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Review Article

Li-ion batteries vs photovoltaic – regenerative hydrogen fuel cell: Comprehensive review

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ABSTRACT

This paper reviews and compares lithium-ion batteries and photovoltaic regenerative hydrogen fuel cell systems as energy storage solutions for solar power. Li-ion batteries offer high efficiency and are well-suited for short- term storage. PV–RHFC systems enable long-term and seasonal storage through hydrogen production and fuel cell conversion. The study highlights key differences in efficiency, cost, and scalability, providing insight into their roles in future energy systems.

Keywords: Lithium-ion batteries, Regenerative hydrogen fuel cell, Photovoltaic systems, Energy storage, Short-term storage, long-term storage.

1. Introduction

The rapid growth of solar photovoltaic (PV) systems has increased the need for reliable energy storage to address short-term variability and ensure long-term supply security. According to a 2024 REN21 report, global battery storage capacity actually grew dramatically in 2023 to about 55.7 GW, mainly for hour-scale balancing. Li-ion battery prices fell from over $700/kWh in 2013 to around $139/kWh [1]. Li-ion batteries dominate short-term storage due to high efficiency (90-95%) and fast response. However, their cycle life (2,000-8,000 cycles) and material constraints (lithium, cobalt, nickel) limit their suitability for long-duration storage at large scale [2]. In contrast, photovoltaic–regenerative hydrogen fuel cell (PV-RHFC) systems convert surplus electricity into hydrogen for long-term and seasonal storage. Current green hydrogen costs range from $3 to $8/kg, with electrolysis efficiencies of 70–80% [3].

This review compares Li-ion and PV–RHFC technologies in terms of efficiency, cost, scalability, and application suitability, highlighting the role of hydrogen as a promising solution for long-duration storage.

2. Energy Storage Needs in Photovoltaic Systems

2.1. Photovoltaic systems supply and demand information

In 2023 global renewable energy investments increased by 8% to USD 623 billion, with solar investments accounting for 63% or USD 393 billion (+12%). The total installed solar photovoltaic capacity exceeded 1.6 TWp at the end of 2023, with an annual newly installed capacity of more than 420 GWp.

Despite this rapid deployment, PV generation remains inherently intermittent due to its dependency on sunlight availability, weather conditions, and diurnal and seasonal cycles. For example, PV output can vary by as much as 75% between summer and winter months in mid-latitude regions such as Germany [4]. This intermittency necessitates robust energy storage solutions to balance supply and demand across different timescales.

2.2. Short and long-term storage details

Short-term storage (from minutes to a few hours) is essential for smoothing fluctuations in solar output caused by passing clouds and for enabling effective grid integration. Lithium-ion batteries, with their high round-trip efficiencies (90-95%) and fast response, have become the dominant technology for these applications [2]. However, they are economically challenged when scaled for durations beyond 8–12 hours due to increasing cost per kilowatt-hour and material supply constraints.

Long-term or seasonal storage addresses the mismatch between generation and demand over days, weeks, or even months. Photovoltaic–regenerative hydrogen fuel cell (PV-RHFC) systems offer a promising solution in this domain by converting surplus electricity into hydrogen, which can be stored and later reconverted into electricity through fuel cells. These systems enable energy resilience during prolonged periods of low solar generation and support the decarbonization of sectors beyond electricity. Current studies indicate that hydrogen-based storage becomes more cost-effective than lithium-ion batteries for storage durations exceeding approximately 8–10 hours [5].

This section provides foundational background on each energy storage technology and how it functions within a PV energy system, setting the stage for detailed comparisons.

2.3. Li-ion battery energy storage for PV systems

Principle and Components: Li-ion batteries store energy via reversible electrochemical reactions. A typical cell consists of a graphite anode, a lithium-metal-oxide cathode (e.g. $LiMO_2$), and a lithium-ion conducting electrolyte. During charging, lithium ions intercalate into the anode; during discharge, they flow back to the cathode, releasing electricity. Cells are assembled into battery packs with battery manage- ment systems (BMS) to ensure safe operation.

