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Moving Toward the Expansion of Energy Storage Systems in Renewable Energy Systems—A Techno-Institutional Investigation with Artificial Intelligence Consideration

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Abstract: The role of energy storage as an effective technique for supporting energy supply is impressive because energy storage systems can be directly connected to the grid as stand-alone solutions to help balance fluctuating power supply and demand. This comprehensive paper, based on political, economic, sociocultural, and technological analysis, investigates the transition toward electricity systems with a large capacity for renewable energy sources combined with energy storage systems (ESS), along with a comprehensive overview of energy storage technologies; the role of AI in the development of ESS is also presented. This study aims to demonstrate how energy storage systems can be implemented with successful integration to increase electric grid flexibility. The results of the study indicate that this goal can be achieved with suitable planning and cooperation by the national, provincial, and local governments, while taking into account stakeholders' needs and environmental concerns. In this regard, comprehensive analysis has revealed that procedures such as planning, increasing rewards for renewable energy storage, technological innovation, expanding subsidies, and encouraging investment in infrastructure for renewable energy and large-scale battery storage are crucial for the development of energy storage systems. Furthermore, stakeholders should be able to comprehend the benefits of energy storage systems and their provided valuable services, and engage in the adoption process. Moreover, leveraging AI can significantly enhance the implementation and operation of energy storage systems in energy systems, enabling governments and policymakers to optimize the storage and distribution of energy from renewable sources.

Keywords: renewable energy; energy storage; policymakers; energy storage systems; AI

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1. Introduction

The utilization of fossil fuels has raised significant environmental and health concerns, in line with the United Nations' targets for addressing these issues by 2030 [1]. To combat these challenges, the development of renewable energy (RE) sources has emerged as a promising avenue [2–4]. However, it is crucial to acknowledge the intermittent nature of many renewable energy sources, which introduces considerable complexities in energy generation and load balancing, particularly within the electricity grid [5,6].

The integration of intermittent renewable energy sources necessitates enhanced system flexibility. This flexibility can be achieved through various means, including production side flexibility, demand-side flexibility, and the adoption of energy storage systems (ESS) [7].

ESS, a fundamental aspect of enhancing renewable energy system reliability and flexibility, plays a pivotal role in supporting the increased production and demand for renewable energy sources [8]. Extensive efforts have been devoted to providing comprehensive insights into various energy storage systems, analyzing their technical and economic aspects, and categorizing EES technologies based on storage duration, functions, and response times [9].

ESS technologies can be broadly categorized into four primary groups, namely electrical, mechanical, thermal, and electrochemical systems [10]. These classifications serve as the foundation for conducting comparative studies encompassing attributes such as cost, response time, energy density rating, environmental impact, advantages, disadvantages, and implementation possibilities. Such comprehensive reviews have enriched our understanding of diverse energy storage technologies. For example, Guney and Tepe's work offered an extensive classification and analysis of ESS, encompassing their characteristics, advantages, disadvantages, environmental implications, and implementation variations, along with a pertinent database on emissions and costs [11]. In a related study, Gomes et al. advocated for energy storage systems to increase the utilization of renewable energy in isolated systems, particularly in isolated microgrids and remote regions. Their work introduced a novel optimization model to determine the cost-efficient renewable power capacity mix for autonomous microgrids supported by energy storage technologies [12]. Zhang et al. provided an inclusive classification of ESS technologies, including chemical, electrical, mechanical, thermal, and electrochemical systems, and delved into biomass and gas storage, facets which are often overlooked in previous research. Their systematic review emphasized the rapid advancements and alterations within each ESS technology, culminating in a discussion of their advantages and disadvantages [13]. Gomes et al. applied linear programming to model and plan an electrical energy system characterized by a high share of renewable supply. Their study not only aligned with the government's strategic plan to reduce CO_2 emissions but also underscored the significance of pumping hydropower plants in facilitating the integration of variable renewable electricity sources, as seen in the context of Portugal [14].

Furthermore, Gomes et al. employed a linear programming approach to maximize the revenue of a hydro-pump storage power plant and a wind farm, exploring scenarios that involved bilateral contracts and day-ahead market sales. The outcomes exhibited revenue enhancements in the day-ahead market scenario and reduced imbalance costs in the bilateral contract scenario, emphasizing the potential advantages of coupling energy storage with renewable energy sources [15]. Cebulla et al. conducted an extensive examination of optimal ESS requirements across Europe, the United States, and Germany, underscoring the importance of grid-based systematic modeling in the energy sector [16]. In a parallel study, Hannan et al. elucidated the challenges related to the sustainable development of ESS technologies in the context of future electric vehicle (EV) generations. They classified EVs into five distinct groups, including battery-powered EVs (BEV), hybrid EVs (HEV), photovoltaic EVs (PEV), fuel cell EVs (FCEV), and plug-in hybrid EVs (HBEV). According to the study, existing technologies for ESS can be used for EV energy storage applications, but they have not yet been optimized for efficient electric cars [17].

Lencwe et al. contributed an overview of higher power density energy storage systems suitable for vehicle applications, offering insights into optimal methods, technologies, and configurations to achieve ideal hybrid energy storage systems (HESSs) [18]. Rui Shan et al. conducted a thorough assessment of emerging long-duration energy storage technologies, reviewing their modularity, long-term energy storage capacity, and associated capital costs [19]. Gamze Kucur et al. presented a comprehensive review of cutting-edge energy storage technologies for smart grid applications, focusing on ESS technologies that address supply-demand balance challenges and deliver power at various scales and response speeds. Their review also underscored the need for ongoing advancements in ESS investment costs and efficiency [20]. In a related endeavor, Majid Moazzami et al. presented an economic model that accounts for uncertainties in microgrid components, facilitating the optimal operation of a grid-connected microgrid. The study incorporates wind farms and advanced rail energy storage (ARES) as renewable resources, further accentuating the versatility of storage solutions in renewable energy contexts [21]. Md Mustafizur Rahman conducted a comprehensive review of energy storage technologies, highlighting the correlation between storage duration and the levelized cost of electricity (LCOE), along with the impact of factors such as lifetime, efficiency, and discharge duration on emissions and final costs [22].

Building upon this body of research, the current study is motivated by the need to examine the expansion of ESS systems within renewable energy-based systems. It employs PEST (political, economic, socio-cultural, and technological) analysis to investigate the role of national, provincial, and local governments in fostering the adoption and implementation of emerging energy storage technologies. Additionally, the study seeks to identify potential barriers to ESS development and explore strategies for overcoming these obstacles.

