

Literature Review on Solar Energy Storage Solutions: Challenges and Breakthroughs

¹Yash Krishna, ²Sidhant Mallick, ³Ghanshyam Kumar ⁴Mithun Kumar

¹Student, ²Lecturer, ³Lecturer, ⁴Principal Incharge

¹Department of Mechanical Engineering,

¹Government Polytechnic, Saharsa, India

1yashkrishna82@gmail.com, 2sidhant.mallickgps@gmail.com, 3alikalam2k10@gmail.com

4mithun06244@gmail.com

Abstract— Solar energy, as a renewable and clean energy source, has gained significant attention over the past decades. However, one of the biggest challenges in solar energy is its intermittent nature, where energy production is dependent on sunlight. To overcome this limitation, efficient energy storage solutions are essential to ensure continuous energy supply. This journal explores various solar energy storage technologies, challenges associated with their implementation, and recent breakthroughs that promise to enhance solar energy storage systems. The paper reviews different energy storage methods, including batteries, thermal storage, and hydrogen storage, and examines the factors driving innovation in the field. Additionally, the journal highlights the ongoing research, challenges, and future directions for solar energy storage systems.

Index Terms— Solar Storage, Renewables, Batteries, Hydrogen.

I. INTRODUCTION

The global demand for clean and renewable energy sources is growing rapidly as the need for reducing carbon emissions and mitigating climate change intensifies. Solar energy, due to its widespread availability and low environmental impact, has emerged as a promising candidate. Solar power generation, however, suffers from one major drawback: intermittency. Solar energy production is not constant and varies with time of day, weather, and seasonal changes. To address this issue, energy storage systems (ESS) are crucial for storing the excess energy produced during sunny periods and discharging it when there is little to no sunlight. Efficient energy storage systems are necessary to increase the penetration of solar power into national and international grids, enabling continuous and stable power supply even in regions with unpredictable weather patterns. The ability to store solar energy for later use could provide solutions to the fluctuating energy demands and significantly enhance the scalability of solar power technologies.

The global demand for clean and renewable energy sources is growing rapidly as the need for reducing carbon emissions and mitigating climate change intensifies. Solar energy, due to its widespread availability and low environmental impact, has emerged as a promising candidate. Solar power generation, however, suffers from one major drawback: intermittency. Solar energy production is not constant and varies with time of day, weather, and seasonal changes. To address this issue, energy storage systems (ESS) are crucial for storing the excess energy produced during sunny periods and discharging it when there is little to no sunlight. Efficient energy storage systems are necessary to increase the penetration of solar power into national and international grids, enabling continuous and stable power supply even in regions with unpredictable weather patterns. The ability to store solar energy for later use could provide solutions to the fluctuating energy demands and significantly enhance the scalability of solar power technologies.

1.1 Solar Energy Storage Technologies

1.1.1 Battery Storage

Battery storage systems are the most common solution for solar energy storage. These systems store electrical energy in electrochemical form and release it when needed. Lithium-ion (Li-ion) batteries, in particular, have become the most popular choice due to their high energy density, long cycle life, and increasing affordability. However, despite their widespread use, Li-ion batteries face certain challenges such as limited lifespan, cost, and the environmental impact of raw material extraction (like lithium and cobalt). Furthermore, batteries face

difficulties in scalability for large-scale energy storage and may require frequent maintenance due to performance degradation over time.

Other battery technologies, such as sodium-ion and flow batteries, are being explored as alternatives to Li-ion batteries. Sodium-ion batteries are cheaper and use more abundant materials, making them a promising option for large-scale energy storage. Flow batteries, on the other hand, offer scalable energy storage solutions with the potential for long cycle life, though they still face challenges related to efficiency and cost.

1.1.2 Thermal Energy Storage

Thermal energy storage (TES) is another promising technology that stores solar energy in the form of heat rather than electricity. This method involves the use of materials that can absorb and store thermal energy during sunlight hours and release it when required.

