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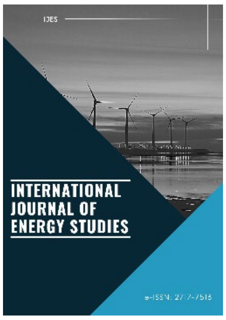

Review Article

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Technological advancements in PV-based energy storage methods

Merve Yılmaz[a]*, Onur Akar[b], Nazmi Ekren[c]

[a]*National Defense University, Naval Academy, Electrical and Electronics Engineering, Istanbul, Turkey, ORCID: 0009-0009-7584-1035.*

[b]*Marmara University, Department of Electronic and Automation, Istanbul, Türkiye, ORCID 0000-0001-9695-886X.[c]Affiliation, ORCID Number*

[c]*Marmara University, Faculty of Technology, Electrical and Electronics Engineering, Istanbul, Turkey, ORCID: 0000-0003-3530-9262.*

*(*Corresponding Author: merveyilmz00@gmail.com)*

Highlights

- Integration of energy storage systems with photovoltaic systems significantly enhances energy reliability and supports grid stability.
- Thermal, electrochemical, and hybrid energy storage solutions are key to addressing the intermittent nature of solar energy.
- Artificial intelligence and machine learning techniques optimize energy management, improve efficiency, and reduce operational costs in PV systems.
- Hybrid energy storage systems combining batteries and supercapacitors ensure both high energy density and rapid power delivery.
- Technological advancements in energy storage systems are essential for sustainable energy transitions, reducing carbon emissions, and ensuring economic viability.

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ABSTRACT

Maximum energy demand exceeded 180,000 TWh in 2024, with renewable sources covering approximately 32%. Solar energy, notable for sustainability and economic viability, reached 1,250 GW installed capacity in 2024 and is projected to double to 2,500 GW by 2030. Despite advancements and cost reductions, the intermittent nature of photovoltaic (PV) generation, meeting 45% of demand on sunny days and less than 10% on cloudy days, poses significant challenges. Energy storage systems (ESS), critical for managing intermittency, achieved 70 GW capacity globally in 2024, expected to reach 300 GW by 2030. Lithium-ion batteries, with an 80% cost reduction and 40% improvement in energy density, along with thermal storage using phase change materials (PCM) and supercapacitors, significantly improved performance. Hybrid energy storage systems (HESS) further enhanced reliability, achieving around a 15% reduction in carbon emissions. Artificial intelligence (AI) and machine learning (ML) play crucial roles in optimizing energy management and efficiency in PV-integrated ESS. This research investigates recent technological developments in PV-integrated energy storage, assessing thermal, electrochemical, and hybrid storage solutions, and highlighting the significance of artificial intelligence (AI) and machine learning (ML) in optimizing energy management and enhancing overall system efficiency.

Keywords: Photovoltaics, Energy storage, Thermal storage, Hybrid storage

1. INTRODUCTION

Global energy demand is rapidly increasing due to population growth, economic expansion, and technological advancements. As of 2024, global energy consumption has surpassed 180,000 TWh, with approximately 32% of this demand being met by renewable energy sources [1]. The environmental impacts and finite reserves of fossil fuels have highlighted the necessity of increasing the share of renewable energy in global energy production. In this context, solar energy stands out among renewable sources due to its low carbon emissions, sustainable nature, and cost-effectiveness [2]. According to the International Energy Agency (IEA), the global installed capacity of solar energy exceeded 1,250 GW as of 2024, with projections indicating an increase to 2,500 GW by 2030 [3]. This rapid growth in solar energy has been supported by technological advancements and cost reductions in photovoltaic (PV) systems [4]. However, the intermittent nature of PV systems poses significant challenges in maintaining the balance between energy supply and demand. For example, a study conducted in Germany reported that PV systems could meet 45% of energy demand on sunny days, but this proportion dropped below 10% on cloudy days [5]. This variability raises concerns regarding energy security and grid stability [6]. Energy storage systems (ESS) play a critical role in addressing these challenges by storing excess energy generated and making it available for use when needed. As of 2024, the global energy storage capacity has reached 70 GW, with a target of expanding this capacity to 300 GW by 2030 [7]. Lithium-ion batteries, in particular, hold a significant position in the energy storage sector, with costs decreasing by 80% and energy densities improving by 40% [8]. These advancements have accelerated the integration of energy storage solutions into PV systems [9]. Energy storage technologies integrated with PV systems not only ensure energy continuity but also provide environmental and economic benefits, such as reducing carbon emissions and lowering energy costs [10]. Studies indicate that energy storage solutions integrated with PV systems have reduced carbon emissions by 15% while enhancing energy efficiency [11]. Innovative approaches like hybrid energy storage systems (HESS) improve energy storage performance in PV systems and support grid stability [12]. Technological innovations in ESS encompass a wide range of solutions, from thermal energy storage (TES) methods and lithium-ion batteries to supercapacitors and HESS. For instance, TES solutions developed using phase change materials (PCM) enhance the thermal efficiency of solar energy systems. These advancements underscore the importance of energy storage technologies not only in ensuring energy continuity but also in terms of economic feasibility and environmental sustainability. The objective of this study is to examine advancements in energy storage technologies integrated with photovoltaic (PV) systems. Thermal, electrochemical and hybrid energy storage solutions are evaluated, focusing on innovative technologies such as lithium-ion batteries, PCM, and supercapacitors. Furthermore, the role of artificial intelligence (AI) and machine learning (ML) in enhancing energy management and efficiency is emphasized. This study aims to highlight the significance of PV systems in terms of sustainability and efficiency [13].

2. OVERVIEW OF ENERGY STORAGE SYSTEMS

ESS is considered a critical component for the integration of renewable energy sources and the enhancement of energy grid stability. The intermittent nature of renewable energy sources necessitates the development of storage solutions to meet energy demand.

2.1. Classification of energy storage technologies

Energy storage technologies are categorized based on storage needs. These categories include electrochemical storage, thermal energy storage (phase change materials and sensible heat storage), mechanical energy storage (pumped hydroelectric storage, compressed air energy storage), electrical storage (supercapacitors), and chemical energy storage (hydrogen and other fuels) [14-17].

Electrochemical Energy Storage: Lithium-ion batteries are among the dominant technologies in the energy storage sector due to their high energy density, long lifespan, and decreasing costs. As of 2024, lithium-ion battery costs have decreased by 80%, while energy densities have increased by 40%. Supercapacitors, on the other hand, are notable for their high-power density and rapid charge-discharge cycles [18].

Thermal Energy Storage: Phase change materials (PCM) are widely used to enhance storage capacity and improve the efficiency of thermal energy systems. Sensible heat storage is generally preferred for large-scale applications [19].

Mechanical Energy Storage: Pumped hydroelectric energy storage (PHES) accounts for approximately 90% of the global energy storage capacity and is the most prevalent mechanical energy storage technology [20]. Figure 1 illustrates a schematic of the energy generation and water pumping processes in a PHES system. Compressed air energy storage (CAES) also presents potential, particularly in large-scale energy projects.

