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Review

# Integrated sustainable energy conversion and storage: Biomass feedstocks, catalytic pathways, electrochemical systems, and hybrid renewable architectures

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**Abstract:** The transition toward low-carbon energy systems requires not only efficient individual technologies but also their coherent integration across feedstock, conversion, storage, and system levels. This review presents a structured analysis of integrated sustainable energy conversion and storage systems, focusing on biomass feedstocks, catalytic pathways, electrochemical storage technologies, and hybrid renewable architectures. Literature published between 2015 and 2025 was critically evaluated using a targeted selection strategy to identify key performance trends, material limitations, and system-level bottlenecks. Quantitative comparisons indicate that biomass conversion efficiencies vary widely (30–75%) depending on lignin content and process conditions, while catalytic systems exhibit strong sensitivity to impurity levels and regeneration cycles. Among storage technologies, lithium–sulfur batteries demonstrate high theoretical energy densities (>400 Wh $kg^{-1}$), but face stability and lifecycle challenges, whereas alternative systems such as sodium–sulfur and flow batteries offer advantages in cost and scalability. Techno-economic indicators reveal that biomass-based energy systems typically exhibit levelized costs of energy in the range of 0.08–0.15 USD $kWh^{-1}$, while emerging storage technologies remain cost-sensitive due to material and system integration constraints. A key contribution of this work is the development of a multi-scale integration framework that connects resource characteristics, catalytic performance, storage behavior, and hybrid system design within a unified analytical structure. This framework highlights critical trade-offs, including the competition between biomass utilization for energy versus soil carbon sequestration and the water intensity of bio-hydrogen production (10–20 L $kWh^{-1}$). The review identifies major research gaps in system-level optimization, economic assessment, and cross-domain integration, providing actionable directions for advancing sustainable and resilient energy infrastructures.

**Keywords:** biomass valorization; catalysis; circular economy; energy storage; hybrid renewable systems; lithium-sulfur batteries; sustainable energy conversion; thermochemical conversion

## 1. Introduction

The accelerating demand for clean and reliable energy, coupled with the urgency of mitigating climate change, has intensified global efforts toward the development of low-carbon and sustainable energy systems. Technologies based on biomass conversion, catalytic transformation, electrochemical storage, and renewable hybridization have emerged as key pillars in this transition. However, despite significant progress in each of these domains, their development has largely occurred in isolation, limiting the realization of fully integrated and optimized energy systems [1–4].

Biomass represents a versatile and carbon-neutral feedstock capable of producing fuels, chemicals, and hydrogen through thermochemical and biochemical pathways. Recent studies further emphasize that biomass productivity and quality are increasingly influenced by climate variability, environmental stress, and resource management practices, which directly affect suitability for energy conversion systems [5–7]. Similarly, advances in catalytic materials have significantly improved conversion efficiencies and product selectivity. In parallel, electrochemical storage technologies particularly lithium-sulfur batteries have demonstrated promising energy densities, while hybrid renewable systems integrating photovoltaic, storage, and conversion units offer pathways for decentralized and resilient energy supply [8–10]. Nevertheless, these technologies face persistent challenges, including feedstock variability, catalyst deactivation, storage instability, and economic constraints, which are often addressed independently rather than within a unified framework [11,12].

A critical limitation in the existing literature is the fragmentation across resource, material, and system domains. Most studies focus on individual components such as biomass conversion, catalytic design, or battery performance without adequately capturing their interdependencies. In addition, key aspects such as techno-economic feasibility, resource competition (e.g., biomass utilization versus soil carbon sequestration), and water-energy interactions are often inconsistently quantified or overlooked. This lack of integration restricts the translation of laboratory scale advancements into scalable and deployable energy systems [13,14].

To address these challenges, the present review adopts an integrated perspective that bridges biomass feedstocks, catalytic pathways, electrochemical storage technologies, and hybrid renewable architectures within a unified analytical framework. Rather than providing a purely descriptive summary, this work emphasizes comparative analysis of performance metrics, cost indicators, and system-level trade-offs. In doing so, it aligns resource characteristics, material performance, and system behavior into a coherent structure.

The novelty of this study lies in three key contributions: (i) the development of a multi-scale integration framework linking resource, material, process, and system levels; (ii) the incorporation of quantitative comparisons across diverse technologies, including efficiency ranges, cost metrics, and resource intensities; and (iii) the identification of cross-domain bottlenecks and optimization opportunities that are not evident in isolated studies. By moving beyond component-level analysis, this review provides a structured basis for designing integrated, efficient, and economically viable sustainable energy systems.