Energy Density: Modern LIBs offer high energy density (260–270 Wh/kg), enabling compact storage. For context, a Li-ion pack can store a few hundred watt-hours per liter of volume – far higher volumetric density than gaseous hydrogen unless compressed to extremely high pressures [6].

Integration with PV: In PV systems, Li-ion batteries are typically coupled via an inverter/charger. Excess solar energy charges the battery, and the battery discharges to supply power when PV output is insufficient (night or cloud cover). This direct electrical coupling makes integration relatively straightforward. Many residential and commercial PV installations already use Li-ion battery banks for daily energy shifting and backup power.

Performance Characteristics: Li-ion storage is known for high round-trip efficiency (often 85–95% of the energy is retained after a charge-discharge cycle), fast response times (near-instantaneous power delivery), and good power capability. However, LIB performance can be temperature-sensitive – efficiency and lifespan degrade if cells run hot (e.g. >45 °C). They also experience self-discharge (on the order of 0.1–0.3% per day), which limits ultra-long-term storage without maintenance charging [7].

Fig. 1 (below), schematically shows a PV + battery system, wherein a battery pack is charged by a PV array via a power converter and then feeds AC loads or the grid when needed.

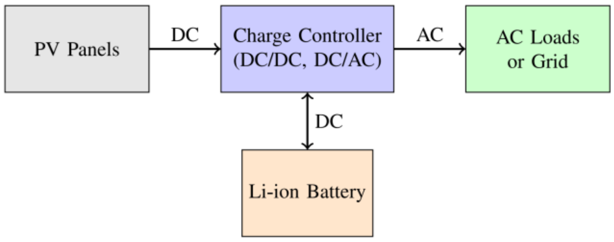

Fig. 1. Schematic of a solar PV system with Li-ion battery storage. PV panels charge the battery through a charge controller/inverter, and the battery discharges power to supply loads or the grid

2.4. Photovoltaic–Regenerative hydrogen fuel cell systems

Concept and Architecture: A PV–RHFC system, often termed a solar-to-hydrogen energy storage system, uses electricity from PV panels to produce hydrogen fuel, which can later be converted back to electricity. The system comprises three main components:

- An electrolyzer that uses solar-generated electricity to split water into hydrogen and oxygen (the hydrogen is collected and the oxygen typically vented),
- A hydrogen storage unit (tanks for compressed H_2, or alternative methods like liquefaction or metal hydrides), and
- A fuel cell (often a PEM fuel cell) that consumes stored hydrogen (with ambient oxygen) to generate electricity when needed, producing water as the only byproduct [8].

Operation in PV Systems: When the PV array produces surplus power (beyond current load demand), the electrolyzer is run to generate hydrogen (“charging” the hydrogen storage system). During periods of deficit (night, cloudy days, or winter), the stored hydrogen is fed to the fuel cell to generate electricity, supplementing or replacing PV output.

This essentially “time-shifts” solar energy on scales from hours to months [9].

Storage Capacity and Duration: Hydrogen storage offers extremely high gravimetric energy density – the higher heat-ing value (HHV) of H_2 gas is 39.4 kWh per kg [10], meaning by weight hydrogen contains far more energy than batteries or even gasoline. This makes it attractive for storing large ab-solute amounts of energy (e.g. seasonal surpluses). However, volumetric energy density is low; even when compressed to 700 atm, hydrogen is about 5.6 MJ/L (1.6 kWh/L), much lower than liquid fuels or tightly packaged batteries. Tanks and auxiliary systems add bulk, but unlike batteries, adding

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more storage capacity (tank volume) is relatively inexpensive on a per-kWh basis (compressed hydrogen storage tanks cost on the order of \$5–\$15 per kWh of capacity) [11].

Efficiency and Dynamics: A key characteristic of RHFC systems is the multi-step energy conversion, which incurs efficiency losses at each step. Typical overall round-trip efficiencies (electricity → H_2 → electricity) range about 30–50% (i.e. half or more of the energy may be lost in conversion). This is much lower than battery efficiency, a critical distinction discussed in. On the other hand, stored hydrogen does not self-discharge over time – once in the tank, it can be kept for months with negligible energy loss, unlike batteries which slowly lose charge and capacity over long idle periods [12]. Fig. 2 (below), the hydrogen system involves additional conversion stages compared to the simpler Li-ion setup.