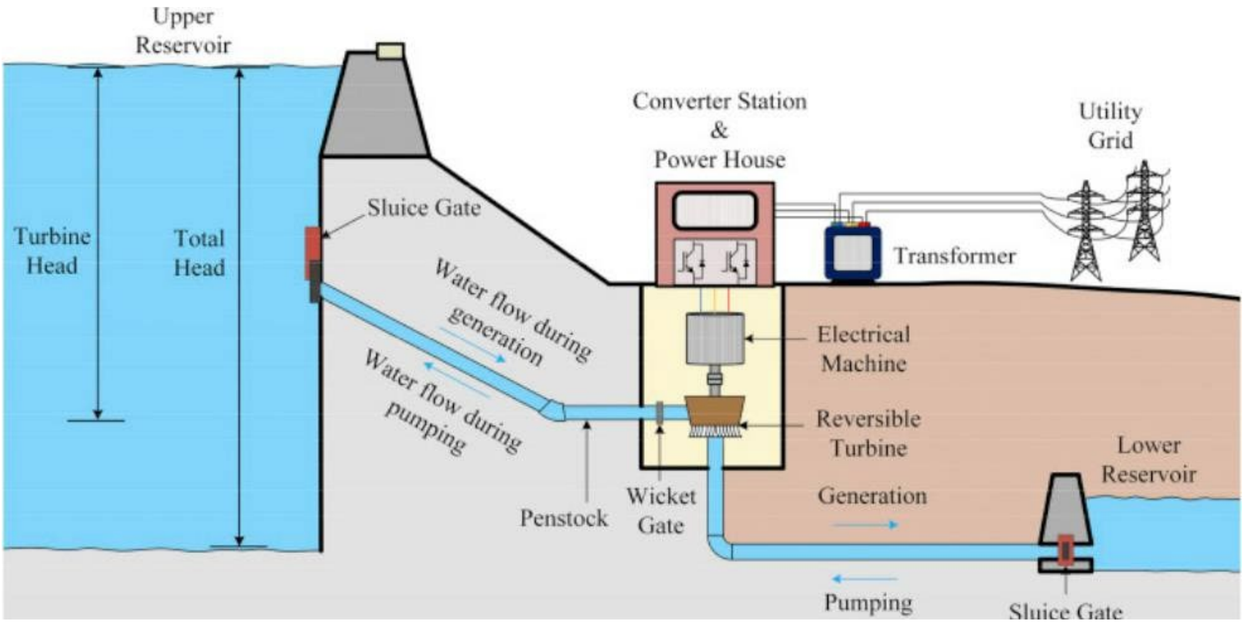

Figure 1. Schematic of a pumped hydroelectric energy storage (PHES) system [21].

Electrical Energy Storage: Electrical energy storage stands out among energy storage technologies with solutions such as lithium-ion batteries and supercapacitors. Lithium-ion batteries deliver remarkable performance in terms of energy density and cycle life, while supercapacitors enable effective management of energy fluctuations due to their high-power density and rapid energy transfer capabilities. These systems play a critical role in the integration of renewable energy sources and in maintaining the energy supply-demand balance. Figure 2 illustrates the applicability of energy storage options across different stages of the electricity supply chain, from generation to consumption. It highlights the importance and functionality of ESS throughout the process, from energy production to the end-user. At the generation stage, centralized storage systems manage grid balance and demand fluctuations by storing excess energy. At the transmission stage, energy storage at transformer substations enhances grid stability and reduces energy losses. During the distribution stage, container-type and large-scale energy storage systems address demand surges and support the integration of local energy sources. At the end-user level, centralized storage systems facilitate the efficient utilization of renewable energy sources, enhance energy independence, and support energy security [22, 23].

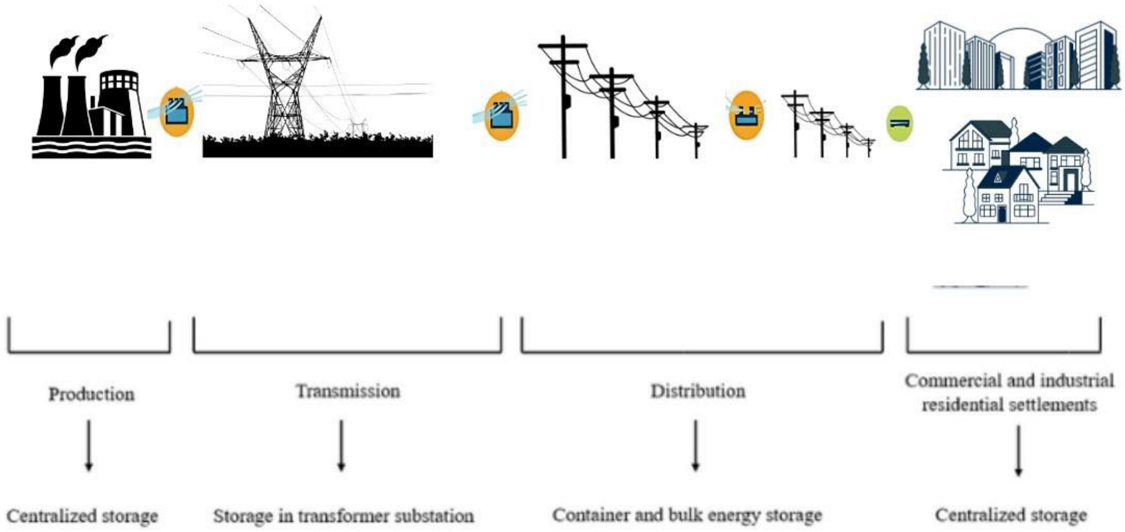

Figure 2. Energy storage options across the energy supply chain from generation to consumption.

Chemical Energy Storage: Hydrogen is considered a significant alternative for the long-term storage of renewable energy sources. Innovative methods such as water electrolysis are utilized for hydrogen production [24]. This study examines PV-based energy storage technologies under three main categories: thermal, electrical, and hybrid storage systems. Figure 3 provides a comprehensive comparison of the performance ranges of various energy storage technologies by presenting their minimum and maximum efficiency values.

Lithium-ion batteries (Li-ion batteries) are prominent for their high energy density and efficiency, while lead-acid batteries offer cost advantages. Flow batteries and sodium-sulfur batteries (NaS batteries) are designed for large-scale and long-duration energy storage applications. Compressed air energy storage (CAES) is employed in long-term energy storage projects, providing extensive storage capacity. Pumped hydroelectric energy storage (PHES) constitutes a significant portion of the global energy storage capacity, delivering high efficiency. Solid-state energy storage (SES), as a next-generation technology, is notable for its high energy density. Superconducting magnetic energy storage (SMES) and flywheel energy storage (FES) play key roles in rapid energy transfer and grid stabilization [25].

Thermal energy storage (TES) is particularly effective for seasonal energy storage, while gravity energy storage systems (GES) and hydrogen energy storage (HES) are crucial for long-term energy management. In Figure 3, blue represents minimum efficiency values, while orange denotes maximum efficiency values, clearly illustrating the performance ranges of each technology.

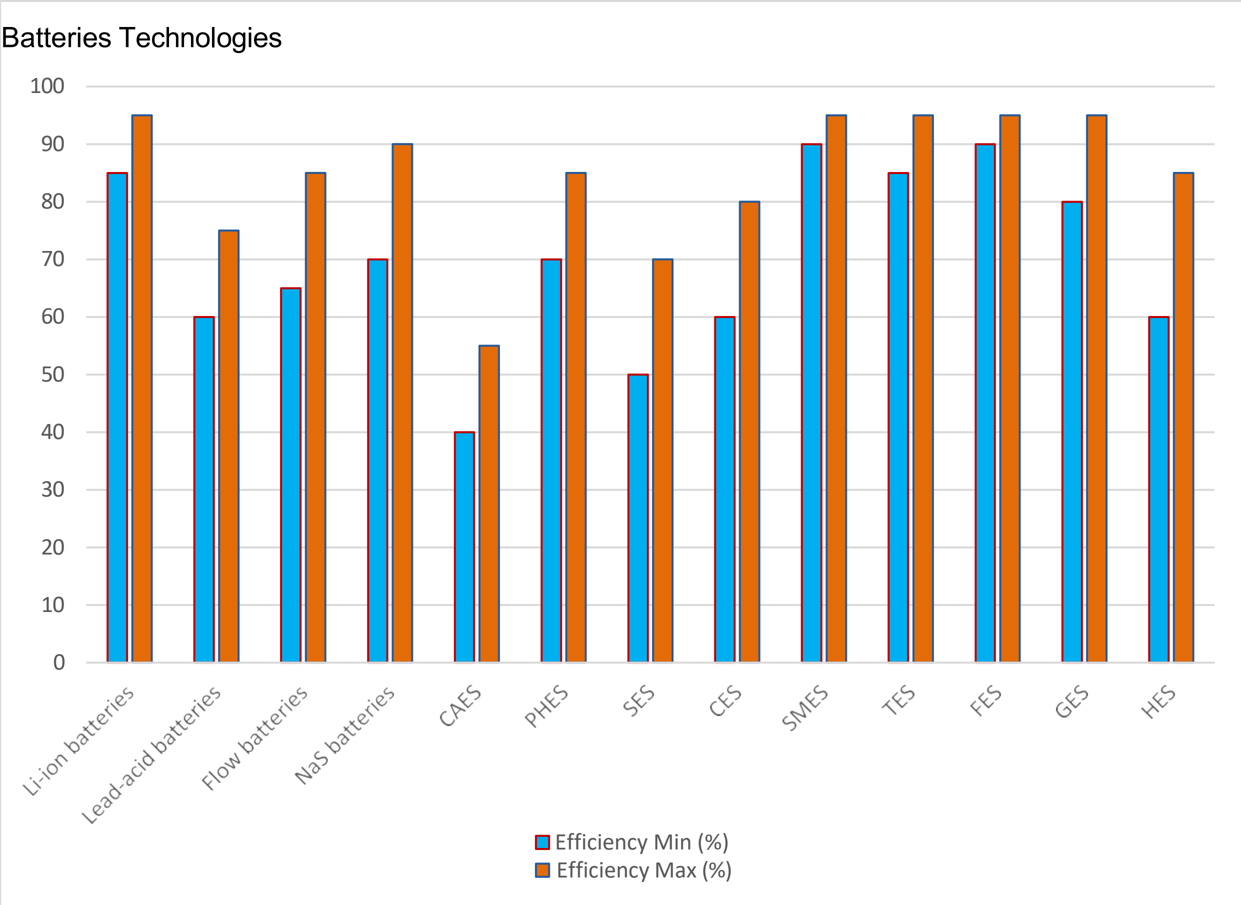

Figure 3: Efficiency of commonly used energy storage technologies [25].