Recent advances in integrated energy systems emphasize the convergence of biomass resources, catalytic processes, electrochemical storage, and digital optimization strategies. These interactions are illustrated schematically in **Figure 1**, which highlights the interconnected roles of feedstock selection, conversion pathways, storage technologies, and system-level optimization within the broader water-energy-environment nexus.

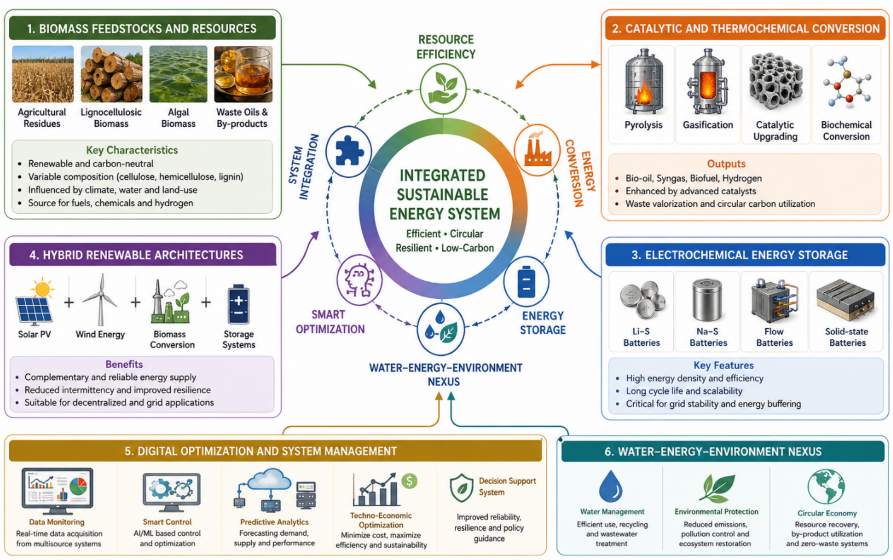


**Figure 1.** Integrated sustainable energy conversion and storage framework.

Note: **Figure 1** illustrates the interactions among biomass feedstocks, catalytic and thermochemical conversion processes, electrochemical storage systems, hybrid renewable architectures, and digital optimization within a circular and resource-efficient energy system.

The remainder of this paper is organized as follows. Section 2 describes the methodology and literature selection strategy. Section 3 examines biomass feedstocks and their role as a climate-resilient resource base. Subsequent sections analyze catalytic systems, energy storage technologies, and hybrid system integration, followed by techno-economic and water–energy–environment considerations, and concluding with future research directions.

Unlike previous reviews that treat biomass conversion, catalysis, and energy storage separately, this study uniquely integrates these domains into a unified resource-to-system framework with explicit inclusion of water-energy-environment constraints.

## 2. Methodology and literature selection strategy

To ensure a structured and reproducible analysis, this review adopts a semi-systematic literature selection approach, combining elements of systematic review methodology with critical qualitative assessment. The objective is to capture recent advancements while maintaining analytical depth across multiple domains of energy conversion and storage.

## 2.1. Data sources and search strategy

Relevant literature was collected from major scientific databases, including Scopus, Web of Science, and ScienceDirect. Searches were performed using combinations of keywords such as biomass conversion, catalytic upgrading, lithium-sulfur batteries, electrochemical energy storage, hybrid renewable systems and water-energy nexus, with Boolean operators applied to refine results and ensure cross-domain coverage

## 2.2. Time frame and scope

The review primarily focuses on studies published between 2015 and 2025 to capture recent technological advancements and emerging trends. Earlier foundational studies were included selectively to support conceptual development.

## 2.3. Inclusion and exclusion criteria

Studies were selected based on relevance to energy conversion, storage, and system integration, as well as the availability of quantitative performance metrics such as efficiency, capacity, and cost indicators. Only peer-reviewed publications with sufficient methodological detail were included, while studies lacking rigor or quantitative support were excluded.

## 2.4. Data extraction and analysis

Key parameters extracted from the literature include conversion efficiency, catalytic activity, energy density, lifecycle performance, and techno-economic indicators, such as CAPEX, OPEX, LCOE, and LCOS. A comparative analytical approach was applied to identify performance trends, trade-offs, and technological limitations across different systems.

## 2.5. Analytical framework

To address the fragmented nature of existing studies, a multi-scale analytical framework was developed to link four interconnected levels:

(i) Resource level (biomass characteristics),
(ii) Material level (catalysts and electrochemical components),
(iii) Process level (conversion and storage performance),
(iv) System level (hybrid integration and techno-economic behavior).