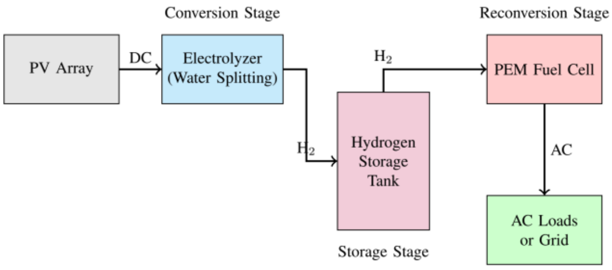

Fig. 2. Diagram of a PV-driven regenerative hydrogen fuel cell system. PV array powers an electrolyzer to produce hydrogen gas, stored in pressurized tanks, and a PEM fuel cell reconverts the stored hydrogen back to electricity

3. Performance comparison and technical characteristics

In this section, we compare Li-ion batteries and PV–RHFC systems across key technical performance metrics. Each subsection provides quantitative contrasts with an engineering focus, using data from recent research.

3.1. Round-trip efficiency and energy losses

One of the most significant differences between LIB and RHFC storage lies in round-trip efficiency (RTE) – the fraction of input electricity that can be retrieved after storage. Li-ion batteries have very high RTE, typically 85–95% under optimal conditions. Only a small percentage of energy is lost as heat during charging/discharging and in power electronics, making batteries very efficient for daily cycling. In contrast, hydrogen-based storage systems have a much lower overall efficiency due to multiple conversion steps. The combined efficiency of electrolysis (often 60–75%) and fuel cell conversion (50–60%) results in a net RTE on the order of 30–50% for RHFC systems. In other words, hydrogen storage may incur roughly double the energy losses of a battery system for each cycle. For example, if 100 kWh of excess PV energy is stored, a Li-ion battery might return 90 kWh, whereas an H_2 system might return only 30–50 kWh. These efficiency gaps have practical consequences: frequent, short-term cycling (daily solar storage) favors batteries, as hydrogen's 50–70% energy loss would greatly reduce usable energy and economic return [13].

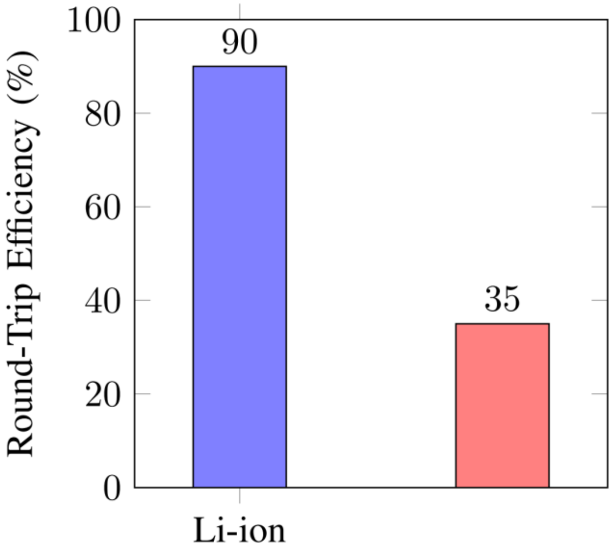

Fig. 3. Comparison of round-trip efficiency: Li-ion battery systems achieve ∼90%, while RHFC systems typically achieve ∼35%

This visual emphasizes the stark contrast in efficiency, reinforcing why batteries are preferred for short-term storage. Despite lower efficiency, RHFC systems are not "inefficient" in all contexts – their ability to store energy long-term with minimal loss can outweigh the conversion inefficiency when bridging seasonal gaps (since batteries, even if efficient, cannot economically store weeks of energy due to self-discharge and cost).