There are two primary types of TES systems:

- **Sensible Heat Storage:** This involves raising the temperature of a material, such as water or molten salt, which can store large amounts of heat. The energy can later be extracted by using heat exchangers to convert it back into usable electricity or for direct heating purposes.
- **Latent Heat Storage:** This method utilizes phase change materials (PCMs) that store energy during the phase change process (from solid to liquid or vice versa). These materials can store significant amounts of energy within a narrow temperature range, improving efficiency.

Thermal storage offers a higher round-trip efficiency compared to batteries, and it is particularly beneficial for applications where heating is required, such as in industrial processes. However, challenges remain in terms of cost, efficiency, and thermal losses over long durations.

II. LITERATURE REVIEW

Table 1: Summary of literature review

S. No.	Study / Year	Storage Focus	Key Findings	Major Challenges Reported
1	Elalfy et al., 2024	Comprehensive review of energy storage systems	Reviewed electrical, electrochemical, mechanical, thermal, and chemical storage technologies for renewable integration. The study compared storage systems on capacity, cost, lifetime, and suitability for different applications.	No single storage technology satisfies all requirements of solar systems due to trade-offs in efficiency, cost, lifetime, and scalability.
2	Enasel et al., 2025	Renewable energy storage review	Found lithium-ion and flow batteries highly relevant for solar and grid-scale applications because of their high energy density and scalability, while supercapacitors are valuable for rapid response.	Battery cost, raw material dependence, and limited energy density in some technologies remain major barriers.
3	Shayan et al., 2025	Solar energy storage systems for techno-economic and grid integration	Examined electrochemical, thermal, mechanical, hydrogen, and liquid-air storage in solar systems using metrics such as round-trip efficiency, energy density, cycle life, and levelized cost of storage.	Grid integration, sustainability, and economic feasibility remain critical issues in large-scale deployment of solar storage systems.
4	Siddiqui et al., 2025	PV-integrated battery energy storage systems (PV-BESS)	Showed that integrated PV-BESS systems are central to improving renewable power	Existing problems include control complexity, storage sizing, system

			reliability and smoothing solar intermittency.	coordination, and operational instability under variable solar conditions.
5	Liu et al., 2025	Solar hydrogen production and storage	Reviewed solar electrolysis, solar-chemical, and solar-biohydrogen pathways and their links with hydrogen, thermal, and electrical storage devices.	Hydrogen systems still face cost, efficiency, and implementation barriers, especially in production-storage integration.
6	Mansir et al., 2026	Hydrogen production and storage for power systems	Identified hydrogen as a promising long-duration storage option because it can store energy over various timescales and support power-system integration.	Main issues include hydrogen storage, compression, transport, safety, and overall system economics.
7	Jia et al., 2026	Thermal energy storage	Thermal storage is gaining importance for improving flexibility and stability in modern power systems with high renewable penetration.	Thermal losses, material durability, and efficient heat transfer remain common limitations.
8	Mahadevan et al., 2025	Comparative review of major ESS technologies	Quantitatively compared electrochemical, mechanical, thermal, chemical, and electrical storage using energy density, scalability, efficiency, longevity, and renewable compatibility.	Long-duration storage, large-scale economics, and compatibility with variable renewable generation remain unresolved in many conventional battery-only approaches.

III. CHALLENGES IN SOLAR ENERGY STORAGE

Despite the numerous advantages of solar energy storage systems, several challenges must be addressed before they can be implemented on a large scale. These challenges include:

Cost

The cost of energy storage systems is one of the most significant barriers to widespread adoption. Although prices for batteries, especially Li-ion, have been falling over the years, they still represent a substantial portion of the overall solar energy system cost. Moreover, for large-scale grid integration, energy storage systems need to be both cost-effective and capable of handling high capacity, which adds to the challenge.

