting and preventing breakdowns and disturbances in nuclear power plants at the earliest possible stage. Falekas and Karlis [9] suggested employing AI, specifically Digital Twin and nexDT, for the Predictive Maintenance (PdM) of electrical machines like Squirrel Cage Induction Motor (SCIM), Synchronous Machine (SM), Wound Rotor Induction Motor (WRIM), Permanent Magnet Synchronous Machine (PMSM), multiphase Alternating Current (AC) machine, and

Switched or Synchronous Reluctance Machine (SRM or SynchRM). Ferrández-Pastor *et al.* [10] designed a process for building AI-powered renewable energy systems that monitor equipment and optimize self-consumption for cost savings.

Yandri *et al.* [11] designed and analize reduction in material costs by using a combination of raw materials and recycled materials. This is also an example of optimization, as it is making the machine more efficient by using less material. Yandri *et al.* [12] optimized a small laundry's energy use through solar integration and practical efficiency upgrades, fueled by an energy audit. Yandri *et al.* [13] designed an information control system that harnesses IoT to energize green manufacturing industries for efficiency and productivity gains. Yandri *et al.* [14] revolutionize textile dyeing with a cleaner production loop that recycles wastewater through inlet-outlet mods, saving energy and water. In the urban sector, Huseien and Shah [15] researched 5G applications for smart buildings, including development, use cases, and future projects supported by the Singapore government. Khajenasiri *et al.* [16] have studied how IoT is used to monitor Emergency Medical Services (EMS) in different urban areas, including telemedicine and health care, smart homes and cities, embedded mobile devices, vehicles, agriculture, energy usage, security and surveillance, and building management. Kanagachidambaresan *et al.* [17] have examined the use of IoT technology in smart parking systems, which will improve time efficiency, save fuel, and reduce emissions. Selvaraj *et al.* [18] suggested an AI technique, named AIMS-SB, to act as a monitoring system in smart buildings. Its primary role is to control the generation, usage, and recycling of energy required by the building.

Chen *et al.* [19] have suggested an outdoor lighting system for residential areas using IoT, named EESSRLS (Energy Efficient Smart Street Road Lighting System). This system can intelligently adjust the on-off and brightness of lights based on human activities, resulting in substantial energy savings. Gu *et al.* [20] have integrated CCHP (Combined Cooling, Heating, Power) with renewable energy sources. This combination offers solutions to energy challenges like rising demand, costly energy, security, and environmental issues. Chinnathambi *et al.* [21] suggested a smart EMS (Energy Management System) for grid-connected solar-powered homes using IoT technology. Tseng *et al.* [22] set up a system that combines cloud management and wireless sensing networks to track and measure the impact of green projects in urban areas, particularly on campuses. Mahmoud *et al.* [23] suggested a real-time IoT-based EMS for green buildings to enhance energy monitoring and save more energy. Hijawi *et al.* [24] suggested an EMS for school buildings using affordable Internet of Things (IoT) devices. Sharaf El-Din *et al.* [25] investigated how the use of renewable energy relates to the adoption of sustainable building design, especially in the context of EMS and environmentally friendly green building design. Giglio *et al.* [26] created a smart EMS for city buildings that efficiently combiness photovoltaic and storage systems, especially in residential areas. Han *et al.* [27] created a smart energy management system using AI to improve efficiency in urban buildings with solar and storage systems.

In the residential sector, Han *et al.* [28] developed a HEMS architecture for enhanced home energy efficiency and cost savings, accessible via smartphone. Hasan *et al.* [29] empowered consumers with remote appliance control through a smart, transparent, and adaptable IoT-based EMS, accessible via smartphones. Gherairi [30] combined solar, fuel cells, supercapacitors, and vehicle-to-home power, and found that smart scheduling saved energy without needing extra grid power. Yousefi *et al.* [31] highlighted how EMS empowers smart homes to be more efficient, economical, reliable, and energy-saving. Kulkarni and Chitre [32] designed, implemented, and tested it to manage energy in an IoT-connected home. Ranjith *et al.* [33] have proposed engineered a multicore brain for smart home energy, optimizing efficiency, performance, and reliability. Sultan *et al.* [34] proposed and implemented a system that uses intelligent agents to schedule and manage appliances seamlessly. Yuan *et al.* [35] pioneered a real-time home energy management system with a cutting-edge algorithm that predicts and optimizes energy scheduling. Condon *et al.* [36] designed and implemented a Cloud-IoT system that optimizes how you use energy. Yandri *et al.* [37] conducted study energy security with an ICT-powered tracking system, diving deep into availability, efficiency, affordability, sustainability, and governance.