2.2. Energy Storage Requirements with PV Systems

The integration of energy storage systems (ESS) with photovoltaic (PV) systems is essential for effectively managing energy supply-demand fluctuations due to the intermittent nature of solar energy. Excess energy generated during peak solar hours must be stored efficiently to compensate for periods of low or no solar production, such as nighttime or cloudy conditions. ESS significantly enhances grid connectivity and reliability, mitigating issues related to power stability and continuity. Moreover, effective integration of ESS contributes substantially to lowering energy costs by optimizing energy consumption patterns and reducing dependence on grid-supplied energy, especially during peak pricing periods. However, the initial investment costs associated with advanced energy storage solutions, such as lithium-ion batteries, can be considerable, presenting a significant economic barrier. Despite recent cost reductions, particularly the 80% decline in lithium-ion battery prices-initial implementation costs remain high, particularly for large-scale applications. Consequently, optimizing storage sizing and selecting cost-effective solutions tailored to specific PV installations are critical steps to ensure economic viability and maximize long-term financial returns [22, 26, 27].

2.3. Challenges in Energy Storage Technologies

The widespread adoption and effective integration of energy storage technologies into energy systems face significant technical, economic, and environmental challenges that must be systematically addressed. From a technical perspective, the efficiency of energy storage systems is constrained by inherent energy losses during conversion, charging, and discharging processes. These losses directly affect the overall performance and reliability of storage solutions, limiting their full-scale deployment and optimal functionality in renewable energy applications. Economically, high initial investment costs pose substantial barriers to the adoption of advanced energy storage technologies, particularly lithium-ion batteries and other emerging storage solutions. Despite recent reductions in costs, initial expenses remain prohibitive for large-scale implementation and widespread commercial viability, especially in developing regions. Economic feasibility studies indicate that continued advancements in production techniques and material innovations are critical for achieving further cost reductions and enhancing market competitiveness. From an environmental standpoint, significant concerns arise regarding the sustainability of energy storage technologies, primarily associated with the lifecycle impacts of manufacturing and disposing storage systems. The extraction and processing of raw materials such as lithium, cobalt, and nickel for battery production generate substantial environmental burdens, including ecological degradation and resource depletion. Furthermore, end-of-life management, recycling, and disposal of energy storage devices present challenges due to potential toxic emissions and environmental contamination risks. Addressing these sustainability concerns necessitates robust recycling strategies, environmentally friendly material selection, and comprehensive lifecycle assessment methodologies [18, 25, 28]. A comprehensive review reveals that the optimal sizing and integration of energy storage within hybrid renewable systems is essential for achieving economic viability, reliability, and long-term sustainability [29-36].

3. THERMAL ENERGY STORAGE SYSTEM

Thermal Energy Storage (TES) solutions play a critical role in enhancing the energy efficiency of PV systems, supporting grid stability, and optimizing the use of renewable energy. The literature extensively examines various TES technologies, including phase change materials (PCM), sensible heat storage, latent heat storage, and thermochemical storage, for their applications in PV systems. Figure 4 illustrates an example of TES applications in Concentrated Solar Power (CSP) systems and the electricity generation process. The upper image shows a typical CSP field, where mirrors, known as heliostats, focus sunlight onto a solar tower. The lower diagram provides a detailed depiction of the system's operational principle: solar energy focused by the heliostat field onto the solar thermal receiver is initially collected in a hot storage tank. This energy is then transferred to the power block via a heat exchanger and converted into electrical energy. During electricity production, the cooled energy is stored in a cold storage tank and reintegrated into the cycle [28].

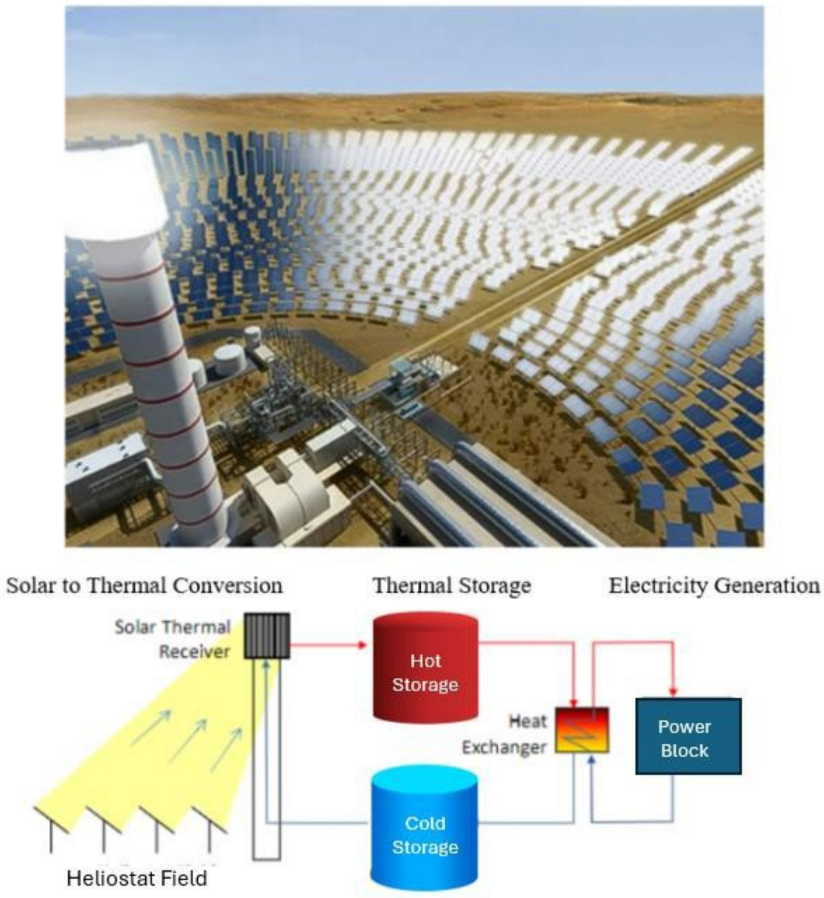

Figure 4: Schematic of a two-tank thermal storage system in a CSP facility.

3.1. Phase Change Materials (PCM) and Their Applications

PCM is one of the most extensively researched and applied technologies in TES. Due to their ability to store large amounts of energy during phase change processes, PCMs provide high energy density. The literature reports that PCMs improve efficiency and ensure energy storage continuity, particularly in PV-T (photovoltaic-thermal) systems. It has been noted that PCMs, with their low melting points, effectively cool PV modules, thereby increasing electrical efficiency by 5–10% [37]. Additionally, when used as a seasonal heat storage solution in ESS, PCMs enhance environmental sustainability [38]. Recent studies have demonstrated significant performance improvements in thermal energy storage processes in PV-T systems using PCMs. By increasing energy storage capacity at low temperatures, PCMs optimize the energy conversion efficiency of PV modules [39]. Furthermore, integrating PCM with thermochemical storage systems has increased storage density by 34% [40]. Recent studies emphasize that the integration of PCMs in thermal storage systems significantly improves storage efficiency and thermal regulation, particularly in PV-T applications where energy continuity is critical [41].