This study addresses the critical need to explore the expansion of Energy Storage Systems (ESS) within renewable energy-based systems. By employing PEST (political, economic, socio-cultural, and technological) analysis, this paper provides a comprehensive examination of the role that national, provincial, and local governments play in promoting the adoption and implementation of emerging energy storage technologies. Furthermore, the study identifies key barriers to ESS development such as regulatory hurdles, financial constraints, and technological limitations, and proposes actionable strategies to overcome these challenges.

This research offers significant contributions to the field by not only analyzing the technical and regulatory dimensions of ESS integration, but also by providing a holistic view of their impact on the renewable energy market. The findings of this study will be a valuable resource for policymakers, energy experts, industry stakeholders, economic agents, and decision-makers, offering insights that can inform future policy frameworks and investment strategies.

Additionally, this work contributes to the academic discourse by conducting a thorough review of current and emerging energy storage technologies, including but not limited to heat pumps, batteries, and hybrid systems. This review enhances understanding of the features, applications, and potential of ESS in accelerating the transition to a sustainable energy future. The findings of this study have the potential to influence both public and private sector approaches to energy storage deployment, facilitating a more resilient and efficient energy system.

Therefore, our contribution is threefold in this paper, as follows: first, it is a comprehensive investigation regarding energy storage systems (ESSs) second, it presents valuable insights to the energy markets by illuminating the features, technologies, and applications of ESS, and third, it highlights the critical role of policymakers, energy experts, media, stakeholders, economic agents, and decision-makers in the development of ESS in the future. In the subsequent section, we conduct a comprehensive review of current storage technologies for renewable energy, including heat pumps and batteries.

2. Methodology

This paper provides a conceptual framework for the development of energy storage systems (ESS). To write this paper, we have conducted an exhaustive review of more than 500 publications relevant to energy storage studies using established scientific databases, such as Scopus, Google Scholar, Web of Science, and scientific journals' websites. Keywords such as energy storage, environment, battery, renewable energy, and policy were used.

In the first step, between 2010 and 2024, we investigated more than 500 review papers to understand the concepts of energy storage and renewable energy, examining more than 200 technical papers, and eventually selected 216 papers, and reports (IPCC). Based on these studies, we investigated relevant papers to know how energy storage can be valuable for societies, and how renewable energy methods can be used to extend energy storage.

Furthermore, it was important to find out precisely how different governments had handled previous efforts. Following this step, the most pertinent articles were categorized, providing us with a starting point for writing this paper. We were able to gain a deeper understanding of the development of energy storage systems and the new technologies that have come under the spotlight within a short period of time. Moreover, technical articles established a deeper understanding of applications, and effective policies in the development of energy storage systems, opportunities, and barriers. The results of these investigations help us to find problems in the expansion of energy storage systems; thus, we have presented effective strategies in this paper.

This study utilizes PEST analysis because it is a simple and widely used tool that helps us to analyze the political, economic, socio-cultural, and technological changes pertaining to the development of technology. We can then take advantage of the opportunities that these changes present and suggest the best solutions and recommendations to maximize the benefits. The following reasons make PEST analysis useful:

We can identify opportunities and detect threats in advance.

1. This method reveals where the business is headed in terms of change, allowing us to adjust our strategy to accommodate the change instead of fighting it.
2. Using this tool, we can analyze risks in the environment, helping us avoid launching projects that are likely to fail.
3. We can develop a long-term strategy that is more effective.

Using PEST analysis, we demonstrated that governments, national officials, and people have key roles in expanding energy storage systems for renewable power integration. Figure 1 shows the framework of the methodology of this paper. It implies that a collaboration between officials and people is necessary to expand energy storage. All relevant papers were collected and classified into two groups, namely technical and review papers; based on these papers, a methodology was developed. In the final step, we defined appropriate actions and policies to finalize the writing of the paper.

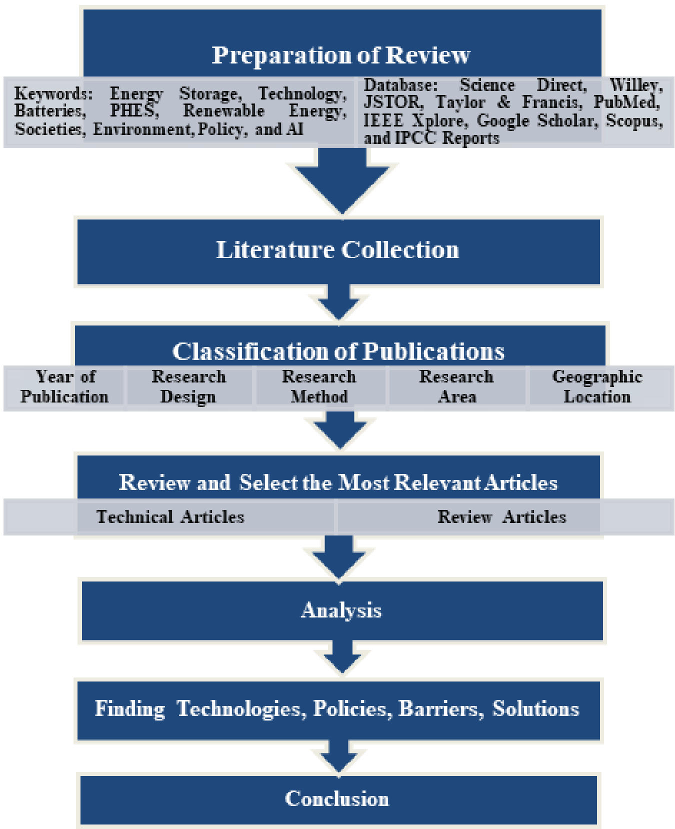

Figure 1. Methodology of the work.

3. Current Storage Technologies for Renewable Energy

According to the IEA, RES had reached a global power generation capacity of 2799 GW by 2020. This accounts for an increase in generation from solar energy (127 GW), wind energy (111 GW), geothermal energy (164 MW), hydropower (20 GW), and bioenergy (2 GW) [23]. Currently, energy storage (ES) is widely used to store renewable energy generation. Consequently, strategies are being implemented worldwide to promote the use of renewable energy sources. In this regard, the use of different sources of renewable energy such as solar [24], wind [25], biomass [26], hydropower [27], tidal energy [28], and geothermal energy [29] are increasing. Figure 2 shows the global stationary energy storage market capacity by the year 2040. Based on this figure, the market is expected to surpass 1000 GW by 2040. It is predicted that utility-scale projects with power installed from 9 GW in 2018 will increase to 1095 GW by 2040. In contrast, the cost of lithium-ion batteries is expected to decline (LIBs) dramatically.