This framework enables the identification of cross-domain interactions and bottlenecks, providing a more coherent understanding of integrated energy systems.

## 2.6. Limitations

Variability in experimental conditions, reporting standards, and system boundaries across studies introduces uncertainty in direct comparisons. These limitations are addressed through range-based evaluation and critical interpretation rather than absolute benchmarking.

# 3. Biomass feedstocks, agricultural residues, and a climate-resilient resource base

Biomass is a key renewable resource for sustainable energy production due to its carbon-neutral nature and wide availability. However, its effective utilization depends strongly on feedstock composition, conversion pathways, and process optimization. Unlike fossil-based systems, biomass exhibits significant heterogeneity in terms of cellulose, hemicellulose, and lignin content, which directly influences conversion efficiency and product distribution [15,16]. This heterogeneity is further amplified by environmental and climatic factors, as variations in temperature, precipitation patterns, and soil conditions significantly influence biomass composition and yield [17,18].

Importantly, biomass should not be viewed as a static resource. Its availability, composition, and quality are strongly influenced by climatic variability, agricultural practices, and land-use dynamics. These factors define the practical limits of feedstock reliability and large-scale deployment, linking agronomic conditions directly to energy system performance [19, 20]. This transition is particularly important because it connects feedstock preparation, conversion efficiency, and storage performance within a unified sustainability framework [21,22].

## 3.1. Influence of biomass composition on conversion efficiency

The relative composition of biomass plays a critical role in determining thermochemical and biochemical conversion performance. In particular, lignin content has been widely reported to negatively impact pyrolysis and gasification efficiency due to its complex aromatic structure and resistance to thermal degradation. Additionally, plant physiological responses to environmental stress can alter lignocellulosic structure, further complicating conversion efficiency predictions [23,24]. Studies indicate that increasing lignin fraction can reduce conversion efficiency by up to 20–30%, while cellulose-rich feedstocks tend to yield higher bio-oil and syngas outputs under optimized conditions [25,26]. These findings highlight the need for feedstock-specific process optimization rather than generalized conversion strategies.

## 3.2. Conversion pathways and process selection

Biomass conversion pathways are broadly categorized into thermochemical processes (pyrolysis, gasification, combustion) and biochemical processes (anaerobic digestion, fermentation). Thermochemical routes provide higher reaction rates and product flexibility, while biochemical processes offer higher selectivity but are more sensitive to feedstock variability and operational conditions [27,28]. The selection of conversion pathways must therefore consider not only efficiency but also scalability, environmental impact, and compatibility with downstream catalytic and storage systems. To enable a structured comparison of major biomass conversion routes, key operating conditions, efficiency ranges, and limitations reported in the literature are summarized in **Table 1**.

**Table 1.** Comparative thermochemical and biochemical biomass conversion pathways with key operating conditions, efficiency ranges, and limiting factors influencing process performance and scalability in sustainable energy systems.

| Conversion pathway | Temperature (°C) | Efficiency (%) | Key limitation | Maturity level |
|---|---|---|---|---|
| Pyrolysis | 400–600 | 35–55 | Tar formation | Medium |
| Gasification | 700–1,000 | 45–65 | Feedstock variability | High |
| Combustion | 800–1,200 | 20–35 | Emissions | High |
| Anaerobic Digestion | 30–60 | 20–40 | Slow kinetics | High |
| Fermentation | 25–40 | 25–45 | Substrate sensitivity | Medium |

### 3.3. Resource trade-offs and sustainability considerations

A critical but often overlooked aspect of biomass utilization is the competition between its use for energy production and its role in soil carbon sequestration. For instance, biochar application and residue retention strategies have been shown to improve soil fertility and crop productivity under water-deficit conditions, highlighting the importance of balancing energy recovery with long-term soil health [29, 30]. Excessive removal of agricultural residues for energy applications can lead to soil degradation and reduced carbon storage capacity [31, 32]. This creates a fundamental trade-off between short-term energy gains and long-term ecosystem sustainability, which must be addressed through integrated resource management strategies [33, 34].

### 3.4. Transition toward residue-based and circular feedstocks

Recent research indicates a clear shift from dedicated energy crops toward residue-based and waste-derived biomass systems. Agricultural residues, lingo-cellulosic waste, algal biomass, and oil-rich by-products are increasingly recognized as sustainable feedstocks that minimize competition with food production while supporting circular resource utilization [35, 36]. Studies demonstrate the feasibility of converting residues and waste streams into fuels and value-added products [37,38]. This transition reflects a broader paradigm shift from fuel-from-crops toward energy and materials from residues and by-products.