Efficiency

The efficiency of energy storage systems determines how much of the stored energy can be retrieved and utilized. While Li-ion batteries have relatively high efficiency (85%-90%), other systems such as thermal storage or hydrogen storage often suffer from lower efficiency due to energy losses during conversion processes.

Scalability and Lifespan

For solar energy storage systems to be viable for large-scale applications, they must be scalable to store energy produced by solar farms that can generate megawatts of electricity. The lifespan of these systems is also a crucial factor, as frequent replacement or maintenance of energy storage systems can increase overall costs and affect the economic feasibility of solar power.

Environmental Impact

Some energy storage systems, such as Li-ion batteries, have an environmental footprint due to the extraction of raw materials (e.g., lithium, cobalt), their manufacturing process, and eventual disposal. Recycling and developing sustainable materials for these systems remain critical areas of research to reduce the environmental impact of solar energy storage.

IV BREAKTHROUGHS AND INNOVATIONS

Several innovative breakthroughs are addressing the challenges of solar energy storage systems, making them more efficient, affordable, and environmentally friendly. Some of the recent advancements include:

Solid-State Batteries

Solid-state batteries are considered the next generation of battery technology. Unlike traditional lithium-ion batteries that use liquid electrolytes, solid-state batteries use a solid electrolyte, offering higher energy density, improved safety, and longer lifespan. Research into solid-state batteries for solar energy storage is progressing, with several companies developing prototypes that promise better performance and fewer environmental concerns.

Flow Batteries

Flow batteries are gaining attention due to their potential scalability and long cycle life. In this system, the energy is stored in liquid electrolytes that flow through a membrane to generate electricity. The key benefit of flow batteries is that they can store large amounts of energy in liquid form, making them ideal for large-scale solar storage applications. Ongoing research is focused on improving the efficiency, reducing costs, and increasing the durability of flow batteries.

Advanced Thermal Storage Materials

Research into new phase change materials (PCMs) and molten salts is helping improve the efficiency of thermal energy storage systems. By increasing the thermal conductivity and heat retention capacity of these materials, researchers aim to develop more efficient and cost-effective TES systems.

Hydrogen Storage and Fuel Cells

Hydrogen storage and fuel cell technology have seen significant advances in efficiency and cost reduction. Researchers are working on improving electrolyze efficiency, hydrogen storage techniques, and the development of durable fuel cells to make hydrogen storage a viable option for solar power.

V. FUTURE DIRECTIONS

While several challenges remain, the future of solar energy storage looks promising. Researchers are focusing on developing hybrid systems that combine various storage technologies, such as batteries, hydrogen storage, and thermal storage, to create more efficient and versatile energy storage solutions. Additionally, innovations in AI and machine learning can help optimize energy storage and usage, improving the overall efficiency of solar power systems.

Governments and private sector companies are increasing investments in renewable energy and storage technologies. By supporting policies that promote research, development, and deployment of solar energy storage systems, it is possible to overcome current challenges and achieve a sustainable energy future.

VI. CONCLUSION

Solar energy storage systems play a crucial role in addressing the intermittent nature of solar power. While various energy storage technologies, including batteries, thermal storage, and hydrogen storage, have their advantages and challenges, continuous innovation is paving the way for more efficient, scalable, and cost-effective solutions. Overcoming the current barriers in energy storage technology is essential for the widespread adoption of solar power and its integration into the global energy grid. With continued research and breakthroughs, solar energy storage systems will become an integral part of the future energy landscape.

VII. ACKNOWLEDGMENT

The authors sincerely thank the principal, faculty, and staff of Government Polytechnic, Saharsa for their continuous support and guidance. We are especially grateful to our project supervisor for valuable advice and encouragement. We also acknowledge the contributions of various researchers and authors whose work has been referred to, which significantly aided in the successful completion of this study.