In the Grid Interactive building sector, Fotopoulou *et al.* [38] introduced a cutting-edge strategy for buildings with solar panels and batteries, maximizing efficiency and control. Tushar *et al.* [39] analysed the pros and cons of Negawatt trading in the context of new energy market technologies. Pinto *et al.* [40] minimized the risks of grid instability and streamlined renewable integration in building energy. Pipattanasomporn *et al.* [41] revealed the power of BEMOSS, an open-source software that connects IoT devices, enabling interactive and intelligent building management. Yandri *et al.* [42] designed a smart energy management system for UNSADA Jakarta, building on a prior audit. In the data center sector, Vasques *et al.* [43] analysed the landscape of energy efficiency and demand response strategies for small and medium-sized data centers through a comprehensive literature review. Dikaiakos *et al.* [44] transformed a mid-scale academic data center into an eco-powered marvel with solar energy, IoT sensors, and smart analytics. Antal *et al.* [45] have addressed the issue of energy efficiency in data center, its integration into electrical and thermal networks. Wan *et al.* [46] greened data centers with a smart system that combines cooling, heating, and power, maximizing efficiency and minimizing waste.

Based on previous research, EMS has been used in various sectors; including industrial applications [3, 4, 5–14], urban [15–27], residential [28–37], commercial buildings [38–46]. However, there is still very little research related to the current state of the art in EMS with a focus on the integration of energy efficiency and renewable energy. Although studies have investigated certain aspects individually, there has been no research in EMS that has discussed them comprehensively. This research aims to review the latest research progress which focuses on EMS from various sectors based on Energy Efficiency and Renewable Energy.

2 Methodology

To review the progress of recent research focusing on energy management systems focusing on EMS from various sectors of the field generally depicted in Figure 1 as can be seen the need for energy management systems that have been widely used in various sectors, from various sectors to make efficiency which will be connected to the grid (power import and export) and renewable energy as a supply.

Several steps were taken to achieve this goal. First, determine the topic of the Energy Management System, namely: (i) **Smart Energy Management for Residential Users:** Discuss how EMS technology is empowering homeowners to monitor and control their energy consumption through smart devices, optimizing energy usage, and reducing costs. (ii) **Renewable Energy Integration via EMS:** Explore how EMS solutions are essential for efficiently integrating intermittent renewable energy sources like solar and wind into the power grid. Discuss the challenges and benefits. (iii) **Hybrid Energy Systems and EMS:** Delve into the role of EMS in managing hybrid energy systems that combine conventional and renewable sources, ensuring reliability, and reducing environmental impact. (iv) **Smart Home Energy Systems with EMS:** Detail the workings of EMS within smart homes, covering aspects such as real-time energy monitoring, load balancing, and integration with IoT devices for a more sustainable lifestyle. (v) **Smart-Green Industry with EMS:** Discuss how EMS is transforming industrial processes by optimizing energy usage, reducing waste, and improving sustainability, ultimately making industries eco-friendlier and more cost-effective

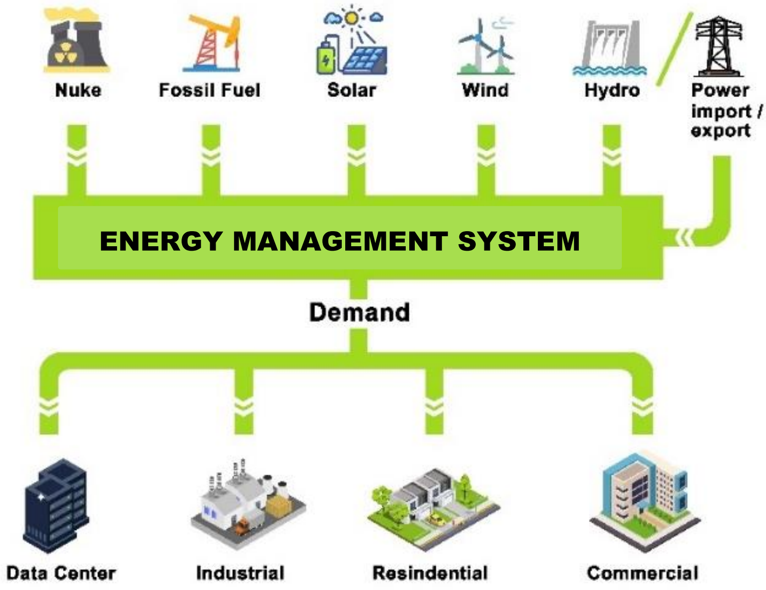

Fig. 1. EMS from various sectors.

(vi) **Green Building Practices and EMS:** Explore how EMS is integral to green building certification standards, such as LEED and BREEAM, by enabling real-time monitoring and control of energy consumption, lighting, and HVAC systems. (vii) **Intelligent Cities and EMS:** Explain how EMS is a cornerstone of smart and intelligent city initiatives, facilitating efficient energy use, reducing carbon emissions, and enhancing overall urban sustainability. (viii) **Grid-Interactive Buildings with EMS:** Discuss the concept of grid-interactive buildings that use EMS to actively respond to grid conditions, adjusting energy usage and even feeding excess power back to the grid. (ix) **Energy Storage Integration via EMS:** Elaborate on how EMS systems are essential for managing energy storage solutions like batteries and their role in balancing supply and demand in renewable energy grids. (x) **Energy Efficiency in Data Centers with EMS:** Explore the critical role of EMS in optimizing energy usage within data centers, which are large energy consumers, to improve efficiency and reduce environmental impact. (xi) **Energy Analytics and Predictive Maintenance:** Explain how EMS utilizes advanced analytics and machine learning to predict equipment failures and optimize maintenance schedules, reducing downtime and energy waste. (xii) **Resilience and EMS in Disaster-Prone Areas:** Discuss how EMS can enhance energy resilience in areas prone to natural disasters by enabling swift response, backup power systems, and efficient resource allocation. (xiii) **Policy and Regulatory Framework for EMS Adoption:** Analyze the role of government policies, incentives, and regulations in promoting EMS adoption across residential, commercial, and industrial sectors, and its contribution to sustainability goals.

Second, searching for related papers using a search engine (Google Scholar) with the keywords EMS implementation in smart grid, smart home and building, smart industry, energy storage, green energy system, IoT and smart city. Third, make a summary based on the papers that have been obtained using keywords and then grouped by category as below: (i) **IoT Devices**: Physical devices that are connected to the internet and can communicate with each other to collect, send, and exchange data to provide integration and automation capabilities in various contexts. IoT devices are used to collect energy consumption data from various sources, such as appliances, HVAC systems, and lighting. This data can then be used to analyse energy consumption patterns and identify opportunities for savings. (ii) **Cloud Data**: Data storage and processing performed in a remote data center over the internet, allowing flexible access, management, and analysis of data without relying on local physical resources. Cloud data is used to store and analyse energy consumption data on a large scale. This allows researchers and developers to develop more efficient energy management algorithms. (iii) **Agent Controller**: A software component responsible for managing and directing the behaviour of agents (software agents) in a distributed system or distributed environment. Agent controllers are used to automate energy management tasks, such as turning appliances on and off or adjusting HVAC system settings. This can help reduce energy consumption without sacrificing comfort. (iv) **Deep Reinforced Learning**: A machine learning approach that combines deep learning techniques with reinforcement learning, where the agent learns to make decisions automatically through interactive experience with its environment. Deep Reinforcement Learning is a machine learning technique that can be used to develop energy management systems that can learn from data and adapt to changing conditions. (v) **Renewable Energy Resources**: Energy sources obtained from renewable natural sources, such as sunlight, wind, water, and biomass, which are not only environmentally friendly but can also be produced sustainably. (vi) **Energy Storage**: The process of storing energy for future use, enabling the collection and storage of energy from non-conventional sources such as solar and wind energy, and the use of energy when needed. (vii) **Energy Trading**: The commercial buying and selling of energy, including electricity or fuel, on energy markets to take advantage of price fluctuations and maximize the efficiency of energy resource management. (viii) **Dashboard**: A visual interface that presents information in a concise and organized manner in the form of graphs, tables, or other metrics, allowing users to quickly understand and monitor relevant performance or data within a system or process.

Fourth, a summary table was created to make it easy to understand the current research collected in step two. The table contains the topics determined in the first step and then combined with the categories in the third step. Next, analyze and discuss based on the summary table.