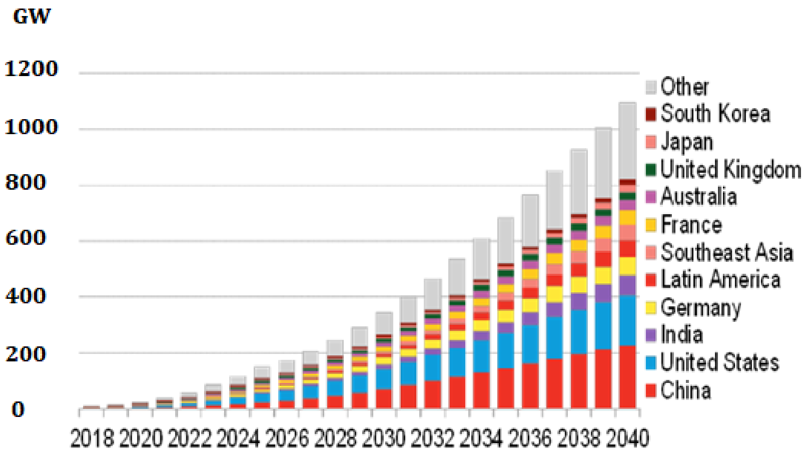

Figure 2. Global stationary energy storage market capacity by 2040 [30].

Furthermore, despite the fact that large-scale storage of renewable energy is relatively new in terms of technology, storage systems, especially in electric vehicles, portable electronics, and grid-scale energy storage are positive steps toward a sustainable energy future for all [31]. The International Renewable Energy Agency (IRENA) predicts an increase in energy storage capacity by 2030. For instance, by 2025, energy storage deployment in emerging markets is expected to increase above 40% per year. In addition, both the battery lifespan and performance continue to improve, resulting in a reduction in the cost of the services delivered. This implies that lithium-ion battery costs for stationary applications could fall below USD 200 per kWh for installed systems by 2030. Utility-scale battery storage systems are mainly deployed in the US, Australia, the UK, Germany, Japan, and other European countries. For example, in Australia, one of the largest Li-ion battery storage projects in terms of capacity; called "Tesla" has been installed at Hornsdale Wind Farm. In Hawaii (the US), almost 130 MWh of battery storage systems for wind energy and solar PV have been implemented to provide smoothening services [32]. Flow batteries have emerged as an energy storage solution that is gaining traction for grid-scale applications. In contrast to conventional lithium-ion batteries, which store energy within solid electrodes, flow batteries utilize liquid electrolytes for energy storage. In summary, flow batteries present a favorable prospect for grid-scale energy storage due to their adaptability, extended lifespan, and their ability to efficiently manage power and energy demands. They play a significant role in advancing the development of a more sustainable and dependable energy grid [33,34].

In the following section, we examine the most widely used energy storage systems, namely pumped storage and batteries. Figure 3 illustrates the rated power of installed energy storage systems [35]. As depicted, pumped hydroelectric energy storage (PHES) dominates contributing 95% of the total 190.36 GW capacity, while hydrogen storage contributes only a minimal fraction.

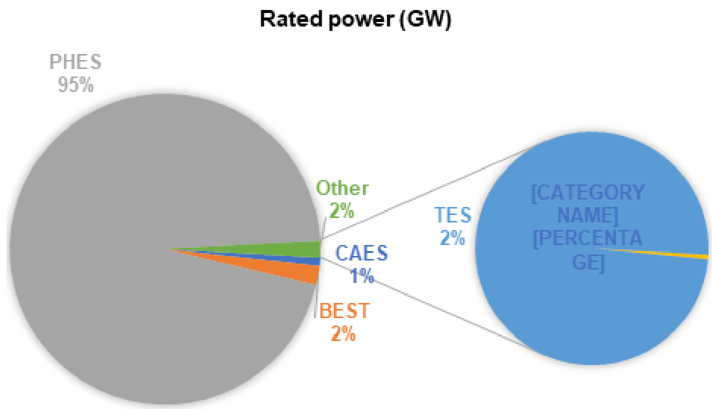

Figure 3. Rated power of installed energy storage systems [35].

3.1. (PHES)

Pumped hydroelectric energy storage (PHES), a venerable technology, made its debut in the Alpine regions of Switzerland, Austria, and Italy during the 1890s [36]. Over the years, it has evolved into a cornerstone of global electricity storage solutions, underlining its exceptional significance [37]. By the early 2000s, PHES had firmly established itself as a technologically advanced, economically viable, and socially acceptable option for a variety of applications, including peak load management and the storage of energy derived from solar and wind sources to ensure power quality [38].

Notably, several countries, including Japan [39], China [40], and the United States [41], have made substantial investments in PHES, cementing its position as a pivotal player in electricity markets worldwide [42]. Furthermore, for utility-scale electricity storage, PHES stands as the most established and reliable technology [43]. In contemporary contexts, innovative PHES technologies have emerged, seamlessly integrated with renewable energy sources such as solar [44], wind [45], and hydroelectric systems [46].

This enduring technology has demonstrated its adaptability and resilience over the years, contributing significantly to the integration of renewable energy sources and the stability of global electricity markets.

3.2. Battery Energy Storage Technologies

In recent years, battery energy storage systems have witnessed a surge in popularity, assuming a pivotal role within the energy industry [47]. This shift is notably accentuated by the global automotive industry's transition towards the widespread adoption of electric vehicles (EVs), amplifying the significance of battery energy storage in contemporary times [48]. An encouraging development within this domain is the proliferation of smart batteries, signifying a noteworthy stride in the advancement of energy storage technologies [49]. The advent of smart batteries has ushered in substantial innovations within the energy storage sector, holding the promise of alleviating the burgeoning energy challenges of our era [50]. Among these innovations, lithium-ion batteries (LIBs) occupy a prominent position, extending their utility across a broad spectrum of applications encompassing electrified transportation, renewable energy integration, portable electronics [51], and building management systems (BMS) [52]. Lithium-ion batteries have gained recognition as an efficient energy storage technology, primarily attributable to their outstanding properties [53]. Equally significant is the fast-charging capability, a defining attribute of LIBs, rendering them highly desirable across a multitude of applications [54]. In addition to the aforementioned applications, these batteries find extensive use in diverse domains, ranging from mobile phones [55], electric scooters [56], flexible and wearable electronic devices [57], to electric bicycles [58]. This burgeoning prevalence of smart battery technologies has the potential to reshape various sectors and significantly contributes to the realization of sustainable and efficient energy storage solutions.