3.2. Energy density and storage duration capability

Energy Density: Li-ion batteries and hydrogen storage differ vastly in how much energy they can store relative to mass and volume. Gravimetric energy density (energy per unit mass) is much higher for hydrogen: the chemical energy of H_2 is 33–39 kWh/kg (depending on lower or higher heating value), which dwarfs Li-ion batteries' 0.2–0.3 kWh/kg. In theory, 1 kg of hydrogen contains as much energy as 130 kg of battery cells. This makes hydrogen an excellent medium when weight is critical (a fact capitalized on in fuel cell vehicles) and for large-scale storage – a few tons of hydrogen could buffer an entire community's renewable energy for days. However, volumetric energy density complicates matters: hydrogen gas is very diffuse and even compressed or liquefied, its energy per liter is modest [14]. At 700 bar (approx. 10,000 psi), H_2 has 1.5 kWh per liter; liquid hydrogen has 2.3 kWh/L at cryogenic temperatures. By comparison, Li-ion batteries (which are solid and packed) achieve about 0.25–0.7 kWh/L. Thus, batteries can store more energy in a given confined space, whereas hydrogen requires large tanks (or underground caverns for really large storage) to contain equivalent energy. For stationary PV installations, space may be available for hydrogen tanks (especially at utility-scale), but in residential settings, bulky hydrogen storage is a concern. Recent systems like the LAVO unit use metal hydride tanks to store hydrogen in a dense solid state form, trading weight for a safer, lower-pressure, more compact storage (30 kWh of H_2 in a cabinet-sized unit) [15].

Storage Duration and Self-Discharge: A critical advantage of hydrogen storage is the ability to retain energy over long periods without significant losses. Once hydrogen is produced and contained, it does not "leak energy" (negligible self-discharge), provided the storage vessel is secure. This makes RHFC ideal for long-duration or seasonal storage – storing surplus solar energy from summer for use in winter, for example. By contrast, Li-ion batteries suffer gradual self-discharge and capacity fade over time. Self-discharge rates of 0.1–0.3% per day are typical, meaning a fully charged battery could lose a few percent of its charge per week even without use [13].

Practical implication: Using batteries to hold a charge for months is inefficient and can degrade the cells; hydrogen incurs almost no storage penalty with time. Research indicates that for fluctuation timescales beyond roughly a few days, H_2 storage becomes more volume- and cost-effective than an equivalently sized battery bank. As summarized in Table 1, Li-ion batteries suit short-term storage, whereas hydrogen excels in long-duration applications.

Table 1. Energy density and duration comparison of li-ion vs hydrogen storage

Metric	Li-ion Battery	Hydrogen (700 bar)
Gravimetric Energy Density	~250 Wh/kg	~33,000 Wh/kg
Volumetric Energy Density	~500 Wh/L	~1,500 Wh/L
Typical Self-discharge	2–3%/month	~0% over months
Best Use Duration	Hours–Days	Days–Months

3.3. Response time and power characteristics

Dynamic Response: Li-ion batteries excel in rapid response and high-power discharge, an important characteristic for grid stability and managing PV output fluctuations. LIBs have virtually instantaneous response (battery inverters can ramp from zero to full power in milliseconds), enabling them to smooth out second-by-second PV variations or provide fast frequency regulation to the grid [16]. RHFC systems involve mechanical and electrochemical processes that introduce some lag. Electrolyzers can typically modulate on the order of seconds – they may require a ramp-up period to reach full hydrogen production when PV power surges. For example, a PEM fuel cell might take 30 seconds to go from cold start to full power output, and even an online fuel cell stack will have a finite ramp rate limited by reactant gas flow and catalyst kinetics. This means that for high-frequency power balancing (sub-second spikes or drops in PV output), batteries are far superior. Hydrogen systems, if used, often need a small battery or capacitor to handle the immediate response and then let the fuel cell take over for sustained output [17].

Power Density and Overload Capability: Batteries can deliver high bursts of power relative to their energy content – e.g., a Li-ion battery might discharge its entire energy in 1 hour (1C rate) or even faster if designed for power (some chemistries can do 2C or higher, meaning 30 minutes or less). Fuel cell systems are usually sized with a certain maximum continuous power, and while they can sometimes exceed this briefly, they are not as flexible in short-term overload. In summary, for applications requiring quick bursts of high power (voltage/frequency regulation, surges), Li-ion batteries are the go to solution. Hydrogen systems are more suitable when high energy capacity is needed relative to power (e.g., long slow discharge) because one can deploy a large H_2 storage tank with a fuel cell sized for average load – but that fuel cell will not be able to supply huge surges beyond its rating [18].