3 Result and discussion

Table 1 describes the research of EMS application in sector overview based on the first step of the methodology (13 topics) and the second step (eight categories). A category mapping was performed on all the research, so that the categories covered by each topic became visible. As can be seen, the number of sector studies addressing EMS refers to the research interest categories of IoT, cloud data, controllers, reinforced learning, renewable energy sources, energy storage, energy trading and dashboards. Almost all sectors fulfill the eight categories of interest. Where the most categories are seen in IoT devices, controllers, reinforcement learning, renewable energy resources and energy storage. However, there is less research in the interest category for energy trading and dashboards.

Table 1. Research of energy management system application in sector overview.

Description	IoT devices	Cloud data	Controller	Reinforced learning	RE resources	Energy storage	Energy trading	Dashboard
Residential	[15, 47]	[15, 47]	[15, 47]	[15]	[15, 47]	[47]	[47]	[15]
Renewable energy	[48]	[48, 49]	[48]	[48]	[48, 49]	[48, 49]		

Continue on the next table.

Table 1. Continue.

Description	IoT devices	Cloud data	Controller	Reinforced learning	RE resources	Energy storage	Energy trading	Dashboard
Hybrid energy systems			[50]		[50]			
Smart home	[31–34, 36]	[32–34, 36]	[31–33, 35, 36, 51]	[31, 34, 35]	[31, 33–36, 51]	[31, 33–36, 51]	[51]	
Smart-green industry	[3]				[3]			
Green building	[22, 23, 52, 53]	[21]	[21, 53, 54]	[26, 53]	[21, 22, 24–26]	[21, 54]		[21, 52, 53]
Intelligent cities	[16, 17]		[16, 17, 20]	[16, 17]	[17, 20]			
Grid-interactive buildings	[39, 41]	[39, 41]	[39–41, 55]	[39–41, 55]	[39–41, 55]	[39, 40, 55]	[39, 55]	[41]
Energy storage	[56]			[56]	[56–58]	[56–58]		
Data center	[44, 56, 59]	[59–62]	[61–65]	[61–63, 66]	[60, 64, 65]	[66]		[44, 60]
Energy analytics and predictive maintenance	[6, 7]		[6, 7]	[6, 7]				
Disaster-prone areas	[67]	[67]	[67, 68]					
Policy and regulation		[48]						

Table 2 describes the implementation of EMS in various sectors by mapping the eight categories of interest focusing on the research described in Table 1. The table shows that the sector that fulfils the eight categories of interest is grid interactive building. This shows that grid interactive building is the most advanced sector in terms of EMS implementation. Meanwhile, the other sectors have not fulfilled all of them. The categories of interest used by all sectors in the study are controllers, renewable energy, and energy storage. This shows that these three categories are important components in EMS systems. IoT devices, reinforcement learning, and dashboards are also categories of interest that are frequently used in EMS implementation.

Table 2. Describes the implementation of EMS.

Description	IoT devices	Cloud data	Controller	Reinforced learning	RE resources	Energy storage	Energy trading	Dashboard
Residential	☑		☑		☑	☑	☑	☑
Renewable energy			☑		☑	☑		
Hybrid energy systems			☑		☑	☑	☑	

Continue on the next table.

Table 2. Continue.

Description	**IoT devices**	**Cloud data**	**Controller**	**Reinforced learning**	**RE resources**	**Energy storage**	**Energy trading**	**Dashboard**
Smart home	☑	☑	☑	☑	☑	☑		☑
Smart-green industry	☑	☑	☑	☑	☑	☑		☑
Green building	☑	☑	☑	☑	☑	☑		☑
Intelligent cities	☑		☑	☑	☑	☑	☑	
Grid-interactive buildings	☑	☑	☑	☑	☑	☑	☑	☑
Energy storage			☑		☑	☑		
Data center	☑	☑	☑	☑	☑	☑		☑
Energy analytics and predictive maintenance	☑		☑	☑	☑	☑		
Disaster-prone areas	☑	☑	☑					
Policy and regulation		☑						

The following is a further explanation of EMS implementation in each sector. First, grid interactive buildings are buildings that can interact with the electricity grid. This building can generate its own energy from renewable energy sources, such as solar and wind power. It can also store the energy generated from these renewable energy sources. Second, industry is a sector that consumes a huge amount of energy. The implementation of EMS in the industry can help the industry to save energy and reduce operational costs. Third, commercial is a sector that includes various buildings, such as offices, shopping center, and hotels. EMS implementation in the commercial sector can help building owners to save energy and improve comfort for their occupants. Fourth, residential is a sector that includes households. EMS implementation in the residential sector can help homeowners to save energy and reduce electricity bills.