3.2. Sensible and Latent Heat Storage Technologies

Sensible heat storage relies on storing heat by raising the temperature of a material. This technology is typically used in large-scale applications due to its cost-effectiveness. Water-based sensible heat storage systems have been shown to enhance energy conversion efficiency in PV-T systems [42]. Latent heat storage, on the other hand, involves energy storage during the phase change of a material. Integrating this technology with PV systems is critical for increasing energy density and minimizing storage losses [43]. The literature highlights latent heat storage as a significant mechanism supporting the use of PCM in thermal energy applications [44]. Latent heat storage technologies play an essential role in reducing energy losses in PV-T systems while ensuring energy density and continuity [45]. Additionally, the cost advantages of sensible heat storage systems make them highly effective for large-scale projects [46].

3.3. The Role of Thermal Storage in PV-T Systems

PV-T systems are hybrid systems that produce both electrical and thermal energy simultaneously. The integration of thermal storage solutions in these systems is considered a critical component for enhancing overall energy efficiency and improving system stability. Studies emphasize that thermal energy storage in PV-T systems increases total energy efficiency by up to 30% and enhances system stability [47]. Moreover, thermal storage is identified as a vital solution for maintaining the energy supply-demand balance and reducing energy costs [48]. As shown in Figure 5, the thermal energy storage system (TESS) control system integrates PCMs into PV-T systems, reducing thermal energy losses by 15%. The literature underscores the contribution of thermal storage solutions to improving the overall energy efficiency of PV-T systems. It is also noted that integrating thermal storage solutions with phase change materials significantly reduces energy costs and enhances system stability [49]. Recent advances in solar thermal systems have demonstrated that the use of nanofluids can considerably enhance the heat transfer capabilities of phase change materials, improving the overall efficiency of PV-T configurations [50]. Photovoltaic-driven cooling systems are increasingly recognized for their dual benefits of thermal management and enhanced power generation, especially in climates with high solar irradiance [51].

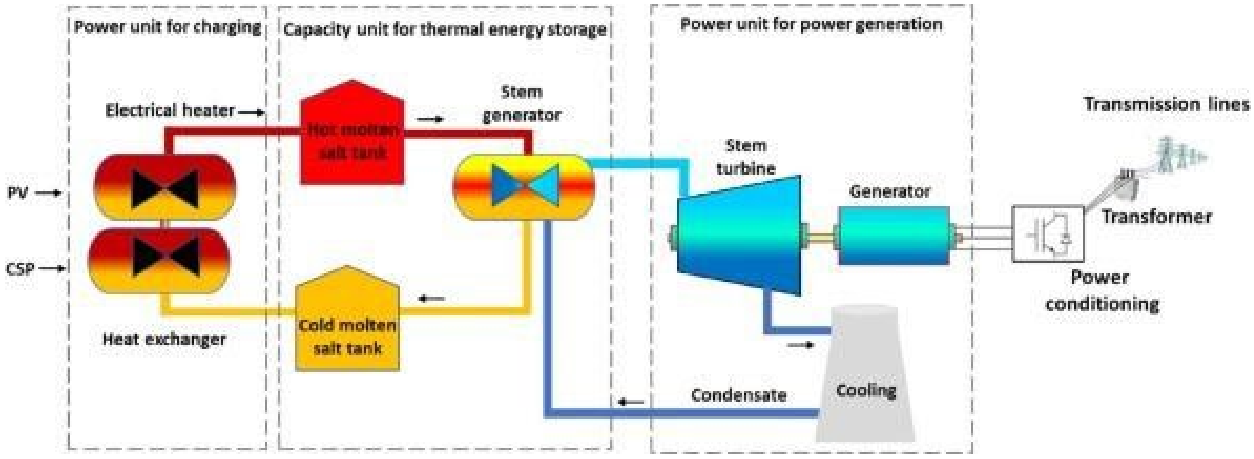

Figure 5: TESS control system [49].

4. ELECTRICAL ENERGY STORAGE SYSTEMS

Electrical energy storage solutions are critically important for integrating renewable energy sources and maintaining grid stability. The integration of ESS with PV systems offers significant potential in terms of energy security, flexibility, and cost optimization. Figure 6 indicates that electrical ESS is categorized into two main types: electrostatic energy storage and magnetic energy storage. Electrostatic energy storage systems are represented by devices such as capacitors and supercapacitors, which operate based on the principle of storing electrical energy in electric fields. Magnetic energy storage systems, on the other hand, include superconducting magnetic energy storage (SMES) technologies, which store energy in magnetic fields. This section evaluates battery technologies, energy storage management systems, and advanced optimization techniques based on recent literature.

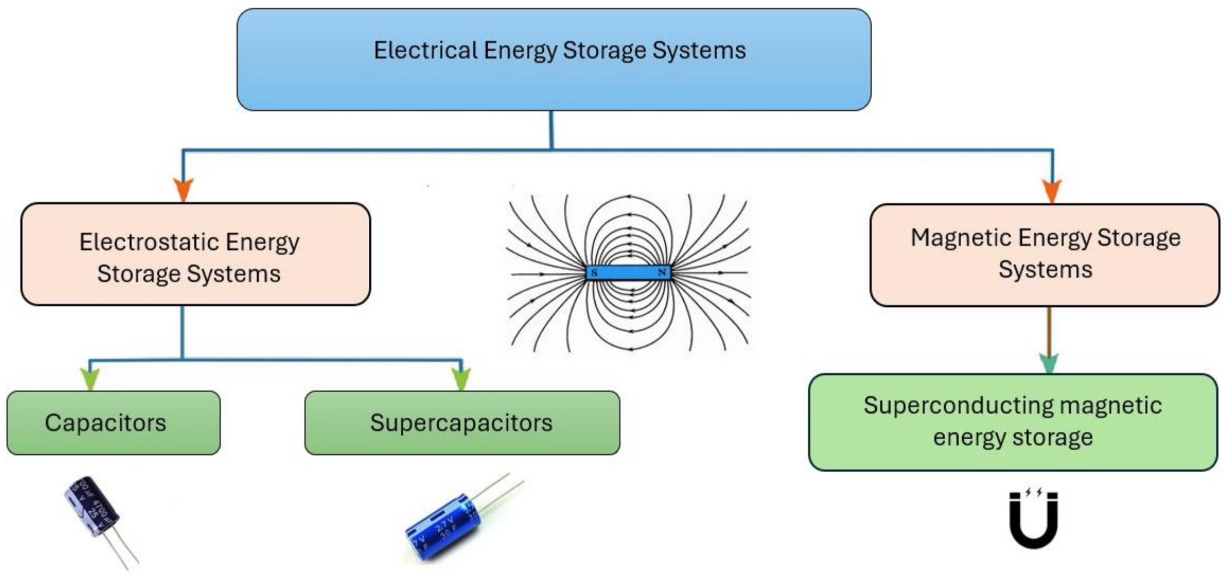

Figure 6: Classification of electrical energy storage systems

4.1. Energy Storage Management Systems

Effective management techniques for ESS integrated with PV systems play a critical role in improving energy efficiency. Optimization techniques maximize system performance by accurately predicting storage capacity [52]. Additionally, linear programming methods have been reported to optimize charging and discharging processes by adapting to the energy demand profiles of PV systems [53]. The application of AI-based algorithms in ESS management for PV systems has been identified as a key factor in optimizing energy flow. Studies have shown that such management systems can reduce carbon emissions by up to 30% and enhance the efficiency of charging and discharging processes. Furthermore, linear programming methods have been demonstrated to optimize energy storage capacity in PV system integration [54].

4.2. Innovations in Battery Technologies

Battery technologies, particularly lithium-ion and vanadium redox flow batteries, are at the forefront of PV system integration. The literature highlights lithium-ion batteries as an effective solution for mitigating energy production fluctuations in PV systems [55]. Vanadium redox flow batteries are noted for their suitability for long-term energy storage and offer a cost-effective alternative for PV system integration [56]. Lithium-ion batteries play a vital role in meeting storage needs due to their high energy density and rapid charge/discharge capabilities. Meanwhile, vanadium redox flow batteries provide long-term performance and are deemed cost-effective for large-scale energy storage projects. Moreover, the application of nanotechnology in batteries has further improved performance by enhancing energy storage density [57]. The integration of energy storage systems with multilevel inverters has been found to enhance power quality and operational efficiency in PV-based microgrids, thereby increasing their feasibility for modern distributed energy systems [58].

4.3. Advanced Optimization Techniques

Optimal placement and sizing of ESS are crucial for minimizing energy losses and enhancing grid stability. The literature identifies Mixed-Integer Linear Programming (MILP) methods as providing the best solutions in terms of cost and performance for ESS integrated with PV systems. MILP techniques have been highlighted for offering optimal solutions for ESS sizing and placement, reducing energy losses by 20% and significantly improving grid stability. Additionally, AI-supported optimization techniques have been reported to increase energy conversion efficiency while reducing costs in PV and ESS integration [59].