Table 1 presents information on the use of batteries and pump hydro storage technologies in 10 different countries with high populations worldwide. Batteries are more advanced than pump hydro storage technology, and a large number of studies have been conducted in this area. In addition, based on the results of the studies reported in Table 1, it is striking that very few comparisons between and simultaneous evaluations of the batteries and hydro pump storage have been conducted. There is also very little information about the levelized cost of electricity (LCOE) for pumped hydro storage, indicating that more research is required.

Table 1. Literature review of recent works aboutbatteries and pumped storage technologies.

No	Country	System Under Study	LCOE (USD/kWh)	References
1	China	PV–Diesel Generator PV–Wind PV–Wind–Grid PV–Wind Wind PV	0.22–0.35 0.877–3.31 0.069–0.508 - - -	[59] [60] [61] [62] [63]
2	India	PV–Wind–Biogas–Fuel cell PV–Wind–Hydro–Diesel Generator Hydro PV–Grid	0.214 0.1–0.162 - -	[64] [65] [66] [67]
3	United States	PV PV–Grid Evaluating of Pumped Storage	0.78–1.07 0.5–1.35 -	[68] [69] [70]
4	Indonesia	PV–Diesel Generator PV–Grid PV–Wind–Diesel Generator PV–Wind	0.163 1.03–1.05 0.17–0.2 0.0362	[71] [72] [73] [74]
5	Pakistan	PV–Diesel Generator PV–Grid–Diesel Generator CHP (PV–Wind–Fuel Cell) PV–Wind–Hydro–Diesel Generator	0.145–0.167 0.072–0.078 0.934–0.974 -	[75] [76] [77]
6	Brazil	PV–Wind PV–Grid PV Hydro	0.266–0.437 0.33 - -	[78] [79] [80] [81]
7	Nigeria	PV PV–Wind–Diesel Cenerator Grid Hydro	0.312 0.138–0.212 - -	[82] [83] [84] [85]
8	Russia	PV–Wind–Diesel Generator PV–Wind–Biomass Hydro	0.24–0.71 0.18–0.28 -	[86] [87] [88]
9	Mexico	PV–Diesel Generator PV–Diesel Generator PV–Wind–Geothermal	0.14 0.205–0.229 -	[89] [90] [91]
10	Japan	PV–Wind–Diesel Generator PV–Wind PV–Wind	0.249–0.526 - 0.086–0.110	[92] [93] [94]

3.3. Compressed Air Energy Storage (CAES)

Compressed air energy storage (CAES) technology is frequently employed alongside renewable energy sources, serving as a valuable solution to contend with the erratic and variable nature of renewable energy generation, specifically wind and solar power [95]. Below, we detail how CAES is applied in the context of renewable energy.

Incorporating Unpredictable Renewables: Renewable energy sources like wind and solar can be capricious, with their energy generation contingent upon weather conditions. CAES aids in mitigating these fluctuations by stockpiling surplus energy generated during high-output periods of renewables [96]. Subsequently, this stored energy can be released during periods when renewable sources are inactive, ensuring a consistent power supply.

Time Shifting: CAES facilitates the temporal adjustment of renewable energy [97]. Excess electricity generated during gusty or sunny intervals can be stored in the form of compressed air and then released during periods of peak demand, thus bolstering the dependability and stability of renewable energy sources.

Enhancing Grid Reliability: When coupled with renewables, CAES technology can enhance grid stability [98]. It offers swift responses to variations in grid frequency and abrupt power imbalances, thereby contributing to the maintenance of a dependable and secure electrical grid.

Storage of Renewable Energy: In regions where renewables constitute a substantial portion of the energy mix, CAES can function as a large-scale energy storage solution, ensuring a continuous power supply even when renewable sources are dormant, such as during nighttime or calm wind conditions [99].

Improving the Economics of Renewables: By optimizing the effective utilization of surplus renewable energy, CAES can bolster the economic feasibility of renewable energy projects and diminish curtailment, which occurs when excess energy goes to waste due to a lack of demand [100].

Nonetheless, its imperative to recognize that the successful integration of CAES with renewables hinges on numerous factors, including local energy infrastructure, regulatory requirements within the grid, and the suitability of geological conditions for storing compressed air. As the realm of renewable energy continues to expand, the role of CAES in bolstering a reliable and sustainable energy grid is poised to grow in significance.

3.4. Thermal Energy Storage (TES)

Thermal energy storage (TES) technology is harnessed in conjunction with renewable energy sources to enhance the efficiency and effectiveness of renewable energy systems [101]. TES has proven invaluable in mitigating the irregularity and variability inherent in certain renewable sources, like solar energy and concentrated solar power.

Below, we detail how TES is employed within the context of renewable energy.

Solar Thermal Energy: TES finds widespread application alongside solar thermal power facilities [102]. These facilities concentrate sunlight through mirrors or lenses to generate high-temperature heat, subsequently utilized for electricity generation. TES enables the capture and storage of surplus heat generated during sunny periods, ensuring a continuous power supply during cloudy or nighttime conditions.

Heightened Solar Efficiency: TES contributes to the overall efficiency of solar power systems [103]. By stockpiling thermal energy for future use, solar plants can function at full capacity even when sunlight is unavailable, thereby diminishing the necessity for backup power sources.

Recuperation of Waste Heat: Industrial settings leverage TES for the recovery and storage of waste heat, which can be channeled to meet energy needs in industrial processes or heating applications [104]. This is particularly advantageous in industries marked by intermittent energy requirements.

Building Heating and Cooling: TES is employed for temperature regulation in buildings. It stores surplus thermal energy obtained from renewable sources or other high-efficiency heating systems, thereby diminishing the reliance on conventional heating and cooling systems [105].

Synergy with Renewable Technologies: TES is frequently incorporated with diverse renewable technologies, such as geothermal and biomass, to stockpile thermal energy for later utilization, ensuring a consistent energy supply [106].

Grid Stability: In certain scenarios, TES contributes to grid stability by providing load-shifting capabilities [107]. Excess electricity generated by renewables can be used to store thermal energy, which can subsequently be converted into electricity when needed, thereby contributing to the equilibrium of supply and demand on the grid.

Efficiency and Cost Advantages: TES can lead to augmented overall system efficiency and a reduction in the expenses linked to backup power generation, rendering renewable energy projects economically more viable [108].

The utilization of thermal energy storage is particularly pertinent in regions characterized by abundant solar energy potential and intermittent renewable sources. By adeptly accumulating and deploying thermal energy, TES reinforces the dependability and cost-effectiveness of renewable energy systems, a pivotal component in the transition toward a more sustainable energy landscape.

3.5. Hydrogen Storage

Hydrogen storage technology is employed alongside renewable energy sources to store and utilize hydrogen as a clean and adaptable energy carrier [109]. Within the context of renewable energy, hydrogen storage plays a pivotal role, serving several key functions as detailed below:

Energy Stockpiling: Hydrogen is utilized for the storage of surplus energy generated from renewable sources during high-production periods, such as when there is ample wind or abundant sunlight [110].

Mitigating Intermittency: Hydrogen storage helps counterbalance the sporadic nature of renewable energy sources like wind and solar. When these sources are not actively generating electricity, stored hydrogen can be reconverted into electricity or utilized as a fuel for various applications, ensuring a dependable energy source [111].

Fuel for Transportation: Hydrogen can function as an eco-friendly fuel for hydrogen fuel cell vehicles [112]. These vehicles generate electricity on-board by combining hydrogen with oxygen from the atmosphere, emitting solely water vapor as a byproduct. Renewable hydrogen can serve as a fuel source for these vehicles, thereby reducing the greenhouse gas emissions linked to transportation.

Grid Resilience: Hydrogen can contribute to grid stability and offer backup power support. During periods of elevated renewable energy generation, surplus electricity can be channeled to produce hydrogen, which is then stored and later used to generate electricity during peak demand periods or when renewable sources are inactive [113].

Industrial Utility: Hydrogen proves versatile as an industrial feedstock and energy source. It finds application in a wide array of industrial processes, such as chemical manufacturing and steel production, acting as a substitute for fossil fuels [114].

Hydrogen storage stands as a critical element in the transition toward a more sustainable and renewable-oriented energy system. It aids in harnessing the intermittent characteristics of renewable energy sources, reducing greenhouse gas emissions, and furnishing reliable energy solutions across diverse applications, including transportation and industrial processes.

4. Analyses of ESS Based on PEST Analyses

In this section, we examine the importance of energy storage, and the expansion of energy storage systems with regard to PEST analyses. Indeed, the following sections discuss the importance of smart energy storage systems for the community, as well as the role of policymakers, and local and national authorities in the expansion of energy systems, the introduction of new technology, and progress.

4.1. Why the Role of PEST in the Development of ESS Is Important?

The role of appropriate policy, special attention to the environment, sociocultural collaborations, and using suitable technology as summary PEST, is very important in the development of energy storage systems (ESS) because PEST analysis considers the most important factors for the development of ESS. Therefore, each of these factors needs to be explained separately to be clear why we considered PEST.

4.1.1. Importance of the Expansion of Energy Storage Systems for Policymakers

It has been proven that policies and policymakers' decisions to expand intelligent energy systems play important roles [115] in energy sustainable transitions [116]. The storage of energy is one of the most important goals for policymakers [117]. Indeed, developing new energy storage systems is crucial for people to overcome energy shortage problems [118]. Accordingly, the expansion of energy storage systems will help accelerate the large-scale adoption of renewable energy resources. Therefore, energy storage provides suitable grid reliability and flexibility [119]. Indeed, storing electricity, mainly using sustainable methods, especially renewable energy, can be harnessed and injected into the electricity grid which has many benefits. Electricity storage can also help generation facilities to operate at optimal levels and reduce the use of less efficient generating units that would otherwise only run during peak times [120]. Even so, there were always significant issues, such as energy efficiency, intelligent energy systems, energy affordability, and residents' access to energy [121]. Thus, by taking the help of other stakeholders to implement appropriate policies for developing new storage systems, policymakers have a remarkable role to play while also requiring coordinated efforts from grid operators, utilities, developers, and others. This includes procedures such as planning, increasing the reward for storage by renewable energy, the expansion of technological innovation, investment, increasing subsidies, and encouraging investment in infrastructure for the integration of distributed generation from renewable energy sources and large-scale battery storage [122–124].

4.1.2. Energy Storage Systems Expansion from the Economic Point of View

It is undeniable that the development of economical energy storage systems is a huge concern for governments and people alike [125]. Different countries are considering suitable strategies and planning to expand energy storage systems as they are economically viable for industry [126] and communities [127,128]. Energy storage technologies are advantageous in terms of reducing electricity costs and ensuring a reliable power supply. For example, energy management for hybrid energy storage systems in electric vehicles have been considered [129], along with the expansion of compressed air energy storage (CAES) [130], the integration of hybrid energy storage systems for wind generators with an economic approach [131], financial investigation into battery storage systems for commercial consumers [132], and analysis of energy storage technologies [133]. A long-term economic approach to energy storage for combined cooling, heating, and power systems has been considered [134]. Moreover, the financial aspects of microgrids [135], and economic assessment of the battery energy storage systems using solar energy in Madeira, Portugal [136], are some economic energy storage systems, that have been utilized in different countries. However, it should be considered that expanding energy storage without considering its economic aspects can result in the failure of investments or a loss of time, as evidenced by these studies

4.1.3. Socio-Cultural Perspectives on Energy Storage Systems

Socio-cultural perspectives on ESS are among the most important subjects in the development of ESS. Numerous studies have shown the importance of new energy storage technologies in facilitating economic, secure, sustainable, and energy-efficient developments for both the present and future [137]. This is due to the fact that the expansion of energy storage systems has both environmental [138] and economic benefits [139]. Furthermore, communities and individuals alike are now aware of the benefits of having new energy storage technologies, and know how these technologies can help them to have a high quality of life [140]. However, the expansion of energy storage systems is not easy, and acceptance of them requires essential factors such as adjustments in use, price, technology (renewable), correct policies, etc. [141]. Therefore, strategic planning and appropriate actions at the provincial, national, and local levels are vital [142]. Governments can play an essential role in supporting the expansion of energy storage systems through planning and sensitizing the public to accept and adopt energy storage systems [143]. On the other hand, government participation as a mediator between national authorities, communities, and other local stakeholders for developing public private projects in line with the expansion of energy storage systems is crucial [144]. The public has a direct role in the expansion of the energy storage systems if they would like to contribute to the preservation and protection of the environment by having an economical energy storage device [145]. Generally speaking, to achieve these goals, cooperation is needed between people and both national and local government authorities in order to expand the energy infrastructure [146] and energy storage systems [147].

4.1.4. Energy Storage Systems Expansion from a Technology Point of View

Fortunately, nowadays, the growth of energy storage systems is based on renewable energy; the development of both sustainable energy and low-carbon electricity systems has resulted in promising solutions for energy system integration [148]. As a matter of fact, suitable research efforts and positive steps taken by governments to successfully expand energy storage technologies by 2050 generally represent realistic goals [149]. Moreover, energy storage devices have become increasingly popular in modern-day devices, such as mobile phones and laptops, proving the importance of technological development in this area [150].

Additionally, energy storage systems can help manage household energy consumption, prevent energy waste, and reduce the costs of energy. In this regard, technology has a remarkable role to play [151]. Sufficient and on-time investment energy storage technology expansion (based on renewable energy) can have significant effects on societies, despite challenges such as socio-political acceptance, community acceptance, and market acceptance [152–154]. As a result, innovations in energy storage, and investments in electric utilities as efficient solutions for reducing costs, are considered as a good vision and strategy [155]. Hence, it can be noted that innovations in energy storage systems will encourage a broader utilization of energy storage systems and improve clean energy markets [156].

For example, although the flywheel is one of the oldest energy storage devices, it has gained significant importance in recent years within energy storage systems (ESS) [157]. Flywheel technology has driven innovation, particularly in automotive and power grid transitions, where it is used for braking energy recovery under the influence of two motors of innovation. Additionally, flywheels offer an environmentally friendly alternative to electrochemical batteries, supporting sustainable energy transitions by storing energy in kinetic form for short-term use. This highlights the important role of flywheels in ESS development. This highlights the important role of flywheels in ESS development. Researchers and engineers working on ESS should advocate for the adoption of flywheel technology by policymakers, particularly as a viable alternative for those facing challenges in ESS development [158,159].

4.2. Causes and Barriers to Implement ESS

In order to complete the discussion about ESS systems, we need to know what prevents them from being more widely used and what resistance policymakers, societies, and the wider economic world to accepting them. There are several categories that make concerns in ESS development relevant to disposal practices for a number of technologies, including environmental impact, trust, local impacts, national economies, health impact, consumer economics, technical feasibility, social and ethical impact, people's acceptance, and environmental and sustainability risks. Therefore, policymakers should anticipate societal concerns and conditions about ESS development [160].

Concerning the importance of ESS systems for the future, people have the right to raise fundamental questions about political, social, and economic systems to challenge the government to accept and invest in them [161]. One dimension of this discussion is people, and the other is governments. In terms of people, local governments play a crucial role in promoting the acceptance of renewable energy storage solutions. The power of the people is more limited than national governments, and it is a big problem even if the right is with the people. Therefore, media play a remarkable role in understanding the social-political dimension of technological development processes, and low-carbon energy transitions in advanced societies. People should also pay attention to the strength of the media because governments are less able to control the media than in the past [162–168].

Alongside governments, issues such as investment, infrastructure, applications, and even the absence of administrative and regulatory considerations are critical. Developing energy storage systems, including pumped hydro, batteries, and compressed air, has dramatic costs for governments, especially governments with low financial support. As a result, the lack of suitable infrastructure is a significant obstacle for governments in the line of ESS development. Because of this, governments have fewer tendencies to use their finances for ESS development when the infrastructures are weak or unsuitable. As a result, they may be resistant to implementing ESS, instead choosing to use different policies or methods [169–173]. Though technological advancements have increased, the widespread deployment of ESS remains uncertain due to low investment power, and geographical conditions are still evolving. Though technological advancements have increased, the widespread deployment of ESS remains uncertain due to low investment power, and geographical conditions are still evolving. Therefore having suitable policies such as investment, encouraging incentives, soft loans, targets, and competition should be considered for ESS development [174–176]. In addition, the local population's resistance to ESS infrastructure and development will hinder the achievement of renewable energy consumption. In this regard, governments should use suitable strategies in order to prevent this [177]. In addition, gaining people's acceptance of ESS, and developing energy infrastructure may be difficult for governments to achieve in the successful deployment of new infrastructure, and people may be hesitant due to increased costs. In order to prevent any potential problems with ESS development, governments must examine charges and fees such as the energy industry act, the regulation of electricity network fees for the new electric grid, the renewable energy sources act, electricity tax law, and the metering point operation act [178]. Therefore, the coordination of governments and people in considering stakeholders is vital to ESS development; in this regard, traditional ideas can be challenged, given the highly important political nature of ESS transitions, preventing the appearance of incrementally radical governments.

4.3. Comparison of the Current Study with Other Relevant Studies from the Point of View of PEST Analysis

In the current study, we investigated ESS development using renewable energy from the point of view of PEST analysis. Below, we examine relevant PEST analyses based on renewable energy development throughout the world. As an example, Wang et al. examined the opportunities and challenges of solar PV power using PEST analysis. In order to reduce CO_2 emissions, they emphasized the development of renewable energy, industry collaboration, the use of integrated applications, investing in storage and hydrogen technologies, and establishing an after-sales service network. These findings are extremely valuable for policymakers and solar PV manufacturers [179].

Using PEST analysis, Valencia et al. analyzed wind energy around the world, focusing mainly on Colombia. In light of the fact that wind energy accounts for 5% of the world's electricity, their findings demonstrate the necessity of researching and analyzing the most important factors hindering the development of the wind energy industry in Colombia [180]. Tan et al. conducted a critical analysis of the energy storage industry in China using PEST-SWOT modelling and developed an application distribution matrix for the energy storage industry [181]. Li et al. provided a framework to determine potential factors of green behaviors using PEST analysis. In this study, PEST factors were investigated for explaining the diffusion of cleaner energy substitution in enterprises. They also explored reinforcing penalties and environmental taxes for pollution using fossil fuels [182].

Holland et al. explored incorporating ecosystem services into the design of future energy systems. As a result of qualitative and quantitative analyses of various influential scenarios concerning energy and ecosystem services, including societies' interest in environmental sustainability, the relative contribution of fossil fuels to energy production, the degree of international cooperation and globalization, the rate at which carbon dioxide is reduced, and the rate at which technology is developed and deployed, they showed how the benefits derived from the natural environment are integrated within current energy scenarios [183]. Nunes et al. investigated energy efficiency and eco-friendly policies for the biomass fuel used in the textile dyeing sector in Portugal. They demonstrated how using clean fuels like biomass, thus reducing greenhouse gas (GHG) emissions, leads to increased use of new technologies related to renewable energy, the creation and preservation of jobs, the use of national technology, and the increased competitiveness of the sector by reducing energy costs [184]. Through PEST analysis, Molamohamadi and Talaei identified the most appropriate solar energy deployment strategies in Iran. According to this study, four effective strategies were considered, including aggressive, conservative, competitive, and defensive strategies, using internal–external and SWOT analysis [185].

