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Review

Battery-Less Off-Grid Renewable Microgrid: A Review of Storage Alternatives and PV-WT-CSP Integration with Green Hydrogen

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Abstract

Renewable energy systems play a critical role in reducing carbon emissions and promoting energy sustainability. Conventional battery storage remains the dominant but problematic solution for intermittency management in off-grid renewable energy systems (RES), imposing high capital costs ($150-400/kWh for lithium-ion), short replacement cycles of 3-15 years, and significant environmental burdens from toxic material disposal barriers that are particularly acute in the remote and resource-limited communities that most need reliable clean energy. This paper presents a systematic review of battery-less off-grid RES, synthesizing evidence across six alternative energy storage and dispatch technologies: supercapacitors, mechanical flywheels, compressed air energy storage (CAES), pumped hydroelectric storage (PHS), hydrogen storage via PEM electrolysis, and molten salt thermal energy storage (TES). The review spans single-source, dual-source, and multi-source configurations, with documented applications in seawater reverse osmosis desalination, agricultural water pumping, rural electrification, and small-scale industrial processes. A comparative performance analysis reveals that no single battery-less technology is universally optimal; rather, hybrid approaches particularly molten salt TES paired with hydrogen storage offer the most robust solution for continuous, dispatchable off-grid power. Building on this synthesis, the paper proposes and characterizes a novel integrated battery-less microgrid combining solar photovoltaic (PV), wind turbine (WT), and concentrated solar power (CSP) with molten salt thermal storage and PEM-based green hydrogen production. The system's defining innovation is the dual-pathway utilization of stored hydrogen: as a long-duration electricity backup via fuel cells and as a direct fuel for agricultural vehicles and equipment, eliminating diesel dependence in off-grid farming contexts. Key findings indicate that such integrated systems can reduce curtailed renewable energy by up to 79%, eliminate battery replacement costs over a 20-year operational lifespan, and provide multi-day energy autonomy without chemical battery storage. Critical challenges including electrolyzer cost reduction, small-scale CSP adaptation, and energy management system design are identified as priority directions for future research to enable widespread deployment. HOMER Pro-based techno-economic validation is identified as the immediate next step in this research work.

Keywords
Battery-less RES; battery storage; green hydrogen; off-grid microgrid

1. Introduction and Background of Study

Renewable energy systems (RES) have become a crucial part of global energy strategies due to their potential to provide sustainable, low-carbon alternatives to fossil fuels. According to Miranda and Infield [1], renewable energy technologies such as wind turbines, solar photovoltaic (PV) systems, and concentrated solar power (CSP) have gained widespread adoption across the globe. They have been under research for various configurations of energy harvesters, converters, controllers, and storage to improve the efficiency of the energy systems in which they are deployed, largely due to their ability to reduce greenhouse gas emissions and contribute to energy security. However, the successful deployment of RES in off-grid applications still faces two critical challenges: renewable-resource variability [2] and environmental constraints [3].

Intermittency of renewable energy sources caused by changing weather patterns, seasonal variations, and time-of-day dependencies makes energy storage a critical component of any RES [4]. Storage systems help ensure that load demands are continually met through a balanced demand-supply mechanism that increases system reliability [5]. Despite the pivotal role that batteries play in energy storage for RES, their high procurement and maintenance costs, short operational life span, and the lack of readily available and affordable battery recycling technologies tend to increase complexity in the design, operation, and maintenance of off-grid systems [6-8]. This has led researchers to explore alternative storage solutions that minimize reliance on battery technologies.

Battery-less microgrids, based on other forms of storage, are evolving as alternatives and encourage autonomous poly-generation (multiple energy generated simultaneously in a single integrated system). Additional benefits include cost efficiency, reduced maintenance, reduced environmental impact, increased reliability, and enhanced long-term sustainability of energy systems [9]. Battery-less systems are particularly useful in off-grid applications where minimizing operational complexity and costs is crucial. For instance, Okura et al. [10] highlights a wind-powered seawater reverse osmosis (RO) desalination system that successfully operates without batteries, demonstrating the feasibility of battery-less configurations in remote settings. Similarly, solar-powered systems without battery storage have been effectively used in water pumping and desalination projects, showcasing the potential of these technologies to provide sustainable, reliable power without the need for batteries.

1.1 Renewable Energy Resources - Global Trends and Prospects

According to the International Energy Agency [11] the world is set to add as much renewable power over 2022-2027 as it did in the past 20 years. This section reviews the current availability and utilization of these resources, highlighting their significant contributions to global energy generation.

In 2022, solar PV generation increased by 270 TWh, representing a 26% rise and bringing total generation close to 1300 TWh [12, 13], which marks the largest generation of all renewable technologies for that year. The trend continued into 2023, where solar PV alone accounted for three-quarters of the total renewable capacity addition worldwide, underscoring its critical role in the global energy transition [14]. Wind energy has also made significant strides, with its share of total utility-scale electricity generation increasing by 265 TWh, a 14% rise, culminating in over 2100 TWh of total generation. This growth positions wind energy as the second highest-growing renewable technology, following solar PV [15, 16]. The complementary nature of solar and wind energy is particularly advantageous; while solar energy is predominantly available during the day, wind energy can be harnessed at night and during periods of reduced solar availability, thus enhancing the stability and reliability of the energy supply. In 2023, these two sources together accounted for a remarkable 96% of renewable capacity additions [17, 18].

Renewable electricity of about 340 GW was added globally in 2022 [19]. This progress is essential for keeping the average global temperature rise below 1.5°C, as outlined in international climate agreements [20]. Moreover, the shift towards battery-less off-grid renewable energy systems is gaining momentum, providing sustainable energy solutions without the need for expensive battery storage [21]. This approach not only reduces costs but also enhances energy accessibility in remote and underserved areas, further promoting the use of clean energy globally [22].

1.2 Key Contribution of Research

This paper provides a comprehensive review of various alternatives to battery storage technologies. It emphasizes the practical application of these systems in off-grid scenarios, such as water pumping, desalination, and rural electrification, etc., where battery-based systems are often limited due to cost. The paper also introduces an integrated system combining solar PV, concentrated solar power (CSP), wind turbines, molten salt thermal storage, and hydrogen production, showcasing an innovative approach to energy management and long-term storage. Additionally, the paper identifies key challenges such as technological limitations, economic viability, and regulatory hurdles, setting the stage for further research in the development of sustainable, cost-effective energy solutions that can drive the global transition to clean energy.

1.3 Review Methodology

This review employed a structured literature-search strategy to ensure comprehensive coverage of the field. Peer-reviewed journal articles, conference proceedings, technical reports, and relevant grey literature published between 2000 and 2026 were searched in Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar. The primary Boolean search string was: (“battery-less” OR “battery-free”) AND (“off-grid” OR “stand-alone” OR “remote”) AND (“renewable energy” OR “solar” OR “wind” OR “photovoltaic”). Additional technology-specific searches were conducted for each storage option considered in the review, using combinations such as “supercapacitor” AND “off-grid solar”, “hydrogen storage” AND “renewable energy system”, and “molten salt” AND “CSP” AND “off-grid”.

Studies were included if they: (i) focused on off-grid, stand-alone, or remote renewable energy systems; (ii) explicitly examined battery-less, battery-free, or reduced-battery configurations; and (iii) were published in English. Studies were excluded if they focused exclusively on grid-connected, utility-scale systems without clear relevance to off-grid applications, did not examine battery-less or reduced-battery configurations, or lacked sufficient technical information for inclusion in the review. Following the screening and eligibility assessment, 153 relevant references were retained and cited throughout the review. The selected literature is organized thematically according to storage technology type in Section 2, renewable energy system configuration in Section 3, application domain in Section 4, and integrated system design in Section 5.