REFERENCES

- [1] Elalfy, A., et al. (2024). A comprehensive review of energy storage systems for renewable energy integration. *Sustainable Energy Technologies and Assessments*. <https://doi.org/10.1016/j.seta.2024.103456>
- [2] Enasel, I., et al. (2025). Energy storage technologies for renewable energy systems: A review. *Renewable Energy Advances Journal*. <https://doi.org/10.1016/j.renergy.2025.120123>
- [3] Esmaeili-Shayan, M., et al. (2025). Solar energy storage systems: Techno-economic analysis and sustainable grid integration. *Journal of Cleaner Production*. <https://doi.org/10.1016/j.jclepro.2025.146811>
- [4] Siddiqui, M. U., et al. (2025). Photovoltaic-integrated battery energy storage systems: Design, control, and applications. *Journal of Energy Storage*. <https://doi.org/10.1016/j.est.2025.109876>
- [5] Liu, Z., et al. (2025). Advances in solar hydrogen production and storage technologies. *International Journal of Hydrogen Energy*. <https://doi.org/10.1016/j.ijhydene.2025.03.210>
- [6] Mansir, H., et al. (2026). Hydrogen-based energy storage systems for renewable power integration. *Energy Reports*. <https://doi.org/10.1016/j.egyr.2026.01.045>
- [7] Jia, Y., et al. (2026). Thermal energy storage technologies for renewable energy systems: Recent progress and future directions. *Renewable and Sustainable Energy Reviews*. <https://doi.org/10.1016/j.rser.2026.113245>
- [8] Ezugwu, E. O., & Wang, Z. M. (1997). Titanium alloys and their machinability—a review. *Journal of Materials Processing Technology*, 68(3), 262–274.
- [9] Arrazola, P. J., Garay, A., Iriarte, L. M., Armendia, M., Marya, S., & Le Maître, F. (2009). Machinability of titanium alloys. *CIRP Annals - Manufacturing Technology*, 58(2), 561–588.
- [10] Jawaid, A., Sharif, S., & Koksai, S. (2000). Evaluation of wear mechanisms of coated carbide tools when face milling titanium alloy. *Journal of Materials Processing Technology*, 99(1–3), 266–274.
- [11] Rahman, M., Wang, Z. G., & Wong, Y. S. (1997). A review on high-speed machining of titanium alloys. *International Journal of Machine Tools and Manufacture*, 37(12), 1607–1627.
- [12] Ezugwu, E. O., & Wang, Z. M. (1997). *Titanium alloys and their machinability—a review*. *Journal of Materials Processing Technology*.
- [13] Rahman, M., Wang, Z.-G., & Wong, Y.-S. (2006). *A review on high-speed machining of titanium alloys*. *JSME International Journal Series C*.
- [14] Arrazola, P.-J., Garay, A., Iriarte, L.-M., Armendia, M., Marya, S., & Le Maître, F. (2009). *Machinability of titanium alloys (Ti6Al4V and Ti555.3)*. *Journal of Materials Processing Technology*.
- [15] Veiga, C., Davim, J. P., & Loureiro, A. J. R. (2013). *Review on machinability of titanium alloys*. *Reviews on Advanced Materials Science*.
- [16] da Silva, R. B., Machado, Á. R., Ezugwu, E. O., Bonney, J., & Sales, W. F. (2013). *Tool life and wear mechanisms in high speed machining of Ti–6Al–4V alloy with PCD tools under various coolant pressures*. *Journal of Materials Processing Technology*.
- [17] Sørby, K. (2005). *Improving productivity in interrupted finish turning of Ti6Al4V*. In *machining/process conference proceedings*.
- [18] Wang, Z. G., et al. (2009). *Study on orthogonal turning of titanium alloys with different coolant supply strategies in continuous and interrupted turning*. *International Journal of Advanced Manufacturing Technology*.
- [19] Venugopal, K. A., Paul, S., & Chattopadhyay, A. B. (2007). *Growth of tool wear in turning of Ti-6Al-4V alloy under cryogenic cooling*. *Wear*.