Operational Flexibility: Li-ion batteries have excellent part-load efficiency – they can operate efficiently from a few percent load to 100% load. Fuel cells have an optimal efficiency range (often around 50–80% of rated load); at very low loads, efficiency falls off, and at overload, they cannot operate. Similarly, electrolyzers have an optimal operating range and may have reduced efficiency at partial loads. These factors mean that in a PV system, a hydrogen storage loop might operate intermittently at planned times (e.g., electrolyzer runs when PV is in surplus above what battery and loads can take; fuel cell runs during prolonged deficits), rather than continuously throttling up and down like a battery inverter can throughout the day. This difference in flexibility underscores the complementary nature of the two: batteries handle fast, frequent charge-discharge cycles, while hydrogen handles infrequent, long-duration cycles [19].

4. System Integration and Operational Considerations

Beyond individual performance metrics, it is crucial to analyze how each technology fits into solar energy systems as a whole. This section discusses the integration of LIB and RHFC storage with PV generation, including considerations of system design, control, scalability, and the ability to meet different temporal demand patterns (daily cycling vs seasonal storage). We also address how each technology can be managed and optimized within hybrid renewable systems.

4.1. Integration with photovoltaic generation and power electronics

Li-ion Integration: Batteries are inherently electrical devices, so integrating a Li-ion bank with PV is relatively straightforward. Common architectures include DC-coupled systems (PV array feeds a charge controller that charges the

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battery directly in DC, then an inverter draws from the battery to supply AC loads) and AC-coupled systems (PV has its own inverter supplying AC, and a separate battery inverter charges/discharges the battery from the AC side). In either case, standard power electronic converters handle the interface. Battery storage can operate flexibly: charging whenever PV output exceeds load or export limits, and discharging when there's a shortfall. Control algorithms (often in an energy management system, EMS) decide when to charge or discharge based on PV production forecasts, state-of-charge, and load needs. Because LIBs can ramp output quickly, they can seamlessly pick up fluctuations in PV output, maintaining smooth power to loads or the grid. This fast-reacting nature also means batteries can provide ancillary grid services (voltage support, frequency regulation) while paired with PV. In grid-tied setups, many PV+battery systems are configured to perform peak shaving (flattening demand peaks) and PV self-consumption maximization (store midday solar excess to use at night), improving economic returns for the owner [20].

RHFC Integration: Integrating a hydrogen storage loop is more complex, as it introduces multi-domain energy conversion (electrical-to-chemical and back). Typically, an electrolyzer unit is added to the PV system, sized to convert excess PV power to H_2. This electrolyzer may be coupled via a DC-DC converter from the PV array (for efficiency) or run off AC if flexibility to take grid power is desired. The fuel cell is essentially a generator that needs an inverter to supply AC power (unless it's a DC fuel cell tied into a DC- bus system). Integration considerations include: coordinating the electrolyzer operation with battery and PV – e.g., one strategy is to let a battery absorb short-term variability and only send power to the electrolyzer when there's a sustained surplus beyond battery capacity. This prevents inefficient on-off cycling of the electrolyzer and maximizes its running at optimal load. Similarly, the fuel cell might be used primarily when the battery state-of-charge falls below a threshold during extended cloudy periods or at night after the battery depletes. Such hierarchical control ensures each device operates in its efficient regime: batteries for fast, small fluctuations; hydrogen for slow, large deficits. Furthermore, integration of hydrogen requires additional supporting systems: water supply and possibly water treatment for the electrolyzer, hydrogen drying/purification, compression or cooling for storage, and safety interlocks (for example, halting electrolyzer if tanks are full, venting procedures if over-pressure, purging the fuel cell before start, etc.). Despite the complexity, pilot projects have successfully integrated PV, batteries, and hydrogen – demonstrating that control systems can manage the power flows between these components to maintain reliable supply. Demonstrated in Figure 4, hybrid systems integrate PV, batteries, and hydrogen subsystems to balance both short-term and seasonal storage needs effectively [21, 22].

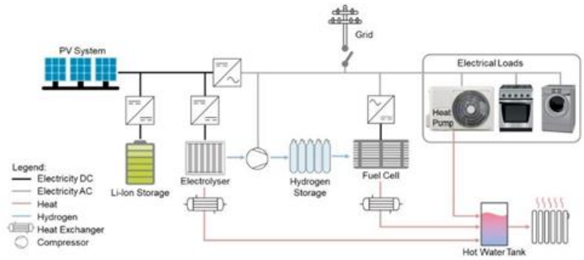

Fig. 4. Residential PV + battery + hydrogen storage system with integrated electrolyzer and PEM fuel cell for extended autonomy

4.2. Scalability and storage duration: daily cycling vs. seasonal storage

A central consideration for energy storage in PV applications is the required duration and scale of storage. Different technologies have "sweet spots" for how long and how much energy they can store cost-effectively. Here we compare LIB and RHFC in the contexts of short-duration (intra-day) vs long-duration (inter-day or seasonal) storage needs:

Daily Cycling (Hourly to Diurnal Storage): For managing day-night cycles and short cloudy spells (lasting hours to a day), Li-ion batteries are generally more practical. They can be sized from a few kilowatt-hours to several megawatt-hours, and their high efficiency minimizes energy loss during daily cycling. For instance, providing overnight power with a 10 kWh battery is increasingly affordable. In contrast, hydrogen systems would incur 50–60% energy loss per cycle, making them less economical for daily use. Additionally, small-scale hydrogen systems are costlier due to electrolyzer and fuel cell components. As a result, virtually all residential PV + storage systems today use batteries, not hydrogen, and effectively reduce grid reliance [23].

Multi-day to Seasonal Storage: For longer storage needs-e.g., several days or seasonal shifting-batteries be- come less feasible due to cost, volume, and aging during idle periods. Hydrogen excels here, as expanding tank capacity is relatively cheap and stored fuel doesn't degrade. Studies show that using hydrogen in high-renewable systems can significantly cut total system costs compared to relying solely on oversized battery banks.

Hydrogen's low per-kWh storage cost (e.g., $5–15/kWh for tanks) makes it attractive at GWh scales. A 100% renew- able system might use batteries for 1–2 days and hydrogen for extended deficits. In Europe, seasonal hydrogen storage is being explored by converting summer surplus energy and storing it for winter use.

Scalability: While Li-ion systems scale linearly by adding modules, hydrogen offers more flexibility: power (electrolyzer/fuel cell) and energy (H_2 storage) can be scaled in- dependently. For extreme autonomy needs (e.g., month-long sunless periods), hydrogen is more viable. Research

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indicates that combining both technologies-batteries for short gaps, hydrogen for long-can optimize cost and reliability [23].