2. Overview of Battery-Less Energy Storage Systems: Methods and Approaches

Battery-less systems focus on harnessing renewable energy sources in a way that directly powers devices, equipment, or processes without the need for large-scale, chemical-based energy storage. There have been several approaches to finding suitable alternatives to battery technology for energy storage such as Supercapacitors [23], Gravitational Energy Storage [24], Compressed Air Energy Storage [25, 26], Liquid Air Energy Storage [26], Thermal Energy Storage using molten salt [27], and Hydrogen production and storage [28]. Next, we discuss the primary methods explored in recent research. Figure 1 provides a classification of Energy Storage Systems (ESS), categorizing them into five primary categories based on the type of energy storage technologies [29].

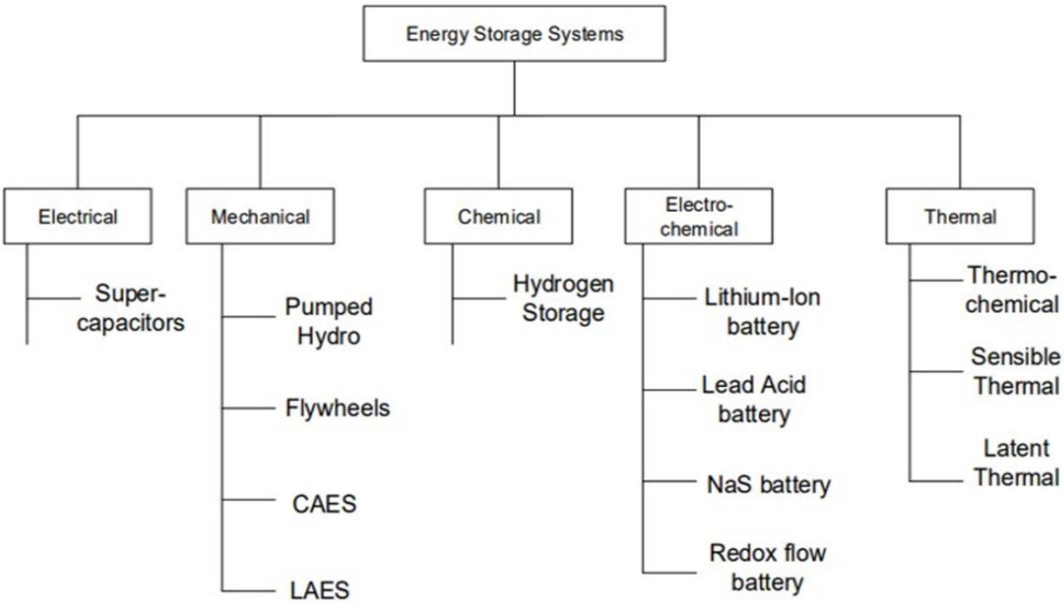

Figure 1 Classification of Energy Storage Technologies.

2.1 Supercapacitors

Supercapacitors are energy storage devices that utilize an electric field to store and release energy rapidly. This characteristic makes them a promising alternative to traditional batteries, especially in applications demanding high power density, fast charging/discharging rates, and a longer lifespan. As highlighted by Gurung et al. [30], supercapacitors are particularly suited for off-grid applications, such as solar-powered systems, where they can provide a continuous power supply for low-energy devices like sensors and small electronics. The key electrode materials enabling supercapacitor performance in off-grid contexts include activated carbon (high surface area, low cost), graphene-based composites (high conductivity, >1000 F/g theoretical), and MnO_2-based pseudocapacitive electrodes (high energy density). Separator materials (polymer membranes, cellulose) and electrolyte choice (aqueous KOH, organic acetonitrile) critically determine operational temperature range and cycle stability. Future materials challenges include improving energy density to bridge the gap with batteries while preserving cycle life advantages exceeding 500,000 cycles. Malek et al. [31] propose a battery-less power supply system that incorporates wireless power transfer (WPT) technology. While WPT offers flexibility in device placement, its efficiency is significantly influenced by the distance between the transmitter and receiver coils. This limitation can hinder practical applications requiring greater flexibility. A more recent study by Rahman et al. [32] presents a self-powered, battery-less wireless sensor mote powered by a micro-solar energy harvesting system. This system employs flexible photovoltaic cells to capture solar energy, which is then stored in supercapacitors for powering a microprocessor unit and wireless communication.

Supercapacitors offer a viable storage solution for off-grid applications, particularly when coupled with renewable energy sources like solar power. While challenges related to charging efficiency exist, ongoing research and technological advancements are addressing these limitations. By optimizing system design and incorporating solutions like WPT and efficient power management circuits, supercapacitors can play a crucial role in enabling sustainable and reliable power supply for a wide range of off-grid applications.

2.2 Mechanical Flywheels

Mechanical Flywheels store kinetic energy by rotating a mass around an axis. Energy is stored when the flywheel spins; when energy is needed, the rotation is slowed, and the energy is converted into usable electricity. Ezhilarasan et al. [33] presented a battery-less power conditioning system utilizing a mechanical flywheel and solar photovoltaic (PV). The system leverages the kinetic energy stored in a mechanical flywheel to provide power during outages. Experimental testing has demonstrated the system's effectiveness in maintaining energy storage during power interruptions. The flywheel's ability to retain energy was validated under various conditions, including supporting a 1 kW load at a constant speed of 1500 RPM for up to 10 seconds. Flywheel performance is primarily governed by rotor material selection. Carbon fiber composite rotors achieve the highest specific energy (100-130 Wh/kg) compared to steel (5-30 Wh/kg), but at higher cost. Magnetic bearing materials (high-temperature superconductors) eliminate friction losses. Vacuum housing materials must balance thermal management and structural integrity under high rotational stress. For off-grid applications, the primary R&D challenge is reducing the cost of carbon fiber rotors and improving durability in dusty or humid environments. While flywheels offer high energy density, they are bulky and have lower energy density compared to batteries. However, their integration with advanced technologies like soft switching converters and DC motors can enhance their performance. By carefully considering its limitations and exploring potential enhancements, this technology can contribute to a more sustainable and reliable energy infrastructure.

2.3 Compressed Air Energy Storage

In compressed air energy storage (CAES) systems, excess energy is used to compress air and store it in large underground caverns or above-ground tanks. When energy demand exceeds generation, the compressed air is released, driving a turbine to generate electricity. While CAES is less common in small-scale off-grid systems, it has shown promise in larger renewable energy projects. The integration of CAES with RES, however, is still in its early stages, with ongoing research to optimize its efficiency [34]. Findings in Thombre et al. [35] suggest that using compressed air could be a viable alternative to water for energy storage, addressing issues like evaporation and energy density limitations associated with water reservoirs. CAES systems face significant materials challenges including high-pressure vessel integrity (carbon-fiber-wound composite tanks for above-ground storage, or salt cavern lining materials), thermal insulation for adiabatic CAES systems, and heat exchanger materials that must withstand cyclic pressure and temperature loads. Compressor valve materials (titanium alloys) and turbine blade coatings are critical for efficiency. For off-grid small-scale CAES, advanced polymer composite pressure vessels and phase-change thermal storage integration represent key materials research directions.

2.4 Pumped Hydro Storage

Pumped hydroelectric systems store potential energy of water by pumping water uphill to a reservoir when excess energy is available. During periods of high demand, the water is released to flow downhill, turning turbines to generate electricity. These systems are highly efficient and scalable but are generally more suited to larger, grid-connected systems due to their significant infrastructural requirements [36]. In remote, off-grid areas, smaller-scale versions of this approach are being explored. Pali et al. [37] present a sustainable power generation solution that combines solar photovoltaic (PV) technology with pumped hydro storage (PHS) to provide continuous electricity, particularly in rural and remote areas. The system, which was designed to produce a continuous power output of 750 W at 230 V, was found to be economically feasible compared to diesel and electric pumping systems, with an overall energy conversion efficiency of 7.11% and a PHS system efficiency of 63.69%. While the system offers several advantages, it also faces some challenges. The efficiency of energy storage can be impacted by low solar irradiance or heavy rainfall. Additionally, the initial costs associated with setting up such system can be significant, leading to a levelized cost of electricity (LCOE) that may not be competitive.

2.5 Hydrogen Storage via PEM Electrolysis

Hydrogen-based systems involve using excess renewable energy to power electrolysis, which splits water into hydrogen and oxygen. The hydrogen is stored and later used in fuel cells to generate electricity when required [38]. This method is particularly attractive due to its scalability and the fact that hydrogen can be stored for long periods. Meziane et al. [39] recommend the implementation of effective hydrogen storage solutions to ensure energy availability during low wind periods in a hybrid power system. Akarsu et al. [40] and Scamman et al. [41] have also highlighted the potential of hydrogen storage systems to significantly enhance the performance of hybrid power systems, particularly in off-grid and remote applications. By storing excess renewable energy as hydrogen, these systems can improve reliability, reduce wasted power, and increase battery efficiency. However, the integration of hydrogen storage also presents challenges, such as the safe handling and storage of hydrogen, increased system complexity, and efficiency losses during the conversion process. Despite these challenges, the benefits of hydrogen storage make it a promising technology for improving the sustainability and performance of hybrid power systems. Hydrogen storage tank materials for compressed gas (350-700 bar) include Type III (aluminum liner with carbon fiber) and Type IV (polymer liner with carbon fiber) vessels, where fiber-resin interface integrity under cycling is a critical durability challenge [42].

2.6 Molten Salt Thermal Energy Storage (TES)

Molten salts, such as sodium nitrate-potassium nitrate mixtures, are used to store and release large amounts of thermal energy efficiently and cost-effectively [43]. Compared to battery-based storage, these systems can achieve higher energy densities and longer discharge durations, making them ideal for applications requiring sustained energy supply. Studies have demonstrated the potential of molten salt storage in various energy systems. For instance, Rahbari et al. [44] presented a novel approach to integrating real-time modeling and optimization with Molten Salt Energy Storage (MSES) and a Supercritical Steam Cycle. This integrated system demonstrated improved renewable energy utilization and uninterrupted energy generation, storage, and distribution. Batgi et al. [45] explored the use of thermal energy storage (TES) and a hydrogen subsystem to meet the fresh water and electricity demands of a community. The TES helped balance the supply-demand energy mismatch, resulting in a system that generated 74.90 GWh of electricity annually and produced enough fresh water to support 4,708 families. Furthermore, a standalone TES system was introduced by Ma et al. [46] as a key component in achieving a carbon-free energy future. The study highlighted the advantages of TES in terms of larger capacity, lower costs, and versatility in driving various thermal power cycles. While there are still technical challenges to be addressed, such as corrosion and thermal cycling, researchers are actively working on developing materials and system designs to mitigate these issues and improve the overall performance of molten salt storage systems. The primary materials challenges in molten salt TES include corrosion, thermal stability at high temperature, insulation breakdown etc. [47].

2.7 Comparative Summary of Battery-Less Energy Storage Technologies

To assist industry experts and researchers in technology selection, Table 1 presents a consolidated performance comparison of the battery-less storage technologies reviewed in this paper. Values are drawn from the literature cited in the preceding subsections and represent typical or reported ranges rather than absolute specifications, as system performance varies substantially with design, scale, and operating conditions with the Technology Readiness Level (TRL) assessment. This TRL can guide technology selection. For instance, near-term deployment in remote off-grid systems, the combination of pumped micro-hydro (where geography permits), PEM hydrogen, and molten salt TES offers the best balance of maturity, economics, and performance, which motivates the integrated system proposed in Section 4.3.

Table 1 Performance comparison of the battery-less storage technologies.

Technology	Energy Density (Wh/kg)	Power Density (W/kg)	Round-Trip Efficiency (%)	Typical Discharge Duration	Cycle Life	Relative Capital Cost ($/kWh)	TRL (1-9)
Supercapacitors	1-10	1,000-10,000	85-98	Seconds-Minutes	>500,000	300-2,000	8-9
Mechanical Flywheels	5-130	400-1,500	70-95	Seconds-Minutes	>100,000	250-500	7-9
Compressed Air (CAES)	3-6	0.5-2	40-70	Hours	>10,000 cycles	50-100	4-6
Pumped Hydro (PHS)	0.5-1.5	0.1-0.3	70-85	Hours-Days	>50 years	5-100	9
Hydrogen (PEM)	800-1,400 (fuel)	0.1-0.5	25-45 (full cycle)	Hours-Weeks	60,000-80,000 hrs	500-2,000	7-8
Molten Salt TES	80-200 (thermal)	-	93-99 (thermal)	Hours-Days	>30 years	15-40	8-9
Lead-Acid Battery	30-50	75-300	70-85	Hours	500-2,000	100-200	9
Li-Ion Battery	100-265	250-340	85-95	Hours	1,000-10,000	150-400	9

Key observations from this comparison: Supercapacitors and flywheels excel in power density and cycle life, making them ideal for short-duration, high-frequency applications (e.g., power quality correction, transient buffering). Pumped hydro and molten salt TES offer the lowest cost-per-kWh for large-scale, long-duration storage subject to specific geographical or infrastructure conditions. Hydrogen storage offers the highest energy density by mass and the longest storage duration, making it uniquely suited to seasonal storage and multi-day backup, but suffers from the lowest round-trip electrical efficiency (25-45%), which substantially affects system economics. These trade-offs motivate the hybrid approach proposed in Section 4.3.

3. Review of Renewable Energy Sources: Single, Dual, and Multiple Battery-Less RES

3.1 Single Source Battery-Less Renewable Energy System

Single-source battery-less renewable energy systems rely on a singular renewable resource for power generation. They offer significant benefits for off-grid applications, especially in rural and remote areas. These systems are often cost-effective and straightforward to implement, especially in regions with an abundance of a specific resource. However, they suffer from variability of renewable energy resources. Table 2 presents a detailed summary of selected single-source renewable energy systems, their applications, inherent challenges, and the ongoing research efforts to mitigate the challenges.

Table 2 Single battery-less RES Applications and Challenges.

Renewable Energy Source	Brief Description	Uses/Applications	Inherent Challenges	Research Efforts
Solar Photovoltaic (PV)	Convert sunlight into electricity using solar cells.	Desalination via reverse osmosis (RO), such as CREST's PV-RO system producing 3 m^3 of fresh water per day in Eritrea [5]. Water pumping in rural, off-grid areas [48].	Intermittency: Solar power is only available during the day, ceasing at night or under cloudy weather. Efficiency: Decreased by shading, soiling, and panel misalignment.	Hybrid systems combining solar PV with hydrogen production to store excess energy [31, 49-51].
Wind Energy Systems	Converts kinetic energy from wind into electricity using turbines.	Wind-powered desalination systems, producing 8.5 m^3/day of freshwater without battery storage [1]. Wind energy systems in remote off-grid areas for power supply [52].	Variability: Wind speeds are inconsistent, leading to irregular power generation. Land Requirements: Large space is needed for wind turbines [53].	Integrating wind energy with energy storage systems (hydrogen, flywheels) for more consistent power [54-56].
Hydropower (Micro-hydro)	Utilizes flowing water from rivers or streams to generate electricity via turbines.	Off-grid electricity in rural areas near water sources [57]. Small-scale power for agricultural or community use [58].	Dependence on Water Flow: Performance is reduced in dry seasons or periods of low water head [59].	Innovations in water storage to ensure more consistent generation [60-64].
Biomass Energy	Converts organic material (e.g., agricultural waste) into electricity via combustion or digestion.	Used for electricity generation in rural households and small-scale industries using agricultural waste [65, 66].	Fuel Availability: Requires a steady supply of organic material [67]. Air Emissions: Potential air pollution depending on feedstock [68].	Research into cleaner combustion technologies to minimize emissions [69-71].

3.2 Dual Source Battery-Less Renewable Energy System

Dual RES systems typically combine two renewable energy sources to provide a more stable and reliable energy supply, taking advantage of the complementary availability of energy resources which reduce the need for expanded energy storage unit [72, 73]. Table 3 presents a summary of the review of recent studies on dual battery-less RES with the aim of highlighting key trends, common challenges, and optimization strategies. This trend underscores a shift towards more sustainable and multifunctional energy solutions that can adapt to varying demands and resource availability.

Table 3 Overview of Recent Studies on Dual Battery-less Renewable Energy Systems.

Authors	Dual RES Type	Study Focus	Methodology	Key Findings	Challenges	Recommendations
[72]	Photovoltaic and Wind	Freshwater supply for remote communities	Iterative optimization process	Optimized 3000 PV panels and 1250 kW wind turbine; effective energy management.	Ensuring consistent energy supply.	Tailor PV and wind components to local conditions.
[73]	Wind and Hydro	Electricity demand fulfillment	Simulation and analysis	Identified optimal configurations for energy supply.	Geographic and climatic variability.	Implement monitoring systems for performance evaluation.
[74]	Wind and Solar	Seawater desalination	Modeling and simulation	Effective integration of wind and solar for desalination.	Fluctuations in energy supply.	Optimize component sizing based on historical data.
[75]	Wind and Solar	Microgrid energy planning	Case study analysis	Successful implementation of microgrid without batteries.	Complexity in design and sizing.	Explore alternative storage solutions.
[76]	Wind and Solar	Water pumping efficiency	Performance evaluation	Hybrid systems outperform single-source systems.	Variability in weather conditions.	Enhance system design for better reliability.
[77]	Photovoltaic and Wind	Hydrogen production	Design and analysis	Effective operation at Maximum Power Point Tracking (MPPT) for hydrogen generation.	Integration complexity.	Optimize control strategies for better efficiency.
[78]	Wind and Solar	Power sharing in microgrid	Case study and simulation	Successful energy-water management for desalination.	Variability in energy supply.	Implement real-time monitoring systems.

[79]	Wind, Solar, and Hydrogen	Poly-generation systems	Modeling and simulation	Demonstrated feasibility of poly-generation in remote areas.	High initial investment.	Explore funding and policy support for implementation.
[80]	Wind and Solar	Brackish water desalination	System design and energy management analysis	Achieved reliable operation without batteries.	Energy supply fluctuations.	Develop advanced energy management systems.
[81]	Wind and Solar	DC-bus control for desalination	Experimental and simulation	Effective DC-bus voltage control under variable conditions.	Stability of the system.	Enhance control algorithms for better performance.
[82]	CSP and Photovoltaic	CSP-PV hybrid power plant in Saudi Arabia	NREL System Advisor Model (SAM) Simulation	Hybrid system reduces required solar multiple, achieves a high-capacity factor of 79%, and lowers LCOE significantly.	Managing power output from PV and CSP for stable baseload supply; solar resource variability complicates design.	Optimize design for local weather, maximize thermal storage to complement PV intermittency.
[83]	Wind Turbine and CSP/CPVT	Thermodynamic comparison for hydrogen production and poly-generation	Thermodynamic modeling, sensitivity analysis	CES-2 (CSP + CPVT) has higher thermal (59.7%) and exergy (43.91%) efficiency than CES-1 (CSP + Wind), versatile poly-generation.	Complex integration of wind and solar systems; variability in solar and wind inputs affects performance.	Optimize parameters (e.g., wind turbine size, heliostat field), monitor performance in real-time, use storage for surplus energy.

[84]	CSP and Photovoltaic with thermal storage	Integration of CSP/PV with two-tank solid particle thermal storage	Simulation and modeling	CSP/PV integration increases dispatchable energy by 40% and meets 60-69% of peak electricity demand in Spain and Australia.	Limited operational flexibility when switching between PV and CSP; efficiency of thermal storage impacts energy output.	Implement control rules for alternating PV and CSP operation, monitor direct normal irradiance (DNI) and storage levels.
[85]	CSP and Wind Turbine	Coordinated operation for energy and reserve services	Stochastic simulation, rolling look-ahead economic dispatch	TES and EH integration boosts capacity factors for wind and CSP and reduces the need for conventional reserves.	Variability of wind and solar output complicates consistent supply and increases reserve costs.	Use stochastic simulation for planning, leverage TES and EH to improve flexibility and reserve provision.
[86]	Hydro and Photovoltaic	Hydro-PV dispatchable microgeneration	Simulation and real-time validation	Hydro-PV system operates effectively without batteries, performs well in varied weather, and reduces dependency on storage.	High installation costs; variability in water flow and solar output limits energy production.	Use robust control mechanisms for reservoir management and conduct real-time testing to validate system performance.

Despite the promising combinations, several common challenges persist across the studies. The inherent variability and intermittency of renewable energy resources [78], need of advanced control strategies to maintain stability and performance [81], and initial high investment costs for such hybrid systems pose significant barriers to implementation, particularly in economically constrained regions. Real-time monitoring and energy management systems allow for better adaptation to changing energy availability, improving overall system reliability [85].

3.3 Multi-Source Battery-Less Renewable Energy Systems

These systems, often referred to as multi-source RES or multi-hybrid systems, combine three or more sources such as solar, wind, hydropower, or biomass to create a more balanced and stable power supply [87-89]. One of the primary drivers behind multi-source RES is the ability to harness energy from multiple sources that peak at different times. While multi-source RES provide unmatched reliability, they come with higher complexity in terms of system management and design. The need to balance the power input from three or more sources requires advanced control systems that can adjust energy production and distribution dynamically [90]. Additionally, the initial costs of implementing such systems are often higher due to the infrastructure required to accommodate multiple energy sources. Despite these challenges, the long-term benefits of hybrid systems such as improved energy reliability and reduced operational costs make them an attractive option for regions with highly variable renewable resources [91]. Table 4 compares battery-less and reduced-battery renewable energy configurations against conventional battery-dominant systems across key performance metrics.

Table 4 Performance benefits of alternative-storage and reduced-battery renewable energy systems relative to conventional battery-dominant configurations.