Following the discussion of relevant studies for renewable energy, and an examination of ESS systems using PEST analysis, our research examines ESS expansion in renewable energy systems. Previous studies only focused on specific industries or countries developing ESS technologies, without taking into account the resulting effects, barriers, and technology in all industrial sectors. This study provides a general overview of obstacles, technologies, policies, barriers, and solutions for all types of energy storage systems. We examined PEST analysis comprehensively, covering all important issues for developing ESS based on RE, and showed which policies and strategies can be effective for ESS development. In this study, we found that most targets can be achieved with appropriate planning and cooperation by the national, provincial, and local governments while considering stakeholders' needs and environmental concerns. PEST analysis also revealed that timely and proper planning, increased subsidies, increased rewards for renewable energy storage, technological innovation, and encouraging investments in the infrastructure for renewable energy and large-scale battery storage are crucial to the development of energy storage systems.

4.4. The Role of AI in the Development of ESS

Artificial intelligence (AI) plays a significant role in the development of renewable energy systems in various countries. In fact, artificial intelligence (AI) plays a crucial role in accurately predicting weather patterns and energy demand, which is essential for optimizing the performance of renewable energy sources such as wind and solar power [186]. By utilizing advanced algorithms, AI can forecast weather conditions and energy demand with remarkable precision, which is vital for maximizing the efficiency and reliability of renewable energy systems like wind turbines and solar panels [187]. In addition, AI significantly enhances the management of energy grids by providing real-time monitoring and control capabilities, enabling the seamless integration of renewable energy sources and maintaining grid stability even as energy demands fluctuate. It means, AI improves the management of energy grids by enabling real-time monitoring and control, which helps integrate renewable energy sources efficiently and maintain grid stability [188]. Through AI-driven analytics, areas of energy waste can be pinpointed and improvements suggested, leading to more efficient energy use and substantial reductions in operational costs [189].

Furthermore, AI algorithms optimize the operation of renewable energy systems, ensuring that maximum energy output is achieved, and downtime is minimized [186]. In addition, AI has a crucial role in optimizing energy and resource management [190]. AI-driven analytics can identify areas of energy waste and suggest improvements, leading to more efficient energy use and reduced operational costs [189]. AI algorithms can optimize the operation of renewable energy systems, ensuring maximum energy output and reducing downtime [186]. In the future, AI will accelerate the energy transition and emerging technologies [191]. Table 2, shows the role of AI in ESS development.

Table 2. The role of AI in ESS development.

Country	Role of AI in Renewable Energy
United States	AI is used for predictive maintenance, optimizing grid operations, and enhancing energy storage systems [192].
China	AI aids in forecasting energy production, managing large-scale solar and wind farms, and improving energy efficiency [193].
Germany	AI supports the integration of renewable energy into the grid, optimizing energy distribution, and reducing carbon emissions [194].
UK	Al is effective in enhancing energy efficiency in residential buildings [195]
Brazil	The role of AI in enabling strategic hydropower planning across the Amazon basin for achieving sustainable hydropower [196]
Australia	AI is used to optimize solar and wind energy production, manage energy storage, and improve grid reliability [197]

5. Important Findings and Suggestions

To reduce CO_2 emissions and fossil fuel dependency, new communities struggle to use efficient energy storage solutions in order to integrate renewable energy into existing or isolated grids. However, expanding energy storage is not easy and represents a big challenge for every country. In this regard, policymakers and energy experts can play a remarkable role and should have a deeper understanding of energy storage for citizens, given the increasing urban population [198]. Therefore, as mentioned previously in Section 4, policymakers and energy experts, supported by other stakeholders to implement suitable policies for developing energy storage systems, have a unique role and the power to make decisions with a coordinated effort from grid operators, utilities, developers, and others. This includes investment, increasing subsidies, rising rewards for storage by renewable energy, planning, expansion of the technological innovation, and promoting investment in renewable energy infrastructure for large-scale battery storage. The expansion of new energy storage systems can also reduce costs, increase efficiency, and enhance energy security [199]. The latest technologies are being used primarily for energy saving in buildings [200], transportation (EVs) [201], industry [202], and the use of electrofuels in future energy systems [203]. Also, the expansion of energy storage systems has a direct positive effect on reducing CO_2 emissions and improving the quality of life [204].

As the essential systems for energy storage are heat pumps and batteries, the development and improvement of these technologies should be taken into account. However, government authorities, national governments, and local officials can contribute positively to promoting energy storage expansion through their influence. In fact, governments play a significant role in educating people about the use of energy storage systems in their homes. In this regard, authorities, especially local leaders, should have a frank dialogue with their citizens about the importance of energy storage systems and the benefits they can gain from these technologies [205,206].

Furthermore, local leaders play a crucial role in implementing energy storage systems, policies, and national legislation [207]. The most crucial responsibility of leaders is training and planning to identify strategic drivers by energy experts and policymakers for policy development and for expanding energy storage systems [208,209]. In addition, paying attention to the needs of stakeholders is essential providing energy security, stakeholder engagement, and affordable energy will cause stakeholders to have active participation in implementing energy storage policies and their practical actions [210].

It is also essential to develop new energy storage technologies that are environmentally friendly for citizens [211]. Innovative solutions play an essential role in supporting the transition to a new energy-saving system by expanding energy storage systems. The growth and development of energy storage systems should be central to planning infrastructure, public transport, new homes, and job creation. Energy storage systems will be encouraged through these measures [212]. In addition, regarding the advantages of proven new energy storage systems, especially concerning energy security and environmentally friendliness, it is better that stakeholders prefer the utilization of energy storage systems [213].

Most countries find it challenging to expand their energy storage systems. Firstly, the development of the energy storage systems nationally requires political clarity with people, new transport (EVs), energy security, comfortable housing, better access to energy, and economic growth. Second, the development of the energy storage systems needs close cooperation between all authorities (national, province, and local governments) and the public. In this regard, different government agencies should have an effective plan in place to support stakeholders with energy storage (delivering information and guidance). Further, energy experts and policymakers should ensure that the planning system and the industry are aligned and mutually informed about key constraints and opportunities [214,215].

Moreover, regarding the impressive role of AI in the future, we will be faced with huge changes in development of ESS using AI as shown in Figure 4 [216].

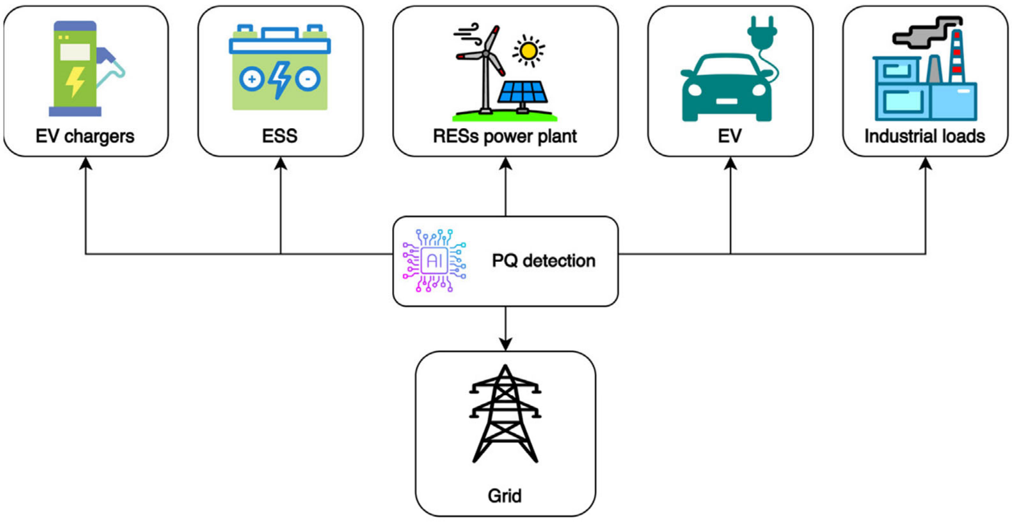

Figure 4. Schematic representation of a smart (or micro) grid and the role of AI in PQ [216].

6. Future Works

For future work, energy storage systems can be analyzed from multiple perspectives as follows:

- Detailed analysis of different regions: The present work actually affects the political, economic, socio-cultural, and technological factors affecting energy storage systems. The aim of the present work is to provide a comprehensive overview. However, it is possible to examine more specific case examples that show how each factor affects energy savings in different contexts. This could include examining regulatory frameworks, market dynamics, and community engagement strategies in greater depth.
- Alternative perspectives on energy storage systems: It is acknowledged that considering energy storage from different angles can yield valuable insights. In future reviews, we can include discussions on innovative business models, the role of decentralized energy storage solutions, and the impact of consumer behavior on energy

conservation. In addition, environmental impact studies and life cycle assessments of different storage technologies can provide a more comprehensive understanding of their benefits and challenges.

7. Conclusions

The development and prioritization of energy storage systems (ESS) are imperative for all nations in the face of critical global challenges, such as climate change, increasing energy demand, and the necessity for sustainable energy solutions. ESS plays an essential role in mitigating greenhouse gas emissions by enhancing energy efficiency and supporting the transition to renewable energy sources. A combination of renewable energy technologies and ESS, particularly heat pumps and batteries, can be utilized to optimize energy flows based on real-time demand. As a result, the integration of energy storage solutions with renewable energy systems is expected to be pivotal in ensuring a stable and reliable power supply to meet future energy demands.

However, the expansion of ESS infrastructure is complex and presents substantial challenges for countries across the globe. Success in this area is contingent upon the implementation of supportive policies, adequate financial investment, technological innovation, grid integration, and public acceptance. Overcoming these barriers is critical to unlocking the full potential of renewable energy and ESS in addressing global energy and environmental challenges.

This study, therefore, investigates the critical expansion of ESS within renewable energy frameworks. Through the application of PEST analysis, it examines the roles of national, provincial, and local governments in advancing the adoption and implementation of emerging energy storage technologies. The study also identifies key barriers—such as regulatory, financial, and technological limitations—and provides actionable strategies to effectively address these challenges.

The findings underscore that policymakers and energy experts play a crucial role in advancing energy storage development, particularly given the growing urban population, the rising demand for energy storage, and public concerns—especially environmental ones. Their guidance and decisions are instrumental in shaping sustainable energy solutions that address climate change and urbanization challenges. Policymakers and energy experts, supported by key stakeholders, hold unique influence in crafting and implementing effective ESS policies. Their coordinated efforts with grid operators, utilities, developers, and other relevant parties are essential for driving the growth of ESS. A collaborative approach is needed to overcome technical, financial, and regulatory challenges, ensuring that ESS can meet future energy demands and contribute to a sustainable energy transition.

It is important to recognize that governments face critical challenges, including limited investment, inadequate infrastructure, practical application difficulties, and a lack of administrative and regulatory frameworks. Developing energy storage systems—such as pumped hydro, batteries, and compressed air—imposes substantial costs, particularly for governments with constrained financial resources. The absence of suitable infrastructure presents a major barrier to ESS development, making it difficult for many countries to effectively implement these systems. As a result, governments are less likely to invest in ESS development where infrastructure is weak or unsuitable, and they may resist adopting alternative methods or policies. Policymakers must, therefore, anticipate and address societal concerns and conditions related to ESS development.

Moreover, given the crucial role artificial intelligence (AI) can play in optimizing ESS, governments, policymakers, and energy experts must collaborate to integrate AI into ESS development and foster public support for these advancements. This strategy should include increased investment, expanded subsidies, and enhanced incentives for energy storage linked to renewable energy. Additionally, the adoption of AI, strategic planning, and technological innovation are essential for the successful expansion of large-scale battery storage and other advanced energy storage systems. Promoting investment in renewable energy infrastructure will be vital for achieving these objectives. The growth of new energy storage systems will not only reduce costs and improve efficiency but also enhance energy security.

Furthermore, local governments can leverage the power of media to raise awareness and promote renewable energy storage solutions, helping to accommodate the growing levels of renewable energy deployment. By effectively communicating the benefits of these technologies, they can drive public support and encourage greater adoption of sustainable energy practices.

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Abbreviation

AI	Artificial intelligence
BEV	Battery-powered EVs
BMS	Building management systems
CAES	Compressed air energy storage
ES	Energy storage
ESS	Energy storage systems
FCEV	Fuel cell EVs
GHG	Greenhouse gas
HBEV	Plug-in hybrid EVs
HESSs	Hybrid energy storage systems
HEV	Hybrid EVs
IRENA	International Renewable Energy Agency
LCOE	Levelized cost of electricity
LIBs	Lithium-ion batteries
PEST	Political, economic, socio-cultural, and technological
PEV	Photovoltaic EVs
PHS	Pumped hydroelectric storage
RE	Renewable energy

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