All implementations in the sector fulfil eight categories of interest where the most categories are seen in IoT devices, controllers, reinforcement learning, renewable energy resources and energy storage. However, there is very little research in the interest category for energy trading and dashboards.

Based on the results of the research that has been grouped by sector and current research interests, there are several things that need further discussion, namely: First, preparedness for anticipation where the EMS implementation aims to prepare the EMS system to deal with various possibilities that may occur in the future. Strategies that can be proposed include to use DRL to analyse trends and potential changes, using DRL, the EMS can identify various possibilities that can occur in the future, such as increased energy consumption, energy changes from renewable energy, and natural disasters. Develop scenarios and action plans, based on the results of trend analysis from the systems monitored by the EMS, scenarios and action plans can be developed to deal with various possibilities that could occur. For example, scenarios of electricity tariff increases can be anticipated by optimizing the use of renewable energy to reduce operational costs. Scenarios can be developed by reducing dependence on fossil fuels and switching to renewable energy sources. Conduct simulations and trials with the controller, to ensure that the EMS system can deal with the various possibilities that can occur. For example, existing controllers were simulated and tested for the effectiveness of the scenarios and action plans that had been developed. Improving system resilience, by implementing technologies such as Internet of Things (IoT) and cloud computing. IoT can be used to collect data from various sources, allowing EMS systems to have a broader view of system conditions and future predictions. Cloud computing can be used to increase system redundancy, so that the EMS system can continue to operate in emergency conditions, *e.g.* disaster or failure of one of the equipment.

Second, EMS applications related to the renewable energy sector, energy storage, hybrid energy systems, disaster-prone areas, and policies have not attracted much attention from existing research results. Therefore, further research on EMS is necessary to achieve energy efficiency from renewable energy sources and energy storage within these sectors. The importance of EMS research in the renewable energy, energy storage, and hybrid energy system sectors is because EMS serves as a monitoring, controlling, and optimizing system for energy use. The benefit of EMS research in the renewable energy sector is the potential to replace unsustainable fossil fuels, such as solar, wind and water energy, by improving energy efficiency through the use of EMS. For example, EMS can optimize the operation of solar power plants, batteries, and energy storage systems to reduce energy consumption and greenhouse gas emissions. In addition, EMS can also improve energy system stability by regulating energy supply and demand, and addressing system disturbances, thereby improving the overall reliability and security of the energy system.

Third, energy trading can be carried out by various connected parties and sectors, including energy producers, energy consumers, and energy traders or IPPs (Independent Power Producers). IoT, cloud data, and DRL technologies can be used to improve the efficiency and effectiveness of energy trading. For example, IoT technology can be used to collect data from various sources, such as power plants, transmission and distribution networks, and energy consumers. This data can be used to analyze energy market conditions and make more informed and affordable trading decisions. And shown display in dashboards are used to display data and information in a concise and easy-to-understand manner. Dashboards to monitor and control systems, including energy systems. IoT technology, cloud data, and DRL can be used to improve energy effectiveness. For example, IoT technology can be used to collect data from various sources [37] and send it to the dashboard.

The outcomes of this study can serve as a gap analysis for the deployment of EMS tailored to energy trading within the realm of renewable energy and dashboard interfaces. This research on EMS contributes significantly to elucidating and facilitating understanding of EMS implementation across diverse sectors and research domains. In the trajectory of prospective research and development, emphasis is encouraged on the advancement of EMS, particularly within research categories associated with energy trading and dashboard functionalities. The overarching objective is to streamline the monitoring of energy consumption for users in industrial [11–14], residential [15, 47], data center [44, 60], urban [16, 17, 20], and commercial building sectors [42], thereby enabling the assessment of energy efficiency and cost-effectiveness.

4 Conclusion

Recent Research Progress on Sustainable EMS Based on Energy Efficiency and Renewable Energy has been discussed with some important notes. The highlights of sector studies on EMS are focused on various research interest categories such as IoT, cloud data, controllers, reinforced learning, renewable energy sources, energy storage, energy trading, and dashboards. The majority of categories in EMS studies are concentrated in IoT devices, controllers, reinforcement learning, renewable energy resources, and energy storage. Conversely, there is comparatively less research in the interest categories of energy trading and dashboards. The main goal is to make it easier for users in various sectors like industry, homes, data centers, cities, and commercial buildings to track energy use, allowing them to evaluate efficiency and cost-effectiveness.

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