Metric	**Battery-Less System Performance**	**Battery Baseline**	**Advantage**	**Source(s)**
O&M Cost — Desalination (RO)	Wind-powered RO: ~$0.002-0.006/m^3 O&M component; no battery replacement cycle needed	Battery-buffered RO systems require battery pack replacement every 3-7 years; O&M premium of 20-35%	↓ 20-35% O&M	[1, 5, 7, 8]
System Lifespan — Hydrogen Storage	PEM electrolyzer: 60,000-90,000 hrs operational life; hydrogen tanks >20 years	Lead-acid batteries: 3-7 years; Li-ion: 8-15 years with degradation	3-6× longer	[41, 42]
Battery Capacity Reduction (Hybrid H_2)	Incorporating hydrogen storage alongside batteries reduces required battery capacity by 54-77%	Full battery-only sizing requires complete battery bank for multi-day autonomy	54-77% less battery	[48]
Wasted Renewable Energy due to Curtailment	Hydrogen + battery hybrid reduces wasted/ curtailed renewable power by 55-79%	Battery-only systems curtail excess generation when banks are full	↓ 55-79% curtailment	[42]
State of Charge (SOC) Stability	H_2-augmented system: minimum SOC raised from 37% to >81.5% year-round	Battery-only: SOC fluctuates widely with seasonal/daily variation; deeper cycling increases degradation	+44.5 pp SOC floor	[78]
LCOE — Pumped Hydro (small-scale)	Solar PV + pumped hydro: LCOE competitive with diesel in rural settings; 750 W continuous at 7.11% system efficiency	Diesel genset LCOE in remote areas typically, $0.25-0.80/kWh	≈Cost-parity to diesel	[37]
Molten Salt TES — Thermal Efficiency	Round-trip thermal efficiency: 93-99%; discharge duration 6-15 hours; cost $15-40/kWh (thermal)	Electrochemical battery round-trip: 70-95%; cost $150-400/kWh	↓ 75-90% cost/kWh	[27, 44]
Supercapacitor Cycle Life	>500,000 charge cycles with <20% capacitance fade; near-zero maintenance	Lead-acid: 500-2,000 cycles; Li-ion: 1,000-10,000 cycles before replacement	50-500× more cycles	[23, 30, 31]

Environmental — End-of-Life	No heavy metals (Pb, Cd, Co) in systems using hydrogen, TES, or flywheels; lower disposal burden	Lead-acid: ~18 kg Pb per kWh; Li-ion: cobalt/nickel mining with high environmental cost index	Near-zero toxic waste	[6]
Water Productivity — Solar RO	Solar PV-RO (battery-less, CREST Eritrea): 3 m^3/day freshwater; direct solar-to-water with no storage losses	Battery-buffered RO: additional energy losses in charge/discharge cycle (5-15% loss)	5-15% more water output	[5]
Community Scale — TES + H_2 System	Integrated TES + H_2 system generates 74.90 GWh/year electricity and freshwater for 4,708 families	Equivalent battery-based system would require prohibitive battery bank replacement costs at scale	Scalable to community	[45]

3.4 Applications of Battery-Less Renewable Energy Systems

Battery-less renewable energy systems are transforming how off-grid regions and industries meet their energy needs. By reducing reliance on conventional batteries, these systems provide a more sustainable and cost-effective approach to harnessing renewable energy sources. 5 highlights key applications where battery-less systems have been successfully implemented, focusing on areas such as water desalination, pumping water, off-grid electrification, and small-scale industrial applications. Each deployment is evaluated based on its operating principles, ideal locations, associated studies, and benefits. A detailed summary of these application areas, along with associated studies and benefits, is presented in Table 5.

Table 5 Key Applications of Battery-less Renewable Energy Systems.

Application Area	Brief Description	Suitable Location	Associated Projects/Studies	Benefits
Saltwater Desalination	Use renewable energy (solar or wind) to power Reverse Osmosis (RO) for converting seawater into freshwater [92, 93].	Coastal areas with limited freshwater supply but abundant solar or wind energy [52, 78].	Hybrid wind-solar-power RO system [78, 80]. Wind-powered RO system [1, 8, 10, 52]. Solar PV-powered RO system [5, 94].	Provides clean drinking water in off-grid coastal areas. Reduces reliance on fossil-fuel-powered desalination systems.
Water Pumping and Irrigation	Renewable energy (solar or wind) is used directly to power water pumps for irrigation purposes [95, 96].	Rural agricultural regions with high solar irradiance or steady wind availability.	Hybrid wind-solar water pumping [76, 87]. Solar water pumping for irrigation [97, 98]. Wind-powered water pumping in remote areas [52].	Provides reliable irrigation, reducing dependency on grid power. Promotes agricultural productivity in off-grid regions.
Off-grid Power Supply	Direct use of solar or wind energy for powering homes, small businesses, and community utilities [5, 99, 100].	Remote villages, islands, and other off-grid communities with no access to centralized grid power [1, 101, 102].	Solar and wind hybrid systems for rural electrification [39, 75, 79, 103-105].	Provides electricity to underserved areas. Reduces the environmental impact of fossil fuel-based power generation [39]. Reduced cost of extending grid infrastructure.
Industrial & Agricultural	Solar or wind power is used directly to power small-scale industrial processes (e.g., food processing, and dairy farming).	Rural areas with agricultural processing need and consistent renewable energy availability [52].	Solar-powered dairy farm operations [76]. Small-scale solar and wind-powered processing plants [74].	Reduces reliance on costly fossil fuels for agricultural and industrial processes. Encourages local economic development in off-grid areas.

4. Battery-Less Systems for Off-Grid Power Generation

In this section, we explore both direct-use approaches and the use of hydrogen as an alternative energy storage method for off-grid power systems.

4.1 Dispatch Generated Power

In these systems, energy produced by say, solar photovoltaic (PV) panels or wind turbines is used for various applications, from powering homes and irrigation systems to driving industrial processes without immediate storage. For example, solar PV-powered water pumping systems have been widely implemented in rural agricultural settings [1]. By aligning energy generation with real-time consumption needs, these systems eliminate the need for expensive battery storage and reduce system complexity [52].

4.2 Hydrogen as an Alternative Energy Storage

Although directly coupled renewable energy systems can operate effectively when generation coincides with demand, energy storage is required when renewable generation and load demand do not occur simultaneously. Hydrogen has emerged as a promising long-duration storage option for off-grid renewable energy systems and can complement or reduce dependence on conventional battery storage [28, 41, 42]. Stored hydrogen may be used directly as a transportation fuel in remote poly-generation systems [79] or reconverted into electricity through a fuel cell when renewable generation is insufficient [39, 41, 42]. In a hydrogen fuel cell, hydrogen reacts electrochemically with oxygen to produce electricity and heat, with water as the principal reaction product [106].

4.2.1 Key Issues and Benefits of Hydrogen in Off-Grid Power Systems

The integration of hydrogen as an alternative energy storage solution in off-grid renewable energy systems presents a range of benefits and challenges. Understanding these factors is crucial for optimizing the deployment of hydrogen technologies in various applications. Some benefits of Hydrogen in Off-grid Energy Storage are highlighted:

i. **Enhanced Reliability and Battery Support**: Hybrid hydrogen-battery storage can improve the reliability of off-grid renewable energy systems by using batteries for short-term balancing and hydrogen for longer-duration and seasonal storage. Scamman *et al.* modeled renewable-powered telecom systems at three locations: Phoenix, Reykjavik, and Heraklion, and found that adding hydrogen production, storage, and fuel-cell conversion reduced the required battery capacity by 54-77% relative to equivalent battery-only systems [107]. The hybrid configurations increased the minimum annual battery state of charge from 36.7-54.7% to 81.5-85.9% and reduced curtailed renewable energy by 55-79% [41]. Maintaining the batteries within a higher and narrower SOC range may reduce deep discharging and improve system reliability, which is particularly important for remote telecom base stations requiring continuous power [41].

ii. **Versatility as an Energy Carrier**: Hydrogen serves as a versatile energy carrier that can be utilized across various sectors, including transportation, industry, and electricity generation [108]. This versatility makes it an attractive option for addressing electricity shortages in regions reliant on renewable energy sources, as highlighted in research from South Africa and

Turkey [109-112]. This capability is essential for maximizing the utilization of renewable resources and minimizing curtailment.

iii. **Economic Viability**: Studies reveal that hybrid systems combining photovoltaic (PV) panels, wind turbines, and hydrogen production can achieve competitive Levelized Cost of Energy (LCOE) figures, making them financially attractive for off-grid applications [96, 113]. Furthermore, as technology advances and economies of scale are realized, the costs associated with hydrogen production and storage are expected to decrease, enhancing its economic feasibility [114].

iv. **Environmental Benefits**: Hydrogen, when produced from renewable sources, offers significant environmental benefits [115, 116]. It can help reduce greenhouse gas emissions and reliance on fossil fuels, contributing to global climate goals.

Hydrogen technologies show great promise; some key issues must be considered in their application in power generation and storage systems. The initial capital costs and ongoing operational expenses of hydrogen integration can be a significant barrier to widespread adoption. The current lack of widespread hydrogen infrastructure can hinder its adoption in off-grid applications [109, 117]. Additionally, market dynamics and regulatory frameworks can affect the economic viability of hydrogen projects [118-121]. While hydrogen presents a compelling alternative for off-grid energy storage, addressing the associated challenges is vital for its successful implementation. By leveraging its benefits and mitigating key issues, hydrogen can play a significant role in the transition to sustainable energy systems.

4.2.2 Hydrogen-Enhanced CSP Systems

The integration of hydrogen storage with Concentrated Solar Power (CSP) systems that utilize molten salt energy storage presents a transformative approach to renewable energy generation and storage. CSP technology harnesses solar energy by concentrating sunlight onto a receiver, generating heat that can be converted into electricity [122]. One of the significant advantages of CSP is its ability to incorporate thermal energy storage, with molten salt being a preferred medium [123-125]. By integrating hydrogen storage into this framework, the system can further enhance its energy management capabilities [126, 127]. The integration of hydrogen storage with CSP and molten salt energy storage systems offers several advantages. This hybrid system can provide a stable and dispatchable power supply, addressing the intermittency challenges associated with solar energy [102, 128]. The system can be scaled to meet varying energy demands and can be adapted to different geographical locations, making it a versatile solution for diverse energy needs [129]. Table 6 highlights how the integration of hydrogen storage with CSP and molten salt energy storage effectively addresses primary RES challenges including intermittency, energy storage limitations, grid stability, cost-effectiveness, environmental impact, and scalability, making it a robust solution for future energy systems.

Table 6 Integrated Energy Storage Solutions to Primary RES Challenges.

Key RES Challenge	Integrated Hydrogen, CSP & Molten Salt Storage Solution
Solar Energy Intermittency	Excess energy generated during peak sunlight hours can be converted into hydrogen, ensuring continuous power supply and mitigating the effects of intermittency [125, 130-132].
Energy Storage Limitations	Offers a longer-term storage solution. Enhances the overall energy storage capacity of the system, allowing for better management of energy supply and demand over extended periods [130, 133-137].
Grid stability and demand response	When electricity demand peaks, stored hydrogen can be converted back into electricity using fuel cells, thus supporting grid stability and responding effectively to fluctuations in demand [128, 138-140].
Cost-Effectiveness	Reduction in the Levelized Cost of Energy (LCOE). By optimizing the use of renewable resources and reducing reliance on fossil fuels, the overall cost-effectiveness of the energy system is improved [109, 141-143].
Environmental Impact	Reduces greenhouse gas emissions by minimizing the use of fossil fuels. By utilizing renewable energy sources for both electricity generation and hydrogen production, the environmental footprint of energy production is greatly diminished [96, 128, 144, 145].
Scalability and Flexibility	Provides scalable solutions that can be tailored to meet specific energy demands in various geographical locations. This flexibility is crucial for adapting to different energy needs and resource availability [102, 146-148].

4.3 Proposed Battery-Less Integrated Energy System

In view of the highlighted benefits as well as challenges associated with multiple RES systems, a conceptual framework for the integration of three renewable sources, namely, Photovoltaic (PV), Concentrated Solar Power (CSP), and Wind Turbine (WT) is presented. The proposed off grid microgrid system aims to establish a robust renewable energy infrastructure that delivers continuous, stable, and reliable power to meet load demands. Figure 2 shows the conceptual diagram of the proposed off-grid battery-less renewable energy system. Unlike previous studies, this system not only generates electricity for various applications but also produces green hydrogen which can be utilized to fuel small equipment and vehicles, particularly in agricultural settings [149-151].

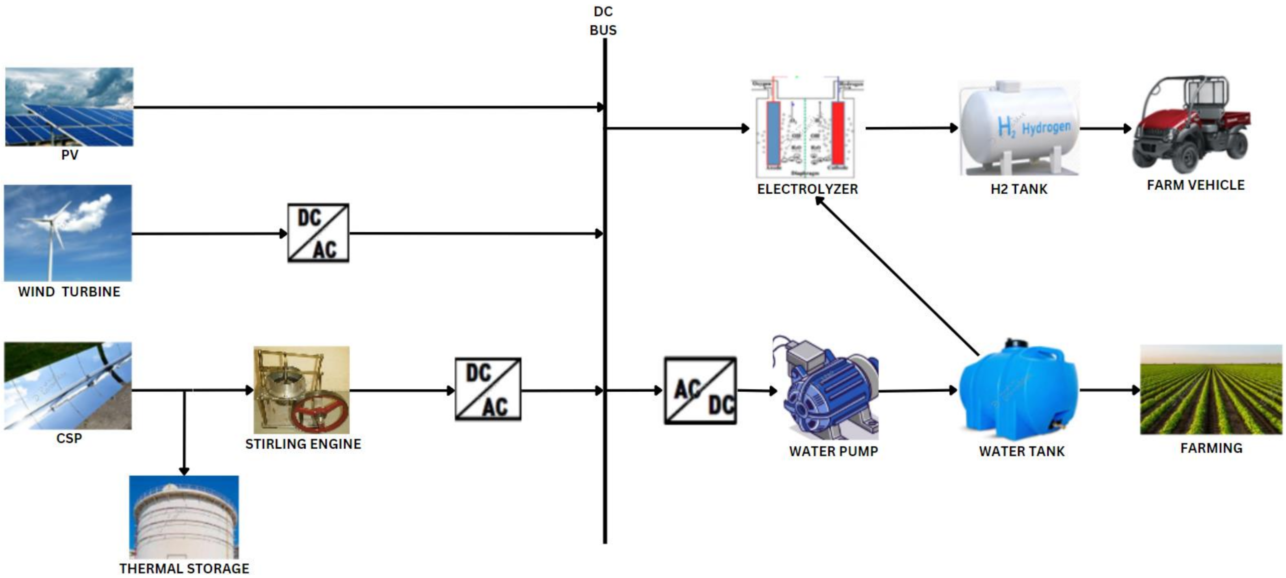

Figure 2 Overall schematic diagram of the proposed off-grid battery-less based on renewable power.

The design and implementation of this system aim to address the challenges faced by battery-operated renewable energy systems, such as the lack of affordable battery recycling technologies, safety concerns, and the complexities that batteries introduce to the design, operation, and maintenance of off-grid systems [152-155]. The proposed integrated energy system represents a significant advancement in renewable energy technology, offering a sustainable solution that enhances energy reliability, reduces environmental impact, and meets diverse energy needs without the reliance on traditional battery storage. The Figure 3 presents the proposed detailed System Schematic battery-less off-grid hybrid renewable energy system in which three generation sources — Solar PV (~10 kWp via MPPT), a Wind Turbine (5-7.5 kW), and a CSP turbine (2.5-10 kW) drawing on molten salt thermal storage converge onto a shared DC bus (200-400 V) managed by an EMS/BMS for intelligent mode switching and priority dispatch. Rather than relying on conventional batteries, the system stores energy through complementary technologies: molten salt TES (380-565°C, $\eta_{thermal}$ ≈ 93-99%, 4-10 hr discharge) for short-to-medium duration buffering, and a PEM electrolyzer coupled with a compressed hydrogen tank (350-700 bar, >20 yr lifespan) and fuel cell stack (1-4 kW, η ≈ 40-60%) for long-duration storage and reconversion. Generated power serves community AC loads, DC water pumps, and a SCADA/IoT monitoring platform, while the stored hydrogen uniquely serves a dual role — as a backup electricity source via the fuel cell and as a direct fuel for agricultural vehicles and equipment, replacing diesel and representing the system's key novel contribution.

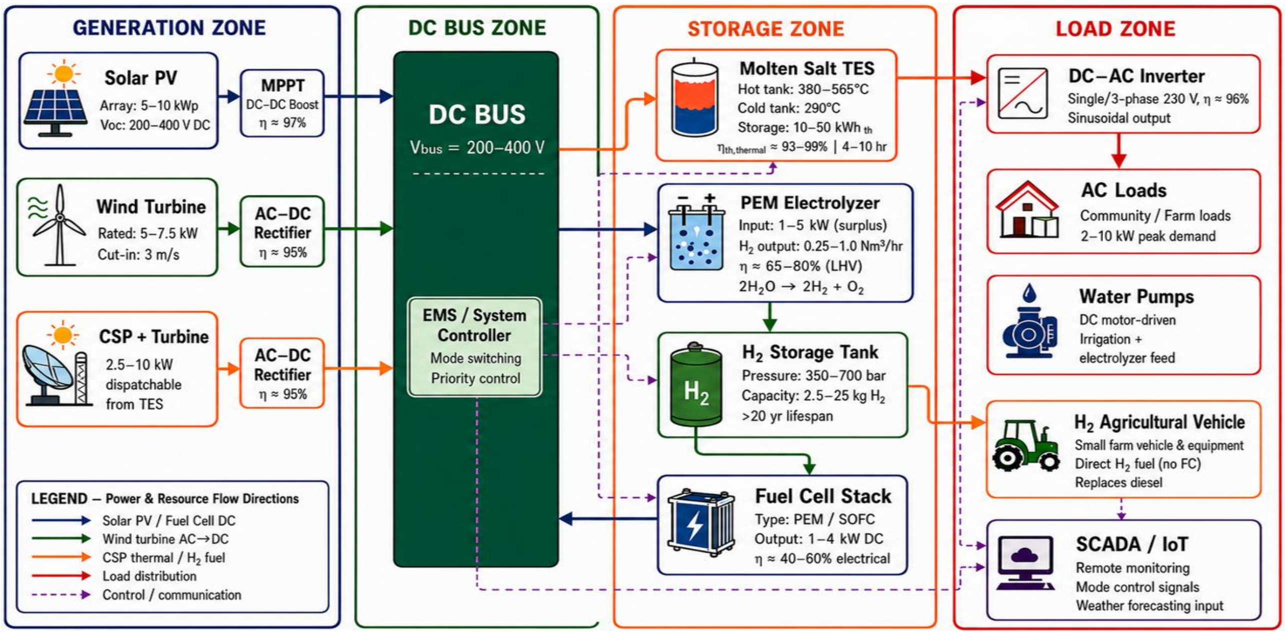

Figure 3 Detailed System Schematic — Proposed Battery-Less Integrated Energy System.

4.4 Key Contribution — Dual-Pathway Hydrogen Utilization

The configuration proposed in this work brings together several elements that have not previously been combined in a battery-less, off-grid context. Specifically, the system integrates: (i) CSP with molten salt thermal storage, (ii) PEM electrolysis for green hydrogen production, (iii) solar PV and wind turbines, and (iv) complete elimination of battery storage in an off-grid setting with dual-hydrogen usage (electricity reconversion + direct agricultural fuel), represents a configuration not previously reported in the battery-less off-grid literature to the authors' knowledge. The central innovation is the dual-pathway of hydrogen utilization for long-duration electricity backup and as a direct fuel substitute which enhances. Table 7 summarizes the differentiation of the proposed system from prior art.

Table 7 Differentiation of Proposed System from Prior work.

Prior Work	Configuration	Gap Addressed by This Work
Alharthi [38]; Ceylan & Devrim [42]	PV-Wind-H2 (with battery)	No CSP; battery present; H2 for electricity only — no direct agricultural fuel use
Campion et al. [149]	CSP-H2 (off-grid green H2 for ammonia)	No PV/WT integration; no dual-use H2 (electricity + agricultural fuel); not a battery-less microgrid framework
D'Auria et al. [84]	CSP+PV with solid particle TES	Grid-connected; battery not eliminated; no hydrogen pathway; not off-grid agricultural application
This Work	PV + WT + CSP + Molten Salt TES + PEM H2 (battery-less, off-grid)	Dual-pathway H2 (electricity reconversion + direct agricultural fuel); complete battery elimination; off-grid agricultural focus; conceptual framework for simulation validation

4.5 Operating Modes

The system operates across four distinct modes depending on the availability of solar irradiance, wind speed, and stored energy levels:

Mode 1 — Surplus Generation: When combined PV and WT generation exceeds the instantaneous load demand ($P_{PV} + P_{WT} > P_{load}$), the surplus power is directed in priority order to: (i) the CSP molten salt heat exchanger via electric heaters to top up thermal storage, and (ii) the PEM electrolyzer for hydrogen production. This prioritization maximizes the utilization of dispatchable thermal storage while producing hydrogen as a secondary long-term energy carrier.

Mode 2 — Balanced Generation: When PV and WT generation approximately meets load demand ($P_{PV} + P_{WT} \approx P_{load}$), the system operates in direct-dispatch mode. The DC bus controller maintains bus voltage regulation through a DC-DC boost converter. No thermal or hydrogen charging occurs in this mode.

Mode 3 — Deficit Generation — Short-Term: During short-term shortfalls (e.g., transient cloud cover, wind lulls), the CSP turbine is activated to draw from molten salt thermal storage to supplement electrical generation. The thermal storage system can provide dispatchable output for 6-12 hours depending on the storage tank sizing.

Mode 4 — Deficit Generation — Extended: During extended low-generation periods (e.g., multi-day low irradiance and wind), stored hydrogen can be converted back to electricity via a fuel cell stack, providing a final layer of energy security. In the proposed agricultural application, hydrogen is also available directly for fueling farm equipment, eliminating the need for diesel.

4.6 Simplified Energy Balance Framework

At any time *t*, the instantaneous electrical power balance of the hybrid renewable-energy system is expressed as

$$P_{PV}(t) + P_{WT}(t) + P_{CSP}(t) + P_{FC}(t) = P_{load}(t) + P_{EL}(t) + P_{TC}(t) + P_{loss}(t) \qquad (1)$$

where $P_{PV}(t)$ and $P_{WT}(t)$ denote the instantaneous electrical power generated by the photovoltaic array and wind turbines, respectively; $P_{CSP}(t)$ represents the dispatchable electrical power supplied by the concentrating solar power plant, including power generated using thermal energy discharged from the molten-salt storage system; and $P_{FC}(t)$ is the electrical power generated by the hydrogen fuel cell. The demand-side terms $P_{load}(t)$, $P_{EL}(t)$, and $P_{TC}(t)$ represent the instantaneous electrical load demand, the power consumed by the proton-exchange-membrane electrolyzer, and the electrical power consumed by the heater used to charge the molten-salt thermal-energy storage system, respectively. The term $P_{loss}(t)$ accounts for conversion, storage, transmission, and distribution losses within the system.

Equation (1) represents an instantaneous power balance, and all terms should therefore be expressed in consistent power units, such as kW or MW. The corresponding daily energy balance is obtained by integrating the power terms over a daily operating period T_d, typically 24 h:

$$E_{PV,d} + E_{WT,d} + E_{CSP,d} + E_{FC,d} = E_{load,d} + E_{EL,d} + E_{TC,d} + E_{loss,d} \qquad (2)$$

where the daily energy associated with each system component *x* is defined as

$$E_{x,d} = \int_{t_d}^{t_d+T_d} P_x\,(t)\,dt. \tag{3}$$

For a discrete-time simulation, Equation (3) can be written as

$$E_{x,d} = \sum_{k=1}^{N_d} P_x\,(k)\Delta t, \qquad N_d = \frac{T_d}{\Delta t}, \tag{4}$$

where Δt is the simulation time-step duration and N_d is the total number of time steps within the daily operating period. The energy quantities in Equations (2)-(4) should be expressed in consistent units, such as kWh or MWh. The term $P_{TC}(t)$ is included in the electrical power balance only when the molten-salt storage system is charged using an electrically powered heater. Thermal energy transferred directly from the CSP solar field to the molten-salt storage system should be represented separately in the CSP thermal-energy balance [156]. This framework provides a simplified representation of the system's energy flows. A full simulation using HOMER Pro or an equivalent tool, incorporating hourly meteorological data for a representative off-grid site, is identified as the next step and will be presented in a follow-on publication.

4.7 Practical Implementation Challenges

The practical deployment of the proposed battery-less PV-WT-CSP-hydrogen system requires coordinated consideration of economic, operational, scalability, and reliability constraints.

Economic feasibility: The system requires substantial capital investment in PV and WT generation, the CSP receiver and power block, molten-salt TES, PEM electrolyzer, water-treatment unit, hydrogen compressor and storage tank, fuel cell, power converters, and supervisory control. Operating costs include CSP cleaning, salt circulation and heat tracing, water purification, compressor servicing, hydrogen-system inspection, and electrolyzer and fuel-cell stack replacement. Feasibility should therefore be evaluated using net present cost, levelized cost of energy, and levelized cost of hydrogen, with sensitivity to equipment cost, discount rate, renewable-resource availability, hydrogen demand, diesel prices, and policy incentives [110, 113, 114, 117, 157]. Dual hydrogen use may improve equipment utilization, but this benefit must be quantified through system-level techno-economic analysis.

System control and coordination: The energy-management system must coordinate variable PV and WT outputs, CSP-TES charging and discharging, electrolyzer and fuel-cell operating limits, hydrogen-reserve allocation, and DC-bus and AC-load regulation. Because the system excludes batteries, converter coordination, short-term power balancing, black-start capability, load shedding, and renewable-generation forecasting are particularly important [81, 85, 90, 125].

Scalability: Deployment is constrained by site-specific solar irradiance, direct normal irradiance, wind availability, land and water requirements, CSP plant scale, hydrogen-storage and dispensing infrastructure, and access to technical support. A staged transition from pilot demonstration to community-scale deployment using measured resources and load data is therefore required [122, 147, 158, 159].

Maintenance and reliability: Major concerns include PV soiling, WT mechanical wear, CSP mirror and receiver degradation, molten-salt corrosion or freezing, electrolyzer and fuel-cell aging, compressor wear, hydrogen leakage, and pressure-vessel inspection [117, 122, 151, 160]. SCADA-based condition monitoring, hydrogen-leak detection, freeze protection, fault isolation, preventive maintenance, and scheduled component replacement are consequently essential for reliable long-term operation.

5. Conclusion and Future Research Directions

This paper has presented a comprehensive review of battery-less off-grid renewable energy systems, surveying storage alternatives (supercapacitors, flywheels, CAES, pumped hydro, hydrogen, and molten salt thermal storage), reviewing their performance characteristics, applications, and limitations, and proposing a novel integrated hybrid system combining PV, wind turbines, CSP with molten salt storage, and green hydrogen production.

Several key findings emerge from the review:

First, no single battery-less storage technology is universally superior. Supercapacitors and flywheels are best suited to short-duration, high-power applications such as transient buffering and power quality management, while pumped hydro and molten salt TES are optimal for large-scale, long-duration storage where geography permits. Hydrogen offers unique advantages for very long-duration storage and multi-vector energy use but carries the penalty of low round-trip electrical efficiency (25-45%), making its economic case dependent on the availability of surplus renewable generation and the presence of non-electrical end uses (transportation, industrial feedstock). Second, dual-source and multi-source hybrid configurations consistently outperform single-source systems in reliability metrics. The complementary generation profiles of solar PV (daytime, weather-sensitive) and wind energy (nighttime and seasonal availability) are particularly well matched, and their combination with a dispatchable storage technology (CSP/molten salt or hydrogen) is the configuration most likely to achieve high renewable energy fractions without batteries. Third, the proposed integrated system - combining PV, WT, CSP with molten salt, and hydrogen in a fully battery-less off-grid configuration — addresses the key intermittency and reliability issues of its constituent technologies through multi-modal dispatch. The dual use of hydrogen for both electricity backup and direct agricultural fuel is a novel feature that improves the economic case for electrolyzer investment. Full system simulation and techno-economic optimization are required to quantify the performance benefits and provide design guidance for practical deployment; this represents the primary direction for future work.

Future research priorities identified from this review include: (i) development and experimental validation of energy management strategies for multi-source battery-less systems; (ii) reduction of electrolyzer capital and operating costs to improve hydrogen system economics; (iii) adaptation of micro-scale CAES and pumped hydro to remote off-grid settings; (iv) life-cycle environmental assessment of battery-less systems compared to battery-augmented systems; and (v) policy and regulatory frameworks that can incentivize battery-less configurations in rural electrification programs. Progress on these fronts will be essential to realizing the full potential of battery-less renewable energy systems in off-grid and remote applications globally.

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Author Contributions

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Competing Interests

The authors have declared that no competing interests exist.

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