5. Environmental and Safety Considerations

Materials and Resource Constraints: Li-ion batteries are made of critical materials: lithium, cobalt, nickel, graphite, etc. Mining and processing these have significant environmental footprints (habitat disruption, water use, energy consumption) and human rights concerns in some regions (e.g., cobalt mining). As LIB deployment grows, material availability and sustainable sourcing are key issues. However, battery recycling is advancing as a solution to recover metals and reduce the need for virgin extraction. Recycling lithium batteries can cut environmental impacts significantly (by >50% for some impacts, according to life-cycle studies) and mitigate toxic waste. Many countries are developing recycling pipelines, but as of now, recycling rates for lithium- ion remain relatively low (though rising) and processes are still being optimized for efficiency and profitability. Improper disposal of LIBs can pose environmental hazards (potential leaching of toxic compounds, fire risk in landfills). Thus, end-of-life management is a concern: by 2030, large volumes of batteries will retire, making recycling essential to prevent waste and recover materials. Hydrogen fuel cell systems use different materials. Electrolyzers and fuel cells often require platinum-group metals (PGMs) like platinum or iridium as catalysts (especially PEM technology). These are rare and expensive; scaling up hydrogen tech raises questions about PGM supply, though efforts are underway to reduce or replace these catalysts. Also, some fuel cell stacks contain perfluorosulfonic acid membranes (like Nafion) which have environmental persistence concerns if not disposed properly. Hydrogen storage tanks might use carbon fiber (energy-intensive to produce) for high-pressure cylinders. On the plus side, hydrogen itself is a clean energy carrier – when produced from renewables, it involves splitting water and the only byproduct of use is water vapor, with zero direct carbon emissions. Over its life-cycle, a green hydrogen system's emissions are mostly from manufacturing the hardware, not from operation (similar to batteries, which have low operational emissions but manufacturing impacts). One unique environmental aspect: water usage – electrolyzers require pure water input to produce hydrogen. Approximately 9 liters of water are needed to produce 1 kg of H_2. If hydrogen storage is deployed at large scale in arid regions, water supply could be an issue. The studies pointed out that hydrogen batteries might not be suitable in areas with water scarcity. However, compared to cooling water for power plants or biofuel production, the water use for grid hydrogen is small; also, water can often be recycled from fuel cell exhaust (capturing the water produced when hydrogen is used) [24].

6. Conclusions

Li-ion batteries and PV-regenerative hydrogen fuel cell systems each offer unique advantages for storing solar energy, and a clear "winner" depends on the context of use. Our review has examined their technical performance, economics, and practical deployment considerations in depth. In summary, Li-ion batteries excel in efficiency (90% RTE), fast response (instantaneous power), and turnkey integration for daily cycling, making them the preferred choice for short-term storage in PV systems (hourly to overnight storage). They have lower maintenance needs and a well- established supply chain. However, LIBs are less suited to long-duration storage due to high cost per kWh for large capacities and self-discharge/aging over long idle periods. Photovoltaic–hydrogen fuel cell systems, in contrast, shine in energy capacity and duration – they can economically store very large amounts of energy for weeks or months with negligible self-loss, a feat battery cannot match. RHFC's downside is conversion inefficiency (50% or less round-trip) and complex, costly equipment at small scale.

List of Abbreviations

PV – Photovoltaic
LIB – Lithium-Ion Battery
RHFC – Regenerative Hydrogen Fuel Cell
RTE – Round-Trip Efficiency
EMS – Energy Management System

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Conflict of interest

There is no conflict of interest.

References

[1] Y. Huang and J. Li, "Key challenges for grid-scale lithium-ion battery energy storage," *Advanced Energy Materials*, vol. 12, no. 48, p. 2202197, 2022.

[2] D. H. Adebayo, J. A. Ajiboye, U. D. Okwor, A. L. Muhammad, C. D. Ugwuijem, E. K. Agbo, and V. I. Stephen, "Optimizing energy storage for electric grids:

doi: 10.31593/ijeat.1730316

Advances in hybrid technologies," *management*, vol. 10, p. 11, 2025.

[3] B. el Ghossein, "Hydrogen fuel cells and lithium-ion batteries for solar energy balancing at varying climates: A review." *International Journal of High School Research*, vol. 7, no. 3, 2025.

[4] P. Ravestein, G. Van der Schrier, R. Haarsma, R. Scheele, and M. Van den Broek, "Vulnerability of European intermittent renewable energy supply to climate change and climate variability," *Renewable and Sustainable Energy Reviews*, vol. 97, pp. 497–508, 2018.

[5] G. Giakoumakis and D. Sidiras, "Production and storage of hydrogen from biomass and other sources: Technologies and policies," *Energies*, vol. 18, no. 3, 2025. Available: https://www.mdpi.com/1996-1073/18/3/650

[6] H. A. Aldawsari, "Energy storage systems for traction and renewable energy applications," Master's thesis, Marquette University, 2020.

[7] A. Gharehghani, M. Rabiei, S. Mehranfar, S. Saeedipour, A. M. Andwari, A. García, and C. M. Reche, "Progress in battery thermal management systems technologies for electric vehicles," *Renewable and Sustainable Energy Reviews*, vol. 202, p. 114654, 2024.

[8] E. M. Barhoumi, P. C. Okonkwo, S. Farhani, I. B. Belgacem, and F. Bacha, "Hydrogen production from renewable energy sources, storage, and conversion into electrical energy," in *Planning of Hybrid Renewable Energy Systems, Electric Vehicles and Microgrid: Modeling, Control and Optimization*. Springer, 2022, pp. 151–176.

[9] K. Z. Rinaldi, *A Technical and Systems Analysis of Hydrogen Fuel in Renewable Energy Systems*. California Institute of Technology, 2022.

[10] N. R. Council, D. on Engineering, P. Sciences, B. on Energy, E. Systems, C. on Alternatives, and S. for Future Hydrogen Production, *The hydrogen economy: opportunities, costs, barriers, and R&D needs*. National Academies Press, 2004.

[11] P. Cavaliere, "Hydrogen: Energy vector and fuel," in *Hydrogen Embrittlement in Metals and Alloys*. Springer, 2025, pp. 1–155.

[12] W. Chen, K. Meng, H. Zhou, Y. Zhou, Q. Deng, and B. Chen, "Optimization research on round-trip efficiency of a chp system based on 10 kw-grade unitized regenerative fuel cell," *Energy Conversion and Management*, vol. 280, p. 116800, 2023.

[13] A. Arsalis, P. Papanastasiou, and G. E. Georghiou, "A comparative review of lithium-ion battery and regenerative hydrogen fuel cell technologies for integration with photovoltaic applications," *Renewable Energy*, vol. 191, pp. 943–960, 2022.

[14] N. Juoperi, "Comparative analysis of battery and hydrogen systems for renewable energy integration," 2025.

[15] M. Aziz, "Liquid hydrogen: A review on liquefaction, storage, transportation, and safety," *Energies*, vol. 14, no. 18, p. 5917, 2021.

[16] H. A. Behabtu, "The application of energy storage technologies for grid integration of renewable systems: A focus on li-ion batteries for wind turbine generators," 2024.

[17] X. Gong, X. Li, and Z. Zhong, "Strategic bidding of hydrogen-wind- photovoltaic energy system in integrated energy and flexible ramping markets with renewable energy uncertainty," *International Journal of Hydrogen Energy*, vol. 80, pp. 1406–1423, 2024.

[18] S. Sahoo and P. Timmann, "Energy storage technologies for modern power systems: A detailed analysis of functionalities, potentials, and impacts," *IEEe Access*, vol. 11, pp. 49 689–49 729, 2023.

[19] L. Jin *et al.*, "Energy storage in multi-energy carrier communities: Li- ion batteries and hydrogen multi-physical details for integration into the planning stage," 2024.

[20] Y. R. Li, F. Nejabatkhah, and H. Tian, *Smart hybrid AC/DC microgrids: power management, energy management, and power quality control*. John Wiley & Sons, 2022.

[21] A. Arsalis, G. E. Georghiou, and P. Papanastasiou, "Recent research progress in hybrid photovoltaic–regenerative hydrogen fuel cell microgrid systems," *Energies*, vol. 15, no. 10, p. 3512, 2022.

[22] M. C. Möller and S. Krauter, "Hybrid energy system model in matlab/simulink based on solar energy, lithium-ion battery and hydrogen," *Energies*, vol. 15, no. 6, p. 2201, 2022.

[23] S. T. Le, T. N. Nguyen, D.-K. Bui, and T. D. Ngo, "Optimal sizing of renewable energy storage: A comparative study of hydrogen and battery system considering degradation and seasonal storage," *arXiv preprint arXiv:2211.07833*, 2022.

[24] A. Gulraiz, A. J. Al Bastaki, K. Magamal, M. Subhi, A. Hammad, Allanjawi, S. H. Zaidi, H. M. Khalid, A. Ismail, G. A. Hussain *et al.*, "Energy advancements and integration strategies in hydrogen and battery storage for renewable energy systems," *iScience*, 2025.

doi: 10.31593/ijeat.1730316