5. HYBRID ENERGY STORAGE SYSTEMS (HESS)

HESS provides innovative solutions for managing the intermittent nature of PV systems, balancing energy supply and demand, and enhancing the sustainability of energy systems. Numerous studies in the literature have examined the efficiency and feasibility of hybrid systems. HESS typically combines different energy storage technologies to ensure energy continuity. For example, integrating batteries with supercapacitors has been shown to improve energy quality and effectively manage rapid load changes in PV systems [59]. Optimizing hybrid systems with pumped hydro storage integrated with wind and solar energy has been demonstrated to reduce costs and enhance energy flexibility. Additionally, thermochemical energy storage methods have been reported to meet seasonal energy storage and load balancing needs for PV systems [28, 37, 54]. Furthermore, the development of IoT-enabled portable solar-powered multifunctional charging devices demonstrates the increasing versatility and real-time management capabilities of hybrid energy systems in decentralized energy access applications [60].

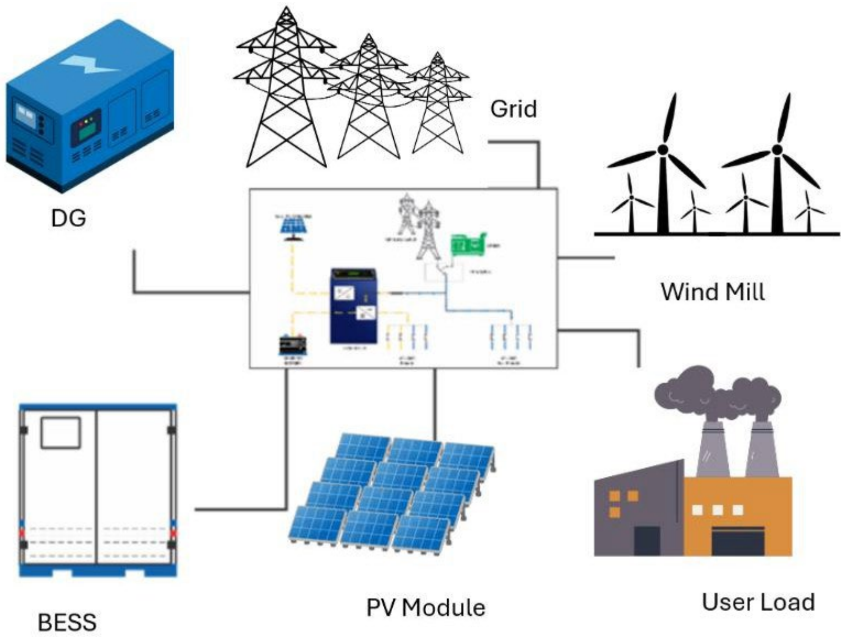

Figure 7: HESS operational diagram

As shown in Figure 7, HESS provides an effective solution for ensuring energy continuity by combining various energy storage technologies. For instance, hybrid systems integrating compressed air and hydrogen carrier technologies have successfully increased energy storage capacity while reducing costs [61]. Furthermore, the integration of supercapacitors with PV systems plays a significant role in improving grid stability by increasing energy density [62]. Figure 8 summarizes the compatibility of the ten most commonly used energy storage technologies in 100 different combinations. Among these, 74 combinations represent real cases currently applicable in energy systems (indicated by blue cells with "X"), 10 represent scenarios with no combinations (orange cells), and 16 involve innovative solutions still under development or requiring expensive materials (green cells).

	BES	SES	FES	TES	SMES	PHES	HES	CAES	GES	CES
BES		X	X	X	X	X	X	X	X	X
SES	X		X	X	X	X	X	X	X	X
FES	X	X		X	X	X	X	X	X	X
TES	X	X	X		X	X	X	X	X	X
SMES	X	X	X	X		X	X	X	X	X

Figure 8: Summary of different combinations of energy storage technologies [25].

5.1. Management Strategies

HESS is supported by advanced energy management strategies to minimize energy losses and enhance system efficiency. Studies have shown that integrating PV systems with hydrogen fuel cells, using artificial intelligence (AI) and optimization algorithms, reduces carbon emissions and decreases energy costs [30, 58]. Energy management systems in grid-connected hybrid systems optimize charging and discharging processes, extending the lifespan of energy storage devices. Additionally, optimization studies conducted using HOMER software reveal the potential of hybrid systems to reduce total energy costs [63]. Advanced energy management strategies play a critical role in enhancing HESS performance. For example, integrating hybrid PV and hydrogen fuel cells optimizes the energy supply-demand balance while reducing carbon emissions [30, 59]. Furthermore, predictive control algorithms used in compressed air and hydrogen-based HESS have proven effective in reducing energy storage losses [64]. Integrated energy management strategies within photovoltaic battery microgrids have shown promise in improving power quality and ensuring stable energy distribution under fluctuating load demands [65].

5.2. Technological Developments

The literature identifies various technological innovations in the HESS field. Thermochemical energy storage technologies are highlighted as suitable for seasonal energy storage in PV and concentrated solar power plants. AI-powered optimization algorithms are employed to improve capacity planning and energy management for hybrid systems. Additionally, integrating PV systems with hydrogen fuel cells is recognized as a significant solution for long-term energy storage and carbon emission reduction [66].

5.3. Future Perspectives

The development of HESS is critical for achieving large-scale applicability and economic sustainability. It is anticipated that the successful commercial-scale integration of hybrid systems in industrial applications will enhance energy supply security [67]. Future studies are recommended to focus on reducing carbon emissions and increasing the integration of renewable energy sources [68].

6. APPLICATIONS OF ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN PV-BASED ENERGY STORAGE SOLUTIONS

Artificial intelligence (AI) and machine learning (ML) are revolutionizing the efficiency of PV-based energy storage solutions and optimizing renewable energy systems. AI and ML applications are employed across a broad spectrum, including energy management, forecasting algorithms, smart grid integration, and system design.

6.1. AI-Assisted Energy Management and Optimization Techniques

AI-based energy management systems optimize the charging and discharging cycles of energy storage devices, extending system lifespan and reducing costs.

- **Energy Management Systems:** AI-assisted energy management reduces energy losses by 28% in PV systems by optimizing energy flow [69].
- **Maximum Power Point Tracking (MPPT):** Machine learning in MPPT algorithms ensures maximum energy efficiency in PV systems. A deep learning-based MPPT algorithm is reported to be 15% faster than traditional algorithms [70].
- **Reinforcement Learning Optimization:** Reinforcement Learning (RL) algorithms are used in energy storage management to reduce costs and increase efficiency. RL-based systems have been shown to decrease energy costs by 20% [71].

6.2. Energy Demand Forecasting and Capacity Planning

ML-based forecasting algorithms enable more accurate predictions of energy demand profiles.

- **Deep Learning for Energy Forecasting:** Deep learning algorithms have improved the accuracy of PV-based ESS energy demand and production forecasting by 39.8% [72].
- **Energy Storage Capacity Optimization:** ML models for capacity planning optimize energy storage capacity, enhancing system performance [73].

6.3. Smart Grid Applications

AI in smart grid systems improves energy efficiency in PV system integration and optimizes energy flow [70, 73]. AI-Assisted Grid Management: AI-enabled smart grids have reduced carbon emissions by 30% by optimizing energy flow Deep Learning and Smart Grids: Deep learning-based forecasting models have improved grid stability and energy management by 25% [74]. Transparency and Traceability with XAI: Explainable AI (XAI) enhances the transparency and reliability of forecasting models in smart grid applications [76]. Figure 9 details the processes of energy production, storage, and load management in a PV-based energy system. The system involves directing electricity generated by PV modules to the grid or load through DC/AC converters, charging or discharging ESS through bidirectional converters, and exchanging data via storage management systems [24, 75].

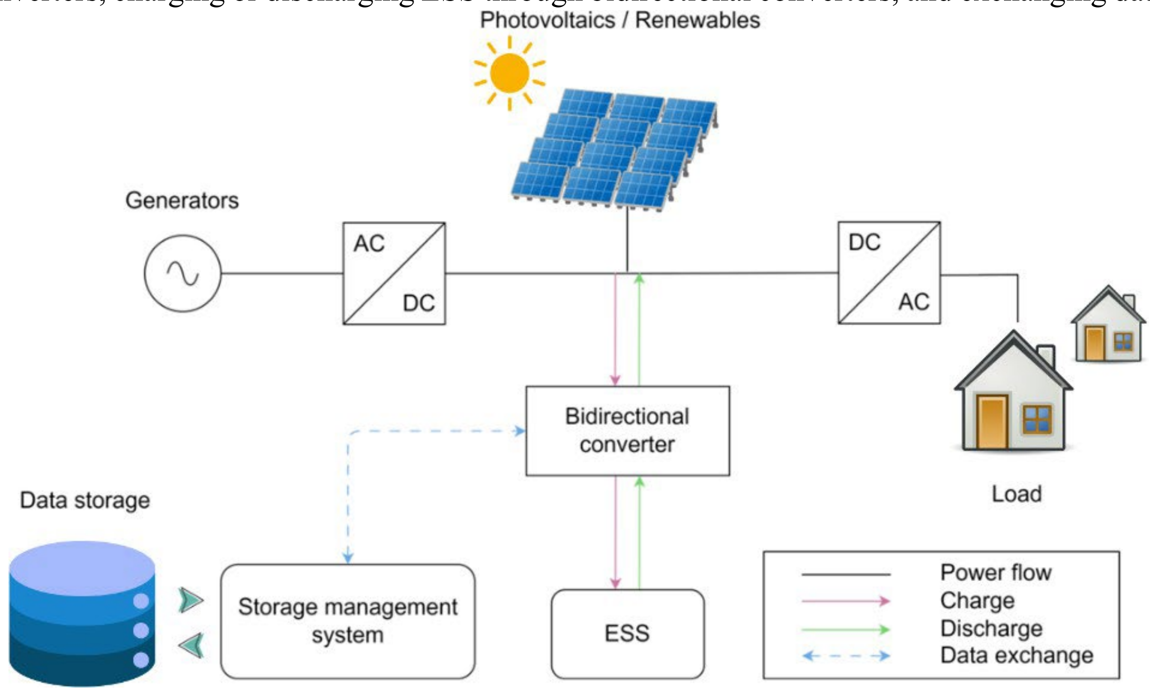

Figure 9: Integration of ESS into the Power Grid [23, 67]

Publication Year	Application	Contribution	Reference
2020	Thermochemical energy storage in CSP systems	Operational optimization and long-duration thermal storage in CSP applications	[28]
2020	Hybrid energy storage system using compressed air and hydrogen	Increased energy storage capacity and reduced costs	[61]
2020	Cost optimization of PV-fuel cell hybrid systems using HOMER	Minimized costs and improved energy flexibility in hybrid design	[63]
2021	Variable speed pumped hydro storage systems	Improved control and energy management in PHES using variable speed converters	[21]
2021	PCMs in building heating and	Improved TES performance and energy	[38]

	cooling	efficiency in buildings	
2021	Integration of PV and supercapacitors	Enhanced grid stability and improved energy density	[62]
2022	Overview of energy storage for solar power systems	Comprehensive review of recent ESS advancements for solar energy	[19]
2022	Technological developments in SMES systems	Distribution-level development of SMES systems for enhanced performance	[22]
2022	Evaluation of biomass-based hybrid power systems with storage	Technical, environmental, and economic assessment of hybrid storage-based rural electrification	[27]
2022	Integration of PCMs in PV-T systems	Enhancing energy efficiency and continuity in PV-T systems	[39]
2022	Review of hybrid energy storage systems for PV generation	Highlighted advantages of HESS in solar PV applications	[66]
2022	Control strategy for PV fluctuation using HESS	Smoothed PV output and improved system response	[67]
2023	Review of energy storage systems for PV and wind	Efficiency classification and integration performance of diverse ESS technologies	[25]
2023	Hybrid 1 MWp PV-farm with energy storage analysis	Feasibility analysis of PV and storage configurations in Poland's energy market	[26]
2023	PCM + thermochemical hybrid storage systems	34% increase in storage density by hybridizing PCM with thermochemical storage	[40]
2023	Latent heat storage with improved PCM usage	Increased energy density and minimized losses using latent heat storage	[44]
2023	Low-temp PCM for thermal regulation	Improved thermal storage under low temperature applications	[45]

2023	Nanofluids in thermal systems	Improved heat transfer performance using nanofluid in solar thermal systems	[50]
2023	Predictive control in compressed air and hydrogen-based HESS	Reduced storage losses and optimized system efficiency	[64]
2023	Integrated energy management in PV-battery microgrid	Enhanced power quality and system stability	[65]
2024	Photovoltaic-driven cooling systems	Dual-function systems for energy efficiency and cooling in PV applications	[17]
2024	Technologies and high-power applications of ESS	Enhanced energy density, lifespan, and reduced cost in modern ESS	[18]
2024	Energy storage systems for non-interconnected islands	Addressing storage needs in isolated systems through diversified ESS technologies	[24]
2024	Optimization of TES in PV-T with AI	Improved energy conversion through AI-supported TES system design	[36]
2024	Advanced TES performance with PCM	Enhanced PCM integration and thermal regulation in solar applications	[41]
2024	Thermal control system in PV- T applications	15% reduction in thermal losses and better system stability with TESS	[49]
2024	Integration of HESS with multilevel inverters	Increased system efficiency and better integration of storage	[58]
2024	Real-time IoT-based hybrid portable solar chargers	Improved energy access and real-time control with IoT-enabled systems	[60]

2025	Systematic review of ESS integration in hybrid renewable systems	Optimization of hybrid ESS configuration and techno economic performance	[29]
2025	Photovoltaic-driven cooling systems	Dual benefit of thermal regulation and electrical efficiency under high irradiance	[51]
2025	HESS strategies to improve supply security in industrial scale	Improved economic sustainability and energy security in industry	[68]

Table 1 presents the developments, application areas, algorithms used, and contributions to the literature of various energy storage technologies between 2020 and 2025. This allows for an analysis of the annual distribution of different storage methods, including thermal, electrochemical, electrical, and hybrid systems.

7. CONCLUSION

Photovoltaic (PV) based energy storage solutions are fundamental to achieving sustainable energy management and enhancing grid stability. This study has comprehensively reviewed the recent advancements in the integration of energy storage technologies within PV systems, focusing on thermal, electrochemical, and hybrid storage methods, along with intelligent energy management systems.

The following conclusions can be drawn from the analysis:

- Thermal energy storage technologies, particularly phase change materials (PCMs) and sensible heat storage systems, contribute significantly to improving energy conversion efficiency and thermal regulation in PV and PV-thermal (PV-T) systems.
- Electrochemical energy storage technologies, with lithium-ion batteries at the forefront, continue to dominate the sector due to advancements in energy density and a substantial reduction in manufacturing costs.
- Hybrid Energy Storage Systems (HESS) offer increased reliability and operational flexibility by combining complementary storage technologies. These systems are particularly effective in addressing the intermittent nature of solar energy and ensuring energy continuity.
- The integration of Artificial Intelligence (AI) and Machine Learning (ML) techniques enhance energy management by optimizing storage operations, improving capacity planning, reducing carbon emissions, and lowering overall energy costs.

- AI-based optimization algorithms and smart energy management systems have been shown to extend the operational lifespan of storage devices while improving system efficiency and responsiveness.

Despite these advancements, several challenges persist, including high capital costs, energy efficiency limitations, and environmental sustainability concerns—particularly related to the lifecycle impacts of battery materials.

In this regard, continued research and development is essential to overcoming these limitations and ensuring the broader applicability and scalability of PV-based energy systems. Future efforts should prioritize the deployment of hybrid storage architectures and the widespread implementation of AI-enabled control systems to foster a more resilient and sustainable energy transition.

NOMENCLATURE

AI	Artificial Intelligence
BES	Battery Energy Storage
CAES	Compressed Air Energy Storage
CES	Chemical Energy Storage
CSP	Concentrated Solar Power
DC	Direct Current
ESS	Energy Storage System
FES	Flywheel Energy Storage
GES	Gravity Energy Storage
HES	Hydrogen Energy Storage
HESS	Hybrid Energy Storage System
HOMER	Hybrid Optimization of Multiple Energy Resources
IoT	Internet of Things
Li-ion	Lithium-ion (Battery)
ML	Machine Learning
MILP	Mixed-Integer Linear Programming
NaS	Sodium-Sulfur (Battery)
PCM	Phase Change Material
PCMs	Phase Change Materials
PHES	Pumped Hydroelectric Energy Storage

PV	Photovoltaic
PV-T	Photovoltaic-Thermal
RL	Reinforcement Learning
SES	Solid-State Energy Storage
SMES	Superconducting Magnetic Energy Storage
TESS	Thermal Energy Storage System
TES	Thermal Energy Storage
XAI	Explainable Artificial Intelligence
AC	Alternating Current

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DECLARATION OF ETHICAL STANDARDS

The author of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Merve Yılmaz: Writing - review & editing.

Onur Akar: Interpretation of data, supervising the whole process.

Nazmi Ekren: Supervising the whole process.

CONFLICT OF INTEREST

There is no conflict of interest in this study

REFERENCES

[1] Yadwad V, Bharamnaikar SR, Bhushi U. Holistic perspective to knowledge integration for performance of renewable and sustainable energy business. In: IOP Conference Series: Earth and Environmental Science. IOP Publishing Ltd, 2021.

[2] Bagherian MA, Mehranzamir K. A comprehensive review on renewable energy integration for combined heat and power production. Energy Conversion And Management 2020; 224: 113454.

[3] "World Energy Outlook 2024 – Analysis - IEA," https://www.iea.org/reports/world-energy-outlook-2024.

[4] Zhou W, Chen Q, Luo D, Jiang R, Chen J. Global energy consumption analysis based on the three-dimensional network model. IEEE Access 2020; 8: 76313–76332.

[5] Canale L, Di Fazio AR, Russo M, Frattolillo A, Dell'Isola M. An overview on functional integration of hybrid renewable energy systems in multi-energy buildings. Energies 2021; 14 (4): 1078.

[6] Ekechukwu DE, Daramola GO, Kehinde OI. Integrating renewable energy with fuel synthesis: conceptual framework and future directions. Engineering Science & Technology Journal 2024; 5 (6): 2065–2081.

[7] Sahoo S, Timmann P. Energy storage technologies for modern power systems: a detailed analysis of functionalities, potentials, and impacts. IEEE Access 2023; 11: 49689–49729.

[8] Authin EA, Liew PY, Klemeš JJ, Ho WS, Che Jusoh NW, Mohammad Rozali NE. Integration of combined heat and power energy systems with gas turbine in locally integrated energy sectors. Chem Eng Trans 2021; 83: 37–42.

[9] Kriechbaum L, Gradl P, Reichenhauser R, Kienberger T. Modelling grid constraints in a multi-energy municipal energy system using cumulative exergy consumption minimisation. Energies 2020; 13 (15): 3900.

[10] Bogdanov D, Gulagi A, Fasihi M, Breyer C. Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination. Applied Energy 2021; 283: 116273.

[11] Huang Z. Analyzing the impact of renewable energy integration on power system reliability. Highlights in Science, Engineering and Technology 2024; 87: 76–81.

[12] Oyekale J, Petrollese M, Tola V, Cau G. Impacts of renewable energy resources on effectiveness of grid-integrated systems: succinct review of current challenges and potential solution strategies. Energies 2020; 13 (18): 4856.

[13] Mir MA, Ashraf MW, Andrews K. Renewable energy sources, sustainability aspects and climate alteration: a comprehensive review. Materials Research Proceedings 2024; 43.

[14] Altun M, Akar O, Terzi ÜK. The impact of energy storage systems on distribution networks' power quality. ISARC-5. International Hasankeyf Scientific Research and Innovation Congress (pp. 218–219). Batman, Turkey, 2023.

[15] Kaya F, Akar O. Geothermal energy-based hydrogen energy storage and charging station system. İstanbul Ticaret Üniversitesi Fen Bilimleri Dergisi 2024; 23 (45): 156–168.

[16] Alghamdi H, Maduabuchi C, Okoli K, Alobaid M, Alghassab M, Alsafran AS, Alkhedher M. Latest advancements in solar photovoltaic-thermoelectric conversion technologies: thermal energy storage using phase change materials, machine learning, and 4E analyses. International Journal of Energy Research 2024; 2024 (1): 1050785.
[17] Jassim L, Mnati HM, Ali FAMA, Majdi HS. Photovoltaic-driven cooling systems: advances, challenges, and future directions. Al Rafidain Journal of Engineering Sciences 2025; 3: 191–209.
[18] Aghmadi, Mohammed OA. Energy storage systems: technologies and high-power applications. Batteries 2024; 10 (4).
[19] Hussen S, Ayalew F, Bajaj M, Sharma NK, Jurado F, Kamel S. An overview of recent advances in energy storage for solar power systems. In: 2022 IEEE International Conference on Automation/XXV Congress of the Chilean Association of Automatic Control (ICA-ACCA). IEEE, 2022; 1–6.
[20] Denholm P, Cole W, Blair N. Moving beyond 4-hour Li-ion batteries: challenges and opportunities for long(er)-duration energy storage. 2023.
[21] Vasudevan KR, Ramachandaramurthy VK, Venugopal G, Ekanayake JB, Tiong SK. Variable speed pumped hydro storage: a review of converters, controls and energy management strategies. Renewable and Sustainable Energy Reviews 2021; 135: 110156.
[22] Çam G, Akar O. Technological developments of SMES systems in distribution networks. Cukurova 11th International Scientific Researches Conference (pp. 22–36). Adana, Turkey, 2023.
[23] Mitali J, Dhinakaran S, Mohamad AA. Energy storage systems: a review. Energy Storage and Saving 2022; 1 (3): 166–216.
[24] Fotopoulou M, Pediaditis P, Skopetou N, Rakopoulos D, Christopoulos S, Kartalidis A. A review of the energy storage systems of non-interconnected European islands. Sustainability 2024; 16 (4): 1572.
[25] Rekioua D. Energy storage systems for photovoltaic and wind systems: a review. Energies 2023; 16 (9): 3893.
[26] Ross K, Matuszewska D, Olczak P. Analysis of using hybrid 1 MWp PV-farm with energy storage in Poland. Energies 2023; 16: 27654.
[27] Demirci O, Akar O, Ozturk Z. Technical-environmental-economic evaluation of biomass-based hybrid power system with energy storage for rural electrification. Renewable Energy 2022; 195: 1202–1217.

[28] Bravo R, Ortiz C, Chacartegui R, Friedrich D. Hybrid solar power plant with thermochemical energy storage: a multi-objective operational optimisation. Energy Conversion and Management 2020; 205.
[29] Khan AA, Minai AF, Godi RK, Sharma VS, Malik H, Afthanorhan A. Optimal sizing, techno-economic feasibility and reliability analysis of hybrid renewable energy system: a systematic review of energy storage systems' integration. IEEE Access 2025.
[30] Tural E, Koca Z, Ok Davarci Z, Akar O. PV-based electricity production and storage in marine vehicles. In: 2024 11th International Conference on Electrical and Electronics Engineering (ICEEE 2024). IEEE, 2024; 327–332.
[31] Ozturk Z, Tosun S, Ozturk A, Akar O. Comparative evaluation of stand-alone hybrid power system with different energy storages. Fresenius Environmental Bulletin 2021; 30 (9): 10908–10924.
[32] Akar O, Terzi ÜK, Tunçalp BK, Sönmezocak T. Determination of the optimum hybrid renewable power system: a case study of Istanbul Gedik University Gedik Vocational School. Balkan Journal of Electrical and Computer Engineering 2019; 7 (4): 456–463.
[33] Ok Davarcı Z, Akar O. Estimation of the electricity to be generated at different wind speeds and turbines through fuzzy logic and ANN: a case study of Balıkesir. International Journal of Energy Studies (Online) 2024; 9 (1): 115–133.
[34] Oz O, Sahin M, Akar O. Modeling of an HPS for the electric power demand of the cattle farm using genetic algorithm. Heliyon 2023; 9 (6).
[35] Celil O, Akar O. Ayvalık coast offshore wind turbine potential and economic evaluation. In: 2024 12th International Conference on Smart Grid (icSmartGrid). IEEE, 2024; 682–686. Setúbal, Portugal.
[36] İzgi B. Machine learning predictions and optimization for thermal energy storage in cylindrical encapsulated phase change material. International Journal of Energy Studies 2024; 9: 199–218.
[37] Arsalis G, Georghiou E, Papanastasiou P. Recent research progress in hybrid photovoltaic–regenerative hydrogen fuel cell microgrid systems. Energies 2022; 15 (10): 3512.
[38] Bayoumi M. Potential of façade-integrated PVT with radiant heating and cooling panel supported by a thermal storage for temperature stability and energy efficiency. Journal of Facade Design and Engineering 2021; 9: 47–58.
[39] Arévalo P, Ochoa-Correa D, Villa-Ávila E. Advances in thermal energy storage systems for renewable energy: a review of recent developments. Processes 2024; 12: 1844.

[40] Barrasso M, Langella G, Amoresano A, Iodice P. Latest advances in thermal energy storage for solar plants. Processes 2023; 11 (6): 1832.
[41] Dumrul H, Bulut A. Phase change materials in thermal energy storage applications. Yaz 54.
[42] Simão M, Ramos HM. Hybrid pumped hydro storage energy solutions towards wind and PV integration: improvement on flexibility, reliability and energy costs. Water (Switzerland) 2020; 12 (9): 2457.
[43] Khirennas A, Talha A, Kaabeche A, Bakelli Y. Overview of fossil fuel-based hybrid power generation systems within mini-grids – the experience of storage-less PV system integration into three of the Great Algerian South mini-grids. Energy Conversion and Management 2020; 221: 113191.
[44] Suresh, Saini RP. Thermal performance of sensible and latent heat thermal energy storage systems. International Journal of Energy Research 2020; 44: 4743–4758.
[45] Hinojosa JF, Moreno SF, Maytorena VM. Low-temperature applications of phase change materials for energy storage: a descriptive review. Energies 2023; 16 (7): 3078.
[46] Liu M, Riahi S, Jacob R, Belusko M, Bruno F. Design of sensible and latent heat thermal energy storage systems for concentrated solar power plants: thermal performance analysis. Renewable Energy 2020; 151: 1286–1297.
[47] Behera MK, Saikia LC. A novel resilient control of grid-integrated solar PV-hybrid energy storage microgrid for power smoothing and pulse power load accommodation. IEEE Transactions on Power Electronics 2023; 38: 3965–3980.
[48] Karampudi N. Thermal energy storage technology in solar energy utilization: a review. International Transactions on Electrical Engineering and Computer Science 2023; 2: 80–87.
[49] Rahman MM, Khan I, Alameh K. The role of energy storage technologies for sustainability in developing countries. In: Renewable Energy and Sustainability: Prospects in the Developing Economies. Elsevier, 2022; 347–376.
[50] Taşkesen E, Uren R. Recent advances in solar thermal system involving nanofluid utilization: a mini review. International Journal of Energy Studies 2023; 8: 581–600.
[51] Jassim, L., Mnati, H. M., Abd Ali, F. A. M., & Majdi, H. S. Photovoltaic-driven cooling systems: advances, challenges, and future directions. Al Rafidain Journal of Engineering Sciences 2025; 3: 191–209.
[52] Abdalla OH, Abdel-Salam G, Mostafa AAA. Multifunction battery energy storage system for distribution networks. Energy Engineering: Journal of the Association of Energy Engineering 2022; 119: 569–589.

[53] Georgiou GS, Christodoulides P, Kalogirou SA. Optimizing the energy storage schedule of a battery in a PV grid-connected nZEB using linear programming. Energy 2020; 208: 118177.
[54] Enescu D, Chicco G, Porumb R, Seritan G. Thermal energy storage for grid applications: current status and emerging trends. Energies 2020; 13 (2): 340.
[55] Chayarun P, Kawabe K, Nanahara T. Determination of optimal battery energy storage system capacity for commercial electricity consumers with photovoltaic systems by integrating battery aging and PV forecast uncertainty. IEEJ Transactions on Electrical and Electronic Engineering 2021; 16: 226–237.
[56] Poli N, Bonaldo C, Trovo A, Guarnieri M. Optimal energy storage systems for long charge/discharge duration. ECS Meeting Abstracts 2022; MA2022-01: 472–472.
[57] Tyagi VV, Chopra K, Kalidasan B, Chauhan A, Stritih U, Anand S, Kothari R. Phase change material based advance solar thermal energy storage systems for building heating and cooling applications: a prospective research approach. Sustainable Energy Technologies and Assessments 2021; 47: 101318.
[58] Fallah Ardashir J, Hasannezhad M, Vatankhah Ghadim H, Sarhangzadeh M. Integration of energy storage systems with multilevel inverters for microgrids. In: Distributed Energy Storage Systems for Digital Power Systems. Elsevier, 2024; 293–318.
[59] Michalski M, Polański J, Nemś M. Storing electric energy generated by a photovoltaic installation to increase profit from its sale—case study in Poland. Sustainability 2024; 16 (13): 5635.
[60] ur Rehman M, et al. A solar-powered multi-functional portable charging device (SPMFPCD) with internet-of-things (IoT)-based real-time monitoring—an innovative scheme towards energy access and management. Green Technologies and Sustainability Volume 3, Issue 1, January 2025.
[61] Bartela Ł. A hybrid energy storage system using compressed air and hydrogen as the energy carrier. Energy 2020; 196: 117088.
[62] Nordin NA, et al. Integrating photovoltaic (PV) solar cells and supercapacitors for sustainable energy devices: a review. Energies 2021; 14 (21): 7211.
[63] Schleifer AH, Harrison-Atlas D, Cole WJ, Murphy CA. Hybrid renewable energy systems: the value of storage as a function of PV-wind variability. Frontiers in Energy Research 2023; 11: 1036183.
[64] Singh S, Chauhan P, Aftab MA, Ali I, Suhail Hussain SM, Ustun TS. Cost optimization of a stand-alone hybrid energy system with fuel cell and PV. Energies 2020; 13 (5): 1295.

[65] Omrane B, Abderrahim S, Alaeddine F. Recent advances in hybrid energy storage systems for remote standalone renewable energy plant. In: 2023 International Conference on Electrical Engineering and Advanced Technology (ICEEAT). IEEE, 2023; 1 (1): 1–6.
[66] Reguieg Z, Bouyakoub I, Mehedi F. Integrated optimization of power quality and energy management in a photovoltaic-battery microgrid. Renewable Energy 2025; 241: 122358.
[67] Sutikno T, Arsadiando W, Wangsupphaphol A, Yudhana A, Facta M. A review of recent advances on hybrid energy storage system for solar photovoltaics power generation. IEEE Access 2022; 10: 42346–42364.
[68] Wang K, et al. Control strategy research of hybrid energy storage system to smooth out PV fluctuations. In: 2022 IEEE Conference on Telecommunications, Optics and Computer Science (TOCS 2022). IEEE, 2022; 887–892.
[69] Javed MS, Ma T, Jurasz J, Amin MY. Solar and wind power generation systems with pumped hydro storage: review and future perspectives. Renewable Energy, Volume 148, April 2020, Pages 176-192
[70] Shen Q, Wen X, Xia S, Zhou S, Zhang H. AI-based analysis and prediction of synergistic development trends in U.S. photovoltaic and energy storage systems. International Journal of Innovative Research in Computer Science and Technology 2024; 12: 36–46.
[71] Haque ME, Mohammad N. Design and performance analysis of neural network-based MPPT in PV system with energy storage management. In: Proceedings - 6th International Conference on Electrical Engineering and Information and Communication Technology (ICEEICT 2024). IEEE, 2024; 1378–1383.
[72] Hartel F, Bocklisch T. Minimizing energy cost in PV battery storage systems using reinforcement learning. IEEE Access 2023; 11: 39855–39865.
[73] Zhu Z, et al. Energy forecasting with robust, flexible, and explainable machine learning algorithms. AI Magazine 2023; 44: 377–393.
[74] Ajibade SSM, Zaidi A, Al Luhayb ASM, Adediran AO, Voumik LC, Rabbi F. New insights into the emerging trends research of machine and deep learning applications in energy storage: a bibliometric analysis and publication trends. International Journal of Energy Economics and Policy 2023; 13: 303–314.
[75] Dimitropoulos N, Sofias N, Kapsalis P, Mylona Z, Marinakis V, Primo N, Doukas H. Forecasting of short-term PV production in energy communities through machine learning and deep learning algorithms. In: 2021 12th International Conference on Information, Intelligence, Systems & Applications (IISA). IEEE, 2021; 1–6.

[76] Teixeira B, Carvalhais L, Pinto T, Vale Z. Application of XAI-based framework for PV energy generation forecasting. In: Proceedings - 2023 IEEE Conference on Artificial Intelligence (CAI 2023). IEEE, 2023; 67–68.