### 3.5. Multi-functionality of biomass in energy systems

Biomass is increasingly recognized as a multifunctional resource extending beyond fuel production. For instance, biomass-derived materials such as biochar and charcoal can support thermal energy storage, soil enhancement, and carbon management. Applications such as phase-change heat storage systems and biochar-assisted soil conditioning demonstrate the integration of energy production with environmental benefits [39,40]. This multi-functionality enhances overall system efficiency and supports circular economy principles.

### 3.6. Water-energy-environment interactions

Water availability is a critical factor influencing biomass production and conversion. Irrigation practices, wastewater quality, and climate-induced hydrological variability directly affect biomass yield and composition. Changes in moisture content, fiber structure, and lignin fraction can influence pretreatment efficiency, catalytic behavior, and overall conversion performance [41, 42]. Therefore, biomass evaluation must extend beyond calorific value to include water-use efficiency, climate resilience, and land management considerations. **Figure 2** illustrates the effects of climate change, nitrogen fertilization, and land-use dynamics on crop yield, emissions, and biomass availability. The figure highlights trade-offs between food production, bioenergy generation (BECCS), and environmental sustainability within the water-energy-environment nexus [43,44].

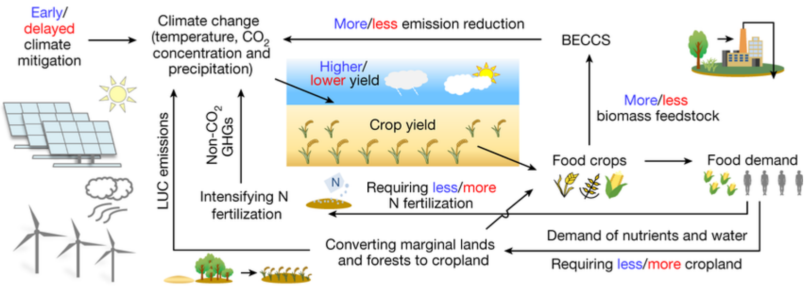


**Figure 2.** Climate-biomass-energy interaction framework.

Variations in biomass properties propagate through the entire energy system, influencing catalytic efficiency, storage integration, and techno-economic feasibility [45, 46]. Field-based studies confirm that biomass yield and structural composition are highly sensitive to ecological conditions and land-use practices, reinforcing the need for region-specific resource assessment in energy system design [47, 48]. Consequently, biomass should be treated as a dynamic and design-dependent component of integrated energy systems rather than a passive input resource.

Overall, the literature indicates a transition toward climate-resilient, residue-inclusive, and water-aware biomass systems. This evolving perspective is essential because the performance of downstream processes including catalytic conversion, electrochemical storage, and hybrid system optimization is fundamentally dependent on the stability and quality of the biomass resource entering the system [49,50].

## 4. Thermochemical and catalytic conversion pathways for sustainable fuels and functional energy materials

Following the establishment of a climate-resilient and composition dependent biomass resource base (Section 3), the next critical stage involves its efficient transformation into fuels, platform chemicals, and functional energy materials. This stage represents a key interface where feedstock variability, process design, and material performance converge. As highlighted in the preceding section, variations in biomass composition particularly lignin content, ash fraction, and moisture levels directly influence conversion pathways and efficiencies. Consequently, thermochemical and catalytic processes must be designed with explicit consideration of upstream resource characteristics. Recent literature indicates that conversion technologies are undergoing a transition from conventional single-route processing toward more flexible, integrated, and sustainability-oriented systems. Rather than relying solely on isolated processes such as combustion or basic pyrolysis, current approaches emphasize waste valorization, catalytic enhancement, process intensification, and multifunctional material design. This evolution reflects a broader shift in energy research, where conversion systems are no longer optimized purely for yield, but for compatibility with circular resource utilization, environmental performance, and downstream integration [51,52].

### 4.1. Waste-to-fuel thermochemical conversion and resource valorization

Among thermochemical strategies, waste-to-fuel conversion has emerged as a particularly attractive near-term pathway due to its dual function of waste mitigation and energy recovery. Researchers investigated the co-pyrolysis of waste frying and engine oils, demonstrating that process temperature plays a decisive role in determining fuel quality, product distribution, and overall conversion efficiency. Such findings reinforce a broader trend in sustainable energy systems: the reclassification of low-value or problematic waste streams as viable carbon resources [53,54].

This approach is particularly relevