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Environmental Impacts on Energy Storage Systems Integrated with Renewables

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Abstract: The integration of energy storage systems (ESS) with renewable energy technologies has become a critical component in the transition toward sustainable and low-carbon power systems. This study examines the environmental impacts associated with ESS deployment through four key perspectives: the influence of climatic and environmental conditions on storage performance, the environmental footprint evaluated through Life Cycle Assessment (LCA), the ecological risks and resource sustainability of materials used in storage technologies, and the environmental benefits achieved in renewable-dominated power systems. Environmental factors such as temperature variation, humidity, dust accumulation, and extreme weather conditions significantly affect the operational efficiency, degradation rates, and reliability of storage technologies including lithium-ion batteries, flow batteries, and hydrogen storage systems, particularly in regions characterized by hot and arid climates. The analysis also highlights the importance of assessing the full life cycle environmental impacts of energy storage technologies, including raw material extraction, manufacturing, transportation, operation, and end-of-life management. Critical materials such as lithium, cobalt, nickel, vanadium, and rare earth elements raise concerns regarding resource sustainability, environmental degradation, and supply chain stability. At the same time, ESS integration provides significant environmental advantages by reducing renewable energy curtailment, improving grid stability, and lowering reliance on fossil-fuel-based backup generation, resulting in reductions in greenhouse gas emissions and air pollutants. Advancements in alternative technologies, including sodium-ion batteries, solid-state batteries, and green hydrogen storage, present promising pathways for improving environmental sustainability. Overall, energy storage systems play a fundamental role in enabling large-scale renewable energy integration, while sustainable material management, improved technology design, and supportive policy frameworks remain essential for minimizing environmental impacts and supporting long-term decarbonization goals.

Keywords: Energy Storage Systems, Renewable Energy Integration, Life Cycle Assessment, Environmental Sustainability.

1. Introduction

The integration of energy storage systems (ESS) with renewable energy technologies has become a fundamental component of modern power systems aiming to achieve sustainability and decarbonization targets. Renewable energy sources such as solar photovoltaic (PV) and wind power are inherently intermittent and variable, which creates challenges for maintaining grid stability and reliable electricity supply [1,2]. Energy storage technologies, including lithium-ion batteries, flow batteries, and hydrogen storage systems, provide critical solutions for balancing supply and demand by storing excess renewable energy and delivering electricity when generation decreases. However, while ESS significantly enhance renewable energy utilization, the environmental implications associated with their deployment must be carefully evaluated to ensure that energy transitions remain environmentally sustainable [3,4].

One of the key environmental considerations involves the influence of climatic and environmental conditions on ESS performance. Environmental factors such as high ambient temperatures, humidity, dust accumulation, and extreme weather events can affect the operational efficiency and lifespan of storage technologies. For instance, elevated temperatures may accelerate electrochemical reactions in lithium-ion batteries, leading to faster degradation and reduced operational life [5,6]. Dust accumulation, particularly in desert and arid regions, may obstruct cooling systems and increase internal temperatures in battery storage units. Such environmental stresses require effective thermal management systems, protective enclosures, and optimized system design to maintain reliable performance in different climatic conditions [7,8].

Another important aspect concerns the environmental footprint associated with the life cycle of energy storage technologies. The production of storage systems requires significant quantities of raw materials and energy-intensive manufacturing processes [9,10]. Extraction of critical minerals such as lithium, cobalt, nickel, and vanadium may result in land disturbance, water contamination, and greenhouse gas emissions [11,12]. In addition, transportation and processing activities contribute to the overall environmental impact of ESS technologies. Life Cycle Assessment (LCA) methodologies are widely used to evaluate environmental indicators such as carbon emissions, energy consumption, and ecological toxicity across all stages of the storage system life cycle, providing valuable insights for identifying more sustainable technology pathways [13,17].

Environmental impacts are also linked to resource sustainability and ecological risks associated with storage materials. Many energy storage technologies rely on critical materials whose supply chains are geographically concentrated and environmentally sensitive [18,19]. Mining operations for lithium, cobalt, and rare earth elements can lead to ecosystem degradation and resource depletion if not properly managed. In addition, improper disposal or leakage of battery components may introduce hazardous substances into soil and water systems [18-21]. To address such challenges, research efforts are increasingly focusing on developing alternative materials and storage technologies, including sodium-ion batteries, solid-state batteries, and green hydrogen storage solutions that may offer lower environmental risks while maintaining high performance [22-25].

Despite such challenges, energy storage systems provide substantial environmental benefits when integrated with renewable-dominated power systems [26-29]. ESS technologies enable higher penetration of solar and wind energy by mitigating intermittency, reducing renewable energy curtailment, and improving grid stability. Reduced reliance on fossil-fuel-based backup generation contributes to lower greenhouse gas emissions and reduced air pollution [30-34]. In addition, energy storage supports more efficient grid operation, decreases system energy losses, and facilitates the transition toward low-carbon energy infrastructures. As renewable energy deployment continues to expand worldwide, careful consideration of environmental impacts alongside technological advancements will be essential for ensuring that energy storage systems contribute effectively to sustainable energy development [35-39]. Several studies have addressed the environmental impacts of energy storage systems integrated with renewable energy sources, as presented below.

The study by [40] assessed the environmental and economic performance of lithium-ion batteries (LIB) and pumped hydro energy storage (PHES) to evaluate their eco-efficiency in renewable energy systems. Results show that LIB currently provides the most favorable environmental performance, followed by PHES. Transitioning to renewable energy sources was identified as the most effective decarbonization strategy, with carbon emission reductions ranging from 75% to 112% for both technologies. When all carbon reduction measures are applied, LIB is projected to achieve carbon neutrality by 2030, while PHES is expected to reach this target by 2040. Future energy mix optimization may further reduce emissions to 22.2 kg CO_2/MWh for PHES and 48.7 kg CO_2/MWh for LIB by 2050. Economically, PHES shows lower life cycle costs at approximately $66.5/MWh, about half that of LIB, with a payback period of 21 years, compared to 28 years for LIB.

According to [41], large-scale energy storage systems can effectively support a wide range of grid applications, including load balancing, renewable energy integration, and grid stability enhancement.

However, evaluating the environmental impacts of such systems remains complex due to variations in electricity demand profiles, grid energy mixes, and the diversity of available storage technologies. As a result, comprehensive sustainability assessments are required to ensure environmentally optimal deployment of grid-scale energy storage systems. To address this challenge, fundamental principles for green energy storage have been proposed, focusing on critical aspects such as sustainable material use, high round-trip efficiency, extended service life, and minimized performance degradation over time.

In [42], the growing environmental concerns and economic considerations have led to a continuous increase in the adoption of renewable energy sources. However, challenges such as uncertainty in generation, output variability, and the difficulty of storing energy at large scales remain significant barriers to higher renewable energy penetration in electricity markets. Energy storage systems provide an effective solution by storing excess energy generated during periods of low demand or surplus production and supplying it when demand exceeds generation. In this context, the present study conducts a comparative analysis of three energy storage technologies applied to a typical wind power plant with a capacity of 109 MW. The investigated storage technologies include compressed air energy storage (CAES), liquid air energy storage (LAES), and hydrogen energy storage (HES). For the analysis, the electricity generated by the wind farm during eight off-peak hours is used as the input energy for the storage systems.

This study provides a comprehensive analysis of the environmental impacts associated with energy storage systems integrated with renewable energy technologies by examining four critical dimensions: climatic influences on storage performance, life cycle environmental footprints, ecological risks related to storage materials, and environmental benefits in renewable-dominated power systems. The research contributes to the existing literature by synthesizing environmental considerations across the full operational and material life cycle of energy storage technologies, offering a holistic perspective on sustainability challenges and opportunities in modern energy systems. In addition, the study highlights the role of environmental conditions, particularly in hot and arid regions, in influencing the efficiency, reliability, and degradation behavior of energy storage technologies such as lithium-ion batteries, flow batteries, and hydrogen storage systems. Furthermore, the study advances understanding of the resource sustainability challenges and ecological risks associated with critical materials used in energy storage technologies, including lithium, cobalt, nickel, vanadium, and rare earth elements. The research also emphasizes the importance of life cycle assessment methods in evaluating environmental footprints and identifies emerging alternatives such as sodium-ion batteries, solid-state batteries, and green hydrogen storage as promising pathways for reducing environmental impacts. Finally, the analysis demonstrates the significant environmental benefits of energy storage integration, including reduced renewable energy curtailment, improved grid stability, and substantial reductions in greenhouse gas emissions and air pollutants, thereby supporting global decarbonization strategies and sustainable energy transitions.

2. Influence of Climate and Environmental Conditions on Energy Storage Performance

The rapid growth of renewable energy sources such as solar and wind has increased the importance of energy storage systems (ESS) in modern power systems. Technologies including lithium-ion batteries, flow batteries, and hydrogen storage systems are essential for mitigating the intermittency of renewable energy and enhancing grid stability, flexibility, and reliability [43,44]. However, the performance, efficiency, and lifespan of these storage technologies are strongly influenced by environmental and climatic conditions, which vary across different geographical regions and deployment environments.

Environmental factors such as ambient temperature, humidity, dust accumulation, and extreme weather events can significantly affect the operational behavior and degradation rates of energy storage systems. High temperatures may accelerate battery aging, while low temperatures can reduce power output and charging efficiency [45,46]. In addition, dust and humidity can cause cooling inefficiencies, corrosion, and equipment degradation, particularly in harsh climates such as hot and arid regions. Understanding these environmental influences is therefore essential for optimizing ESS design, improving operational reliability, and supporting the large-scale integration of renewable energy technologies. Table 1 demonstrates the influence of Climate and Environmental Conditions on energy storage performance

Table 1. The influence of climate and environmental conditions on ESS performance [46-50].

Environmental factor	Typical exposure context (renewables sites)	Key performance impacts (generic)	Lithium-ion batteries (Li-ion)	Flow batteries (e.g., VRFB)	Hydrogen storage systems
High ambient temperature	Hot/arid PV farms, desert microgrids, rooftop PV	Accelerates aging; increases self-discharge; raises thermal risk;	↑ degradation rate (calendar & cycling), ↑ thermal runaway risk, BMS derating, capacity fade if cooling inadequate	Electrolyte conductivity may improve, but pump/auxiliary loads ↑; materials/seals can age faster;	Pressure rise in tanks; boil-off for liquid H_2; higher compressor energy
Low ambient temperature	Wind farms in cold regions, high-altitude sites	Reduced power capability; higher losses; slow kinetics; potential freezing	Power fade, charge acceptance ↓, lithium plating risk during charging, RTE ↓	Electrolyte viscosity ↑; pumping power ↑; risk of electrolyte freezing (depending on chemistry)	Lower pressure; embrittlement risk for some metals; liquid H_2 handling still complex
High humidity / condensation	Coastal wind/PV, humid subtropical sites	Corrosion, insulation breakdown, sensor drift, leakage currents	Corrosion at terminals/busbars; BMS/connectors at risk; insulation resistance ↓	Corrosion in piping/stack frames; membrane/electrode durability affected if contaminants ingress	Corrosion in balance-of-plant; moisture impacts fuel cell/PEM systems strongly
Dust / sand / soiling	Desert PV, semi-arid wind, construction zones	Thermal blockage, filter clogging, reduced cooling efficiency	Cooling path obstruction → cell temperature ↑ → degradation ↑; fan/filter maintenance ↑	Abrasive particles can wear pumps/seals; radiator clogging; heat rejection ↓	Filters clog; heat exchanger fouling; valves/seals wear
Extreme heatwaves	Increasingly common in MENA, South Asia, Mediterra-nean	Prolonged high-T exposure → accelerated aging + derating	Rapid SoH drop if unmanaged; derating reduces usable capacity; thermal runaway risk management critical	Auxiliary loads ↑; potential derating to protect stacks; increased evaporation/thermal stress on tanks	Tank pressure management; venting risk; higher compressor duty; liquid H_2 boil-off ↑
Extreme cold snaps / icing	Temperate wind sites, highlands	Reduced power availability; mechanical issues; icing blocks vents/air paths	Charging constraints; RTE ↓; power limits; possible shutdown	Pumping issues; viscosity ↑; freeze risk; startup delays	Valve freezing/icing risk; vent line blockage; instrument-ation errors
High wind / sandstorms	Desert storm events, coastal gusts	Structural stress, airborne	Enclosure integrity challenged; cooling	Mechanical vibration on	Mechanical stress on piping/tanks;

		debris, rapid dust ingress	disruption; particulate ingress	piping; seal fatigue	debris impacts vents and sensors
Heavy rainfall / flooding	Monsoon regions, flash floods, coastal storms	Water ingress, short circuits, contamin-ation, access limitations	Critical safety risk if water ingress; insulation breakdown; BMS faults	Electrolyte contamination risk if seals compromised; corrosion	Electrical/control system vulnerability; corrosion; access constraints
Salt spray / marine atmosphere	Offshore wind, coastal PV	Aggressive corrosion; connector failure; reduced insulation	Terminal/busbar corrosion; cabinet corrosion; maintenance ↑	Piping/stack corrosion; pump/fastener corrosion	Corrosion in BoP; seals/valves degrade; leak risk increases
Air quality pollutants (SOx/NOx, industrial VOCs)	Industrial zones, ports, near refineries	Material degradation, sensor drift, corrosion acceleration	Corrosion/contamination at electronics; filters load faster	Membrane/electrode poisoning (chemistry-dependent); corrosion	Catalyst poisoning relevant if H_2 conversion devices used; BoP materials degrade
Altitude / low air density	Mountain wind farms, high plateaus	Cooling effectiveness reduced; different pressure regimes	Air-cooling derates; higher cell temps under same load	Heat exchangers less effective; pump curve changes	Compressor performance shifts; pressure control differences

Table 1 highlights the significant role that climatic and environmental factors play in influencing the operational performance, efficiency, and longevity of energy storage systems integrated with renewable energy sources. Among these factors, ambient temperature emerges as one of the most critical determinants of storage performance. High temperatures, commonly experienced in desert and hot-climate regions, accelerate electrochemical reactions within lithium-ion batteries, which can lead to increased degradation rates, capacity fading, and potential safety risks such as thermal runaway. Although elevated temperatures may temporarily enhance electrochemical kinetics, the long-term impact is typically negative due to faster aging of battery components. In contrast, low temperatures reduce charge acceptance and power output by increasing internal resistance and slowing ion transport within the electrolyte. Consequently, both high and low temperature conditions require appropriate thermal management systems to ensure stable ESS operation.

Another important environmental variable identified in the table is humidity and moisture exposure, particularly in coastal or humid regions. High humidity levels can cause corrosion of electrical connectors, busbars, and control components, potentially reducing insulation resistance and system reliability. In lithium-ion battery systems, moisture ingress may also lead to electrolyte degradation and safety risks. Similarly, flow battery systems may experience corrosion in pipelines and structural components, while hydrogen storage systems may face additional operational complexities related to moisture management in associated equipment such as compressors and fuel cells. These findings highlight the importance of sealed enclosures, corrosion-resistant materials, and environmental control systems for maintaining the durability of energy storage infrastructure.

Table 1 also indicates that dust accumulation and particulate matter, which are common in arid and semi-arid regions, can significantly affect ESS performance. Dust deposition can block ventilation systems and cooling pathways, reducing heat dissipation efficiency and increasing operating temperatures within battery modules. This can accelerate thermal stress and shorten the operational lifespan of lithium-ion batteries. In flow battery installations, abrasive particles may contribute to mechanical wear in pumps and seals, while hydrogen storage systems may experience clogging of filters and degradation of sensitive instrumentation. These impacts emphasize the need for effective filtration systems, regular maintenance schedules, and protective enclosures in dusty environments.

Finally, the table 1 demonstrates that extreme weather events, including heatwaves, storms, flooding, and strong winds, pose additional risks to the stability and resilience of energy storage systems. Prolonged heatwaves can lead to system derating and increased cooling demand, while flooding and severe storms may cause water ingress, electrical faults, or structural damage to storage facilities. Such conditions can result in temporary shutdowns or permanent system failures if adequate protective measures are not implemented. Therefore, resilient ESS design, incorporating elevated installations, weather-resistant enclosures, and robust monitoring systems is essential for ensuring continuous operation in diverse climatic conditions.

3. Environmental Footprint and Life Cycle Assessment of Energy Storage Technologies

Environmental sustainability has become a critical consideration in the deployment of energy storage systems (ESS) supporting renewable energy integration [51,52]. While ESS technologies such as lithium-ion batteries, flow batteries, and hydrogen storage systems enable higher penetration of intermittent renewable resources, their environmental implications extend beyond the operational phase. To fully understand these impacts, it is necessary to evaluate the entire life cycle of energy storage technologies, including raw material extraction, manufacturing, transportation, operation, and end-of-life management. Such comprehensive evaluation ensures that the environmental benefits achieved through renewable energy integration are not offset by hidden environmental costs associated with storage technologies [53,54]. Figure 1 illustrates the evaluate the entire life cycle of energy storage technologies. Total life-cycle environmental impact can be calculated by Eq. (1). Life-cycle carbon footprint can be calculated by Eq. (2). A practical full expression for life-cycle carbon footprint per delivered kWh can be formulated by Eq. (3).

$$EI_{total} = \sum_{i=1}^{n} A_i \times EF_i \quad (1)$$

Where:
EI_{total} = total environmental impact
A_i =activity data for process i
EF_i= emission or impact factor for process i
n= number of life-cycle processes

$$CF_{total} = CF_{raw} + CF_{man} + CF_{trans} + CF_{use} + CF_{eol} \quad (3)$$

Where:
CF_{total}= total carbon footprint (kg CO_2-eq)
CF_{raw} = emissions from raw material extraction
CF_{man} = emissions from manufacturing
CF_{trans}= emissions from transportation
CF_{use}= emissions during operation/use phase
CF_{eol}= emissions from end-of-life treatment or disposal

$$CF_{kWh} = \frac{CF_{raw} + CF_{man} + CF_{trans} + CF_{use} + CF_{eol} + CF_{recycling\ credit}}{E_{cap} \times \mathrm{DoD} \times \eta_{rt} \times \mathrm{N}_{cycles}} \quad (3)$$

Where:
E_{cap} = nominal storage capacity (kWh)
DoD = depth of discharge
η_{rt} = round − trip efficiency
N_{cycles} =number of lifetime cycles

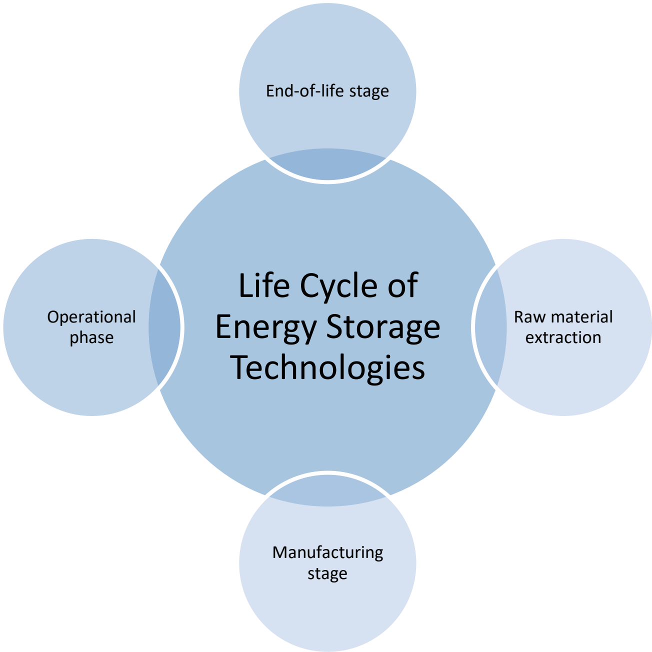

Figure 1. Evaluate the entire life cycle of energy storage technologies.

The raw material extraction phase represents one of the most environmentally sensitive stages in the life cycle of many energy storage technologies. For example, lithium-ion batteries rely on critical minerals such as lithium, cobalt, nickel, and graphite, which are often extracted through mining activities that may lead to land degradation, water contamination, and high energy consumption. Similarly, vanadium used in certain flow batteries and metals used in hydrogen storage infrastructure require resource-intensive extraction processes [55,56]. These activities can contribute to ecological disruption and resource depletion, emphasizing the importance of sustainable mining practices and the development of alternative materials with lower environmental impact.

The manufacturing stage also contributes significantly to the environmental footprint of energy storage systems. Battery cell production, electrode fabrication, electrolyte preparation, and system assembly require substantial energy input, often derived from fossil fuel sources. As a result, the production phase may generate considerable greenhouse gas emissions and industrial waste. In addition, the complexity of advanced battery chemistries and hydrogen storage technologies can increase manufacturing energy intensity [57-60]. Therefore, improving manufacturing efficiency, adopting cleaner production technologies, and integrating renewable energy into industrial processes are essential strategies for reducing the environmental burden associated with ESS production.

During the operational phase, energy storage systems generally provide environmental benefits by enabling more efficient integration of renewable energy sources and reducing reliance on fossil-fuel-based generation. ESS technologies facilitate energy balancing, load shifting, and grid stability, which can lead to significant reductions in greenhouse gas emissions and air pollutants at the system level. However, operational impacts still exist, including energy losses during charging and discharging cycles, cooling requirements, and maintenance activities [61,62]. These factors influence the overall environmental performance of storage technologies and should be considered when assessing their long-term sustainability.

Finally, the end-of-life stage, including disposal, reuse, and recycling, plays a crucial role in determining the overall environmental footprint of energy storage systems. Improper disposal of battery components may lead to soil and water contamination due to hazardous materials such as heavy metals and electrolytes. Conversely, effective recycling processes can recover valuable materials such as lithium, cobalt, and nickel, reducing the need for new resource extraction and minimizing environmental impacts. Life Cycle Assessment (LCA) methodologies provide a systematic framework for quantifying environmental indicators such as greenhouse gas emissions, energy consumption, resource depletion, and ecological toxicity across all life-cycle stages [63,64]. Through LCA-based comparisons, policymakers and engineers can identify the most environmentally sustainable energy storage technologies and guide future developments toward greener renewable energy systems.

4. Ecological Risks and Resource Sustainability in Energy Storage Materials

The rapid expansion of renewable energy systems has significantly increased the deployment of energy storage technologies, which play a critical role in enhancing grid stability, improving energy reliability, and enabling the large-scale integration of intermittent energy sources such as solar and wind power. However, the growing demand for energy storage systems has intensified the extraction and utilization of various critical materials, including lithium, cobalt, nickel, vanadium, and rare earth elements. While these materials enable high energy density and improved storage performance, their extraction, processing, and disposal can generate substantial ecological and environmental risks. Mining activities associated with these resources often lead to land degradation, water contamination, habitat destruction, and increased greenhouse gas emissions, raising concerns about the long-term environmental sustainability of energy storage technologies [65,66].

In addition to environmental impacts from raw material extraction, resource availability and supply chain sustainability have become important challenges for the global energy transition. Many of the materials used in advanced energy storage systems are geographically concentrated and subject to geopolitical, economic, and ethical concerns, which may affect long-term supply stability. Furthermore, improper disposal or leakage of storage components can result in environmental contamination and ecological damage. Consequently, there is increasing interest in developing alternative storage technologies and materials, such as sodium-ion batteries, solid-state batteries, and green hydrogen storage systems, which may offer reduced environmental risks while maintaining high performance and reliability [67,68]. Evaluating the ecological implications and resource sustainability of storage materials is therefore essential for guiding the development of more environmentally responsible and resilient energy storage solutions. Table 2 outlines ecological risks and resource sustainability in energy storage materials.

Table 2. Ecological Risks and Resource Sustainability in Energy Storage Materials [68-76]

Material / Component	Common ESS Applications	Main Ecological Risks (Extraction & Processing)	Supply Chain Risks	End-of-Life / Contamination Risks	Mitigation Strategies	Emerging Alternatives
Lithium	Lithium-ion batteries, grid storage	Water depletion, land disturbance from mining	Geographical concentration of lithium resources	Electrolyte leakage and battery waste contamination	Recycling systems, responsible mining practices	Sodium-ion batteries, solid-state batteries
Cobalt	NMC/NCA lithium-ion batteries	Toxic mining waste, ecosystem damage	Ethical concerns and supply chain instability	Heavy metal contamination if improperly disposed	Low-cobalt battery chemistries and recycling	LFP batteries and cobalt-free cathodes
Nickel	High-energy lithium-ion batteries	Deforestation and pollution from mining	Refining concentrated in limited regions	Metal leaching from disposed battery materials	Cleaner refining processes and recycling	Manganese-rich or LFP battery chemistries
Vanadium	Vanadium redox flow batteries	Industrial waste and chemical contamination	Price volatility and limited producers	Electrolyte leakage affecting soil and water	Electrolyte recycling and improved containment	Iron-based flow batteries

Rare Earth Elements	Renewable system components and specialty storage technologies	Radioactive tailings and chemical processing waste	Geopolitical supply risk	Waste contamination from processing residues	Recycling and diversified supply sources	Alternative magnetic materials
Electrolytes & Chemical Solvents	Lithium-ion battery cells	Toxic and flammable chemicals	Transportation and storage hazards	Leakage and fire-related contamination	Safer electrolyte formulations and containment	Solid-state electrolytes
Hydrogen Storage Materials	Hydrogen tanks and energy storage systems	Energy-intensive steel and composite production	Supply chain dependence on specialized materials	Leakage risks and equipment disposal impacts	Low-carbon materials and leak detection systems	Green hydrogen storage technologies

The table 2 provides a comprehensive overview of the ecological risks and resource sustainability challenges associated with materials commonly used in energy storage technologies. Among these materials, lithium is one of the most widely used components in modern battery systems, particularly lithium-ion batteries deployed in grid storage and electric mobility applications. Although lithium extraction has enabled rapid advancements in energy storage capacity, mining activities, especially in lithium-rich brine regions can result in significant water consumption and ecosystem disturbances. As global demand for lithium continues to grow, concerns about resource availability and environmental degradation highlight the need for improved recycling processes and the development of alternative battery chemistries such as sodium-ion and solid-state batteries.

Cobalt is another critical material used in several lithium-ion battery chemistries due to its role in enhancing battery stability and energy density. However, cobalt mining has been associated with serious environmental and social challenges, including toxic waste generation, ecosystem disruption, and supply chain ethical issues in certain mining regions. These concerns have encouraged researchers and manufacturers to reduce cobalt content in battery cathodes and develop alternative chemistries such as lithium iron phosphate (LFP) batteries, which offer improved sustainability while maintaining acceptable performance characteristics for many energy storage applications.

Nickel and vanadium also play significant roles in energy storage systems, particularly in high-energy lithium-ion batteries and vanadium redox flow batteries. Nickel extraction and refining processes may contribute to deforestation, soil contamination, and greenhouse gas emissions, particularly when mining activities occur in environmentally sensitive regions. Similarly, although vanadium-based flow batteries are attractive for large-scale stationary storage due to their long cycle life and safety characteristics, vanadium mining and processing can generate industrial waste and chemical pollution if not properly managed.

The table 2 also highlights the environmental implications associated with rare earth elements, electrolytes, and hydrogen storage materials, which are essential components of emerging energy storage and renewable energy technologies. Rare earth extraction and separation processes often generate radioactive tailings and chemical waste, raising concerns about environmental contamination. In lithium-ion batteries, electrolytes and chemical solvents may pose toxicity and flammability risks if leakage or improper disposal occurs. Similarly, hydrogen storage technologies require specialized materials and infrastructure whose production may involve significant energy consumption. Therefore, improving materials management, strengthening recycling frameworks, and adopting cleaner manufacturing processes are essential strategies for reducing environmental risks.

Overall, the analysis presented in the table demonstrates that achieving a sustainable energy transition requires not only the deployment of renewable energy technologies, but also careful consideration of the environmental footprint and resource sustainability of the materials used in energy storage systems. Advances in alternative technologies—including sodium-ion batteries, solid-state batteries, and green hydrogen storage offer promising pathways for reducing dependence on environmentally sensitive materials while maintaining high energy storage performance. By integrating responsible resource management, technological innovation, and circular economy strategies, the energy sector can enhance the ecological sustainability of future energy storage solutions.

5. Environmental Benefits of Energy Storage in Renewable-Dominated Power Systems

The rapid transition toward low-carbon energy systems has significantly increased the deployment of renewable energy sources, particularly solar and wind power. However, the intermittent and variable nature of these resources presents operational challenges for modern power systems, including supply–demand mismatches, grid instability, and increased reliance on fossil-fuel-based backup generation. In this context, energy storage systems (ESS) have emerged as a critical enabling technology for renewable-dominated power systems. By storing excess renewable electricity and delivering it when needed, ESS improves grid flexibility, supports frequency regulation, and enhances the reliability of electricity supply. Figure 2 highlights environmental benefits of energy storage in renewable-dominated power systems.

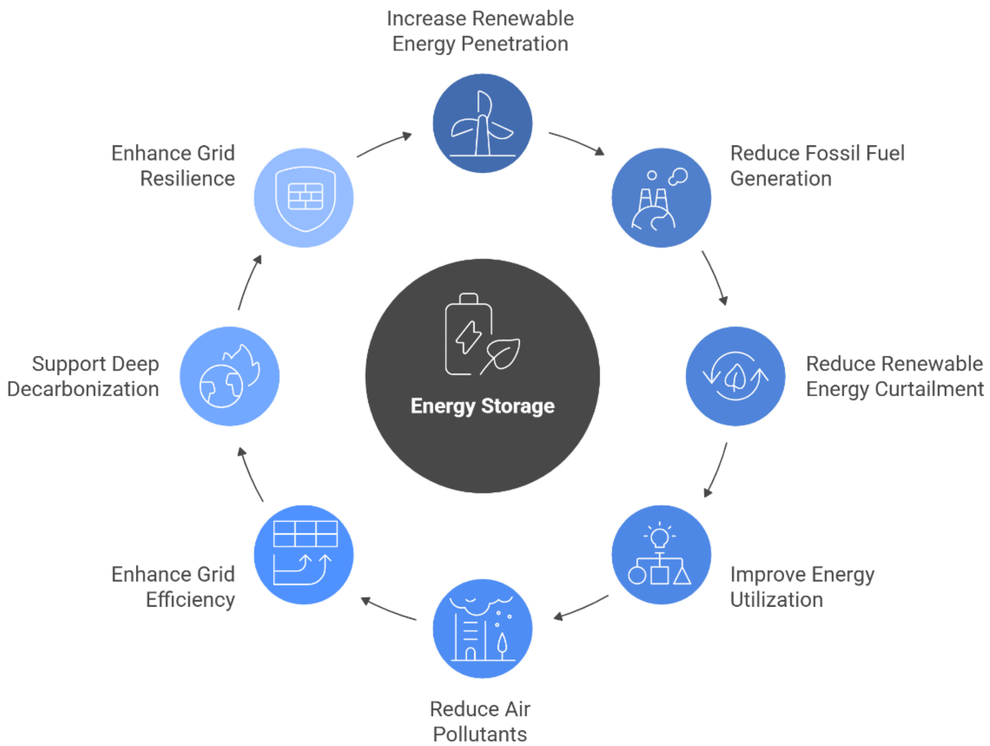

Figure 2. Environmental Benefits of Energy Storage in Renewable-Dominated Power Systems

Beyond their technical benefits, energy storage technologies play an essential role in promoting environmental sustainability and decarbonization. By reducing renewable energy curtailment, decreasing dependence on carbon-intensive power plants, and improving overall system efficiency, ESS integration can significantly lower greenhouse gas emissions and air pollutants. Furthermore, energy storage facilitates sector coupling strategies such as electric mobility, hydrogen production, and electrified heating, which contribute to broader climate mitigation goals. Therefore, evaluating the environmental benefits of energy storage in renewable-dominated power systems is essential for understanding its role in supporting sustainable energy transitions and achieving global decarbonization targets.

A. Increasing Renewable Energy Penetration and Reducing Fossil Fuel Generation

Energy storage systems (ESS) enable higher integration of intermittent renewable energy sources such as solar photovoltaic (PV) and wind by storing excess electricity and releasing it during periods of low generation or high demand. In renewable-dominated grids, storage can increase renewable penetration levels from typical values of 30–40% to more than 60–80% without compromising grid stability. For example, integrating 1 GWh of battery energy storage in a solar-dominated grid can offset approximately 0.6–0.8 TWh of fossil-fuel-based electricity annually, depending on system utilization. This can lead to reductions of approximately 300–500 thousand tons of CO_2 emissions per year, assuming average emission factors of 0.4–0.7 tCO_2/MWh for fossil fuel power plants.

B. Reducing Renewable Energy Curtailment and Improving Energy Utilization

In high-renewable systems, excess electricity production during peak generation hours often leads to curtailment due to limited grid flexibility or demand mismatches. Energy storage systems can capture this surplus energy and supply it during evening or nighttime demand peaks. Studies show that ESS integration can reduce renewable energy curtailment by 40–70%, depending on storage capacity and grid configuration. For example, in a 100 MW solar farm, installing a 50 MW / 200 MWh battery storage system can recover up to 15–25% of otherwise curtailed solar energy, significantly improving overall renewable energy utilization and reducing reliance on fossil backup generation.

C. Reduction of Air Pollutants and Improvement of Environmental Quality

By replacing fossil-fuel-based peak power plants, energy storage can significantly reduce emissions of harmful air pollutants such as nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulate matter ($PM_{2.5}$). Conventional peaker plants typically emit around 1.5–3.0 kg of NO_x per MWh and 0.5–1.0 kg of SO_2 per MWh, depending on fuel type and combustion technology. When energy storage replaces 1000 MWh of peak fossil generation, emissions reductions may include approximately 1500–3000 kg of NO_x and 500–1000 kg of SO_2 annually, in addition to significant reductions in CO_2 emissions. These reductions contribute to improved air quality, reduced environmental degradation, and enhanced public health outcomes.

D. Improved Grid Efficiency and Reduced System Energy Losses

Energy storage systems contribute to improved grid efficiency by providing frequency regulation, voltage support, load leveling, and peak shaving services. Without storage, power systems often rely on thermal power plants operating in part-load conditions, where efficiency can drop from 55–60% to around 35–40%. ESS can reduce the need for inefficient ramping and cycling of fossil plants, lowering overall fuel consumption. In addition, storage can help reduce transmission and distribution losses, which typically account for 6–8% of total electricity generation globally. Strategic placement of ESS near demand centers can reduce these losses by 1–3%, improving overall system efficiency.

E. Supporting Deep Decarbonization and Sector Coupling

Energy storage plays a critical role in enabling deep decarbonization pathways by supporting sector coupling strategies such as power-to-hydrogen, electric vehicle charging, and electrified heating systems. For example, excess renewable electricity stored in batteries or converted into green hydrogen can be used to decarbonize industrial processes and transportation sectors. In integrated energy systems, hydrogen production through electrolysis powered by renewable energy can achieve emission reductions of 8–10 kg CO_2 per kg of hydrogen compared to conventional fossil-based hydrogen production (steam methane reforming). Such integration enhances overall system flexibility and supports national and global net-zero emission targets by 2050.

F. Enhancing Grid Resilience and Avoiding Carbon-Intensive Backup Generation

Energy storage systems significantly enhance grid resilience by providing fast-response power support during outages, renewable variability, and extreme weather events. ESS technologies can respond within milliseconds to seconds, compared to several minutes required for conventional gas or diesel generators to ramp up. By reducing dependence on emergency fossil-fuel-based generators, ESS can prevent substantial emissions during grid disturbances. For example, replacing 50 MW of diesel backup generation operating 500 hours per year with battery storage could avoid approximately 20,000–30,000 tons of CO_2 emissions annually, while also reducing fuel consumption, noise pollution, and local air contaminants.

Energy storage systems represent a fundamental component of modern renewable energy infrastructures, enabling higher penetration of solar and wind power while enhancing grid stability and operational efficiency. The integration of ESS can significantly reduce renewable energy curtailment, improve energy utilization, and minimize reliance on fossil-fuel-based peaking plants. As a result, large-scale deployment of energy storage technologies can contribute to substantial reductions in greenhouse gas emissions, air pollutants, and overall system energy losses, thereby improving both environmental quality and energy system sustainability. Moreover, energy storage technologies support the broader objectives of global decarbonization by enabling sector coupling, facilitating clean hydrogen production, and enhancing grid resilience against variability and extreme conditions. As renewable energy penetration continues to increase worldwide, the strategic deployment of energy storage systems will be essential for achieving net-zero emission targets and building sustainable, reliable, and low-carbon energy systems. Continued technological innovation, supportive policy frameworks, and integrated energy planning will further strengthen the environmental and economic benefits of energy storage in future power systems.

6. Conclusion

This study investigated the environmental impacts of energy storage systems (ESS) integrated with renewable energy technologies through four key research perspectives: the influence of climatic conditions on storage performance, the life cycle environmental footprint of storage technologies, the ecological risks associated with storage materials, and the environmental benefits of ESS in renewable-dominated power systems. The study highlights that environmental conditions such as temperature fluctuations, humidity, dust accumulation, and extreme weather events significantly influence the operational efficiency, degradation rates, and reliability of storage technologies including lithium-ion batteries, flow batteries, and hydrogen storage systems. Environmental stresses are particularly critical in regions characterized by hot and arid climates, where renewable energy deployment is rapidly expanding, and appropriate thermal management and environmental protection strategies are required to ensure long-term system performance.

Evaluation of life cycle environmental impacts demonstrates that sustainability of energy storage technologies must be assessed beyond operational benefits. Extraction of critical materials, energy-intensive manufacturing processes, transportation activities, and end-of-life management contribute to the overall environmental footprint of ESS technologies. Life Cycle Assessment (LCA) provides an effective framework for quantifying environmental indicators including greenhouse gas emissions, energy consumption, resource depletion, and ecological toxicity. Results emphasize the importance of adopting cleaner manufacturing practices, improving recycling technologies, and promoting circular economy strategies in order to reduce the environmental burden associated with energy storage systems.

The study also highlights ecological risks and resource sustainability challenges related to materials used in advanced energy storage technologies. Critical minerals such as lithium, cobalt, nickel, vanadium, and rare earth elements play essential roles in modern battery and storage systems, yet extraction and processing activities may lead to environmental degradation, water pollution, and supply chain vulnerabilities. Addressing such challenges requires responsible mining practices, improved resource management, and expanded recycling infrastructure. Emerging technologies such as sodium-ion batteries, solid-state batteries, and green hydrogen storage systems present promising alternatives that may reduce reliance on environmentally sensitive materials while maintaining high energy storage performance.

Integration of energy storage systems provides substantial environmental benefits in renewable-dominated power systems. Mitigation of solar and wind intermittency through ESS deployment reduces renewable energy curtailment, improves grid stability, and decreases dependence on fossil-fuel-based backup generation. Such capabilities contribute to measurable reductions in greenhouse gas emissions, air pollutants, and system-level energy losses, supporting the transition toward low-carbon and sustainable energy systems. Overall findings indicate that energy storage systems represent a fundamental component of the global energy transition, yet environmental implications require careful management through sustainable material sourcing, improved technology design, and comprehensive policy frameworks. Implementation of integrated strategies will ensure that energy storage technologies effectively support global decarbonization objectives and development of resilient, environmentally sustainable power systems.

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References

[1] A. Panesar and O. Sampson, "Environmental impact of energy storage technologies and future renewable grids," *J. Energy Storage*, vol. 152, no. 120501, p. 120501, 2026.

[2] Y. F. Nassar *et al.*, "Carbon footprint and energy life cycle assessment of wind energy industry in Libya," *Energy Convers. Manag.*, vol. 300, no. 117846, p. 117846, 2024.

[3] A. Stoppato, A. Benato, and F. De Vanna, "Environmental impact of energy systems integrated with electrochemical accumulators and powered by renewable energy sources in a life-cycle perspective," *Appl. Sci. (Basel)*, vol. 11, no. 6, p. 2770, 2021.

[4] Y. F. Nassar *et al.*, "Assessing the viability of solar and wind energy technologies in semi-arid and arid regions: A case study of Libya's climatic conditions," *Appl. Sol. Energy*, vol. 60, no. 1, pp. 149–170, 2024.

[5] S. Ould Amrouche, D. Rekioua, T. Rekioua, and S. Bacha, "Overview of energy storage in renewable energy systems," *Int. J. Hydrogen Energy*, vol. 41, no. 45, pp. 20914–20927, 2016.

[6] M. Yekini Suberu, M. Wazir Mustafa, and N. Bashir, "Energy storage systems for renewable energy power sector integration and mitigation of intermittency," *Renew. Sustain. Energy Rev.*, vol. 35, pp. 499–514, 2014.

[7] M. Farghali *et al.*, "Social, environmental, and economic consequences of integrating renewable energies in the electricity sector: a review," *Environ. Chem. Lett.*, vol. 21, no. 3, pp. 1381–1418, 2023.

[8] I. Imbayah, M. Khaleel, and Z. Yusupov, "Optimization of Hybrid Renewable Energy Systems: Classical optimization methods, artificial intelligence, recent trend, and software tools," *ijees*, vol. 3, no. 4, pp. 47–69, 2025.

[9] M. Khaleel, I. Imbayah, Y. Nassar, and H. J. El-Khozondar, "Renewable energy transition pathways and net-zero strategies," *ijees*, vol. 3, no. 4, pp. 01–16, 2025.

[10] M. A. Inweer *et al.*, "Carbon footprint life cycle assessment of cement industry in Libya," *Discov. Concr. Cem.*, vol. 1, no. 1, 2025.

[11] X. Zhang and F. Wang, "Life-cycle assessment and control measures for carbon emissions of typical buildings in China," *Build. Environ.*, vol. 86, pp. 89–97, 2015.

[12] B. G. Hermann, C. Kroeze, and W. Jawjit, "Assessing environmental performance by combining life cycle assessment, multi-criteria analysis and environmental performance indicators," *J. Clean. Prod.*, vol. 15, no. 18, pp. 1787–1796, 2007.

[13] A. F. Abd Rashid and S. Yusoff, "A review of life cycle assessment method for building industry," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 244–248, 2015.

[14] N.-W. Kuo and P.-H. Chen, "Quantifying energy use, carbon dioxide emission, and other environmental loads from island tourism based on a life cycle assessment approach," *J. Clean. Prod.*, vol. 17, no. 15, pp. 1324–1330, 2009.

[15] R. S. Srinivasan, W. Ingwersen, C. Trucco, R. Ries, and D. Campbell, “Comparison of energy-based indicators used in life cycle assessment tools for buildings,” *Build. Environ.*, vol. 79, pp. 138–151, 2014.

[16] N. Bani Khalifi, D. D. Avgoustaki, and T. Bartzanas, “Integrating life cycle assessment into green infrastructure: a systematic review and meta-analysis of urban sustainability strategies,” *Front. Sustain. Cities*, vol. 7, no. 1601091, 2025.

[17] N. Akhtar, A. F. Ismail, M. Mohd Hanafiah, S. Mohd Fadzil, and S. Park, “Evaluating environmental impacts of thorium extraction: A comparative study of solvent and electrosorption technologies using life cycle assessment (LCA),” *Clean. Eng. Technol.*, vol. 26, no. 100960, p. 100960, 2025.

[18] C. Bordin *et al.*, “Energy storage in the energy transition and blue economy: challenges, innovations, future perspectives, and educational pathways,” *Discov. Appl. Sci.*, vol. 7, no. 10, 2025.

[19] A. F. M. Fahad Halim, G. E. J. Poinern, D. Fawcett, R. Sharma, S. Surendran, and Rajeshkannan, “Biomass-derived carbon nanomaterials: Synthesis and applications in textile wastewater treatment, sensors, energy storage, and conversion technologies,” *CleanMat*, vol. 2, no. 1, pp. 4–58, 2025.

[20] S. A. Hosseini, V. Asghari, X. Liu, S.-C. Hsu, and C.-S. Poon, “Cross-country life cycle assessment of construction and demolition waste recycling with evaluation of energy use, carbon emissions, and regional trade-offs,” *Sci. Rep.*, vol. 15, no. 1, p. 41377, 2025.

[21] M. M. Khaleel, T. Mohamed Ghandoori, A. Ali Ahmed, A. Alsharif, A. J. Ahmed Alnagrat, and A. Ali Abulifa, “Impact of mechanical storage system technologies: A powerful combination to empowered the electrical grids application,” in *2022 IEEE 2nd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2022.

[22] M. Khaleel, Z. Yusupov, and S. Rekik, “Advancing hydrogen as a key driver for decarbonized power systems,” *Unconventional Resources*, vol. 9, no. 100278, p. 100278, 2026.

[23] M. Khaleel and Z. Yusupov, “Advancing sustainable energy transitions: Insights on finance, policy, infrastructure, and demand-side integration,” *Unconventional Resources*, vol. 9, no. 100274, p. 100274, 2026.

[24] M. Mohamad and A. Hesri, “Hydrogen storage methods: Opportunities, safety, risk, and compliance assessment,” *ijees*, vol. 3, no. 4, pp. 17–32, 2025.

[25] M. Khaleel and A. Hesri, “Improving power system reliability using hydrogen fuel cell–integrated D-FACTS for power quality enhancement,” *ljsdr*, vol. 1, no. 1, pp. 01–16, 2025.

[26] K. Shafiei, A. Seifi, and M. T. Hagh, “A novel multi-objective optimization approach for resilience enhancement considering integrated energy systems with renewable energy, energy storage, energy sharing, and demand-side management,” *J. Energy Storage*, vol. 115, no. 115966, p. 115966, 2025.

[27] M. U. Aslam, M. S. Miah, B. M. R. Amin, R. Shah, and N. Amjady, “Application of energy storage systems to enhance power system resilience: A critical review,” *Energies*, vol. 18, no. 14, p. 3883, 2025.

[28] V. R. Chowdary, S. Gope, S. Dawn, M. M. Islam, and T. S. Ustun, “Economic sustainability enhancement by the integration of renewable energy in a deregulated system: A study,” *Energy Explor. Exploit.*, vol. 43, no. 2, pp. 865–905, 2025.

[29] D. Ochoa-Correa, P. Arévalo, and S. Martinez, “Pathways to 100% renewable energy in island systems: A systematic review of challenges, solutions strategies, and success cases,” *Technologies (Basel)*, vol. 13, no. 5, p. 180, 2025.

[30] O. S. Abualoyoun and A. A. Amar, “Toward achieving net-zero in the evolution of the global energy sector,” *ijees*, vol. 3, no. 1, pp. 143–156, 2025.

[31] B. Ahmed, Y. Nassar, H. El-Khozondar, and M. Khaleel, “Optimal design of hybrid renewable energy system (PV/wind/PHS) under multiple constraints of connection to the electricity grid: A case study,” *waujpas*, pp. 83–93, 2026.

[32] M. Elmnifi *et al.*, “Solar and wind energy generation systems with pumped hydro energy storage: City of Derna,” in *Environmental Science and Engineering*, Cham: Springer Nature Switzerland, 2025, pp. 209–226.

[33] Y. F. Nassar *et al.*, “Sensitivity of global solar irradiance to transposition models: Assessing risks associated with model discrepancies,” *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 11, no. 100887, p. 100887, 2025.

[34] M. Khaleel *et al.*, “Emerging issues and challenges in integrating of solar and wind,” *ijees*, vol. 2, no. 4, pp. 1–11, 2024.

[35] M. Elmnifi *et al.*, “Design of an innovative wastewater treatment system using photovoltaic-hydro system coupled with reverse osmosis technology: Sustainability and continuous improvement,” in *Environmental Science and Engineering*, Cham: Springer Nature Switzerland, 2025, pp. 137–157.

[36] M. Khaleel, Z. Yusupov, and S. Rekik, “Exploring trends and predictions in renewable energy generation,” *Energy 360*, vol. 4, no. 100030, p. 100030, 2025.

[37] M. Khaleel, Z. Yusupov, A. Ahmed, A. Alsharif, Y. Nassar, and H. El-Khozondar, “Towards sustainable renewable energy,” *Appl. Sol. Energy*, vol. 59, no. 4, pp. 557–567, 2023.

[38] S. Abdulwahab, Y. F. Nassar, H. J. El-Khozondar, M. Khaleel, A. A. Ahmed, and A. Alsharif, “Meeting solar energy demands: Significance of transposition models for solar irradiance,” *ijees*, vol. 1, no. 3, pp. 90–105, 2023.

[39] F. Alasali, A. S. Saidi, N. El-Naily, O. Alsmadi, M. Khaleel, and I. Ghirani, “Assessment of the impact of a 10-MW grid-tied solar system on the Libyan grid in terms of the power-protection system stability,” *Clean Energy*, vol. 7, no. 2, pp. 389–407, 2023.

[40] K. Zhang, J. Mo, Z. Liu, W. Yin, F. Wu, and J. You, “Life cycle environmental and economic impacts of various energy storage systems: eco-efficiency analysis and potential for sustainable deployments,” *Integr. Environ. Assess. Manag.*, vol. 22, no. 1, pp. 289–302, 2026.

[41] M. Arbabzadeh, J. X. Johnson, and G. A. Keoleian, “Parameters driving environmental performance of energy storage systems across grid applications,” *J. Energy Storage*, vol. 12, pp. 11–28, 2017.

[42] S. Yazdani, M. Deymi-Dashtebayaz, and E. Salimipour, “Comprehensive comparison on the ecological performance and environmental sustainability of three energy storage systems employed for a wind farm by using an emergy analysis,” *Energy Convers. Manag.*, vol. 191, pp. 1–11, 2019.

[43] A. Jahanbin, L. Abdolmaleki, and U. Berardi, “Cross-climate analysis of techno-economic metrics in bi-level electrical and hydrogen storage systems for off-grid electrification of buildings,” *J. Energy Storage*, vol. 107, no. 114938, p. 114938, 2025.

[44] M. Khaleel, Z. Yusupov, N. Yasser, H. Elkhozondar, and A. A. Ahmed, “An integrated PV farm to the unified power flow controller for electrical power system stability,” *ijees*, vol. 1, no. 1, pp. 18–30, 2023.

[45] M. M. Rahman, S. Imani, N. Anjum, A. A. Sijuade, and O. Okoli, “Materials and design strategies for next-generation energy storage: A review,” *Renew. Sustain. Energy Rev.*, vol. 212, no. 115368, p. 115368, 2025.

[46] M. Khaleel, Z. Yusupov, Y. Nassar, H. J. El-khozondar, A. Ahmed, and A. Alsharif, “Technical challenges and optimization of superconducting magnetic energy storage in electrical power systems,” *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 5, no. 100223, p. 100223, 2023.

[47] M. Andeef, Y. F. Nassar, H. Awad, H. J. El-Khozondar, and M. Khaleel, "Transitioning to solar fuel instead of fossil fuel in the electricity industry," *ijees*, vol. 1, no. 4, pp. 32–46, 2023.

[48] Y. Nassar and M. Khaleel, "Sustainable development and the surge in electricity demand across emerging economies," *ijees*, vol. 2, no. 1, pp. 51–60, 2024.

[49] J. Liu, Z. Liu, Y. Wu, X. Chen, H. Xiao, and L. Zhang, "Impact of climate on photovoltaic battery energy storage system optimization," *Renew. Energy*, vol. 191, pp. 625–638, 2022.

[50] Y. Shang, Y. Huang, L. Li, F. Wu, and R. Chen, "Electrochemical energy storage toward extreme conditions: Driving human exploration beyond current boundaries," *Chem. Rev.*, vol. 125, no. 12, pp. 5674–5744, 2025.

[51] T. Fan, W. Liang, W. Guo, T. Feng, and W. Li, "Life cycle assessment of electric vehicles' lithium-ion batteries reused for energy storage," *J. Energy Storage*, vol. 71, no. 108126, p. 108126, 2023.

[52] X. Han *et al.*, "Comparative life cycle greenhouse gas emissions assessment of battery energy storage technologies for grid applications," *J. Clean. Prod.*, vol. 392, no. 136251, p. 136251, 2023.

[53] M. Khaleel, Z. Yusupov, M. Elmnifi, T. Elmenfy, Z. Rajab, and M. Elbar, "Assessing the financial impact and mitigation methods for voltage sag in power grid," *ijees*, vol. 1, no. 3, pp. 10–26, 2023.

[54] A. Lin and G. Bagnato, "Revolutionising energy storage: The Latest Breakthrough in liquid organic hydrogen carriers," *Int. J. Hydrogen Energy*, vol. 63, pp. 315–329, 2024.

[55] M. Gutsch and J. Leker, "Global warming potential of lithium-ion battery energy storage systems: A review," *J. Energy Storage*, vol. 52, no. 105030, p. 105030, 2022.

[56] I. Imbayah, M. Hasan, H. El-Khozondare, M. Khaleel, A. Alsharif, and A. Ahmed, "Review paper on green hydrogen production, storage, and utilization techniques in Libya," *jsesd*, vol. 13, no. 1, pp. 1–21, 2024.

[57] P. Wang, Q. Li, S. Wang, T. Xiao, and C. Wu, "Thermo-economic and life cycle assessment of pumped thermal electricity storage systems with integrated solar energy contemplating distinct working fluids," *Energy Convers. Manag.*, vol. 318, no. 118895, p. 118895, 2024.

[58] M. Khaleel, Z. Yusupov, M. Guneser, H. El-Khozondar, A. Ahmed, and A. A. Alsharif, "Towards hydrogen sector investments for achieving sustainable electricity generation," *jsesd*, vol. 13, no. 1, pp. 71–96, 2024.

[59] K. Jia, C. Liu, S. Li, and D. Jiang, "Modeling and optimization of a hybrid renewable energy system integrated with gas turbine and energy storage," *Energy Convers. Manag.*, vol. 279, no. 116763, p. 116763, 2023.

[60] A. Alsharif *et al.*, "Applications of solar energy technologies in north Africa: Current practices and future prospects," *ijees*, vol. 1, no. 3, pp. 164–173, 2023.

[61] M. Khaleel *et al.*, "An optimization approaches and control strategies of hydrogen fuel cell systems in EDG-integration based on DVR technology," *J. Eur. Syst. Autom.*, vol. 57, no. 2, pp. 551–565, 2024.

[62] S. Kapila, A. O. Oni, E. D. Gemechu, and A. Kumar, "Development of net energy ratios and life cycle greenhouse gas emissions of large-scale mechanical energy storage systems," *Energy (Oxf.)*, vol. 170, pp. 592–603, 2019.

[63] Y. Ren, Z. Ren, G. Zou, P. Zhang, X. Xu, and Y. Xiao, "Multi-objective optimization of capacity configuration for district heating and cooling system based on life cycle cost and annual carbon dioxide emissions," *J. Build. Eng.*, vol. 109, no. 113038, p. 113038, 2025.

[64] M. Khaleel *et al.*, "The impact of SMES integration on the power grid: Current topologies and nonlinear control strategies," in *New Technologies, Development and Application VII*, Cham: Springer Nature Switzerland, 2024, pp. 108–121.

[65] Y. Yi *et al.*, "Life cycle assessment of energy storage technologies for new power systems under dual-carbon target: A review," *Energy Technol. (Weinh.)*, vol. 12, no. 5, 2024.

[66] Y. Zhang, Q. S. Hua, L. Sun, and Q. Liu, "Life cycle optimization of renewable energy systems configuration with hybrid battery/hydrogen storage: A comparative study," *J. Energy Storage*, vol. 30, no. 101470, p. 101470, 2020.

[67] B. R. David, S. Spencer, J. Miller, S. Almahmoud, and H. Jouhara, “Comparative environmental life cycle assessment of conventional energy storage system and innovative thermal energy storage system,” *International Journal of Thermofluids*, vol. 12, no. 100116, p. 100116, 2021.

[68] A. Alsharif, E. Almabsout, A. A. Ahmed, M. Khaleel, Y. F. Nassar, and H. J. El-Khozoadar, “Optimal sizing of hybrid renewable system for residential appliances,” in *2024 IEEE 4th International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2024.

[69] M. Zarei, S. Rashidi, R. Rafee, and G. Li, “Effects of thermal energy storage and solar water preheater on the performance of cascade solar still - An experimental study,” *J. Energy Storage*, vol. 112, no. 115520, p. 115520, 2025.

[70] B. Nienborg *et al.*, “Life Cycle Assessment of thermal energy storage materials and components,” *Energy Procedia*, vol. 155, pp. 111–120, 2018.

[71] R. Dhivagar, S. Shoeibi, S. M. Parsa, S. Hoseinzadeh, H. Kargarsharifabad, and M. Khiadani, “Performance evaluation of solar still using energy storage biomaterial with porous surface: An experimental study and environmental analysis,” *Renew. Energy*, vol. 206, pp. 879–889, 2023.

[72] A. M. Makhzom *et al.*, “Carbon dioxide Life Cycle Assessment of the energy industry sector in Libya: A case study,” *ijees*, vol. 1, no. 3, pp. 145–163, 2023.

[73] M. Almamoori, M. Almaktar, M. Khaleel, F. Mohamed, and A. Elbreki, “Assessing STATCOM-enabled reactive power control in fragile power transmission systems: A case study perspective,” *Math. Model. Eng. Probl.*, vol. 11, no. 8, pp. 2019–2028, 2024.

[74] M. M. Khaleel, M. R. Adzman, S. M. Zali, M. M. Graisa, and A. A. Ahmed, “A review of fuel cell to distribution network interface using D-FACTS: Technical challenges and interconnection trends,” *Int. J. Electr. Electron. Eng. Telecommun.*, pp. 319–332, 2021.

[75] M. Mohamed, Wahab Shah, & Mohamed Amer. (2025). Concentration Dynamics in Solar PV Supply Chains: Lessons for Clean Energy Transitions. *Libyan Journal of Sustainable Development Research*, *1*(1), 52-60.

[76] Muftah Ali, & Mohamed Khaleel. (2025). Decarbonizing Buildings at Scale: Energy Codes, Innovation Pathways, and the Net-Zero Transition. *Libyan Journal of Sustainable Development Research*, *1*(1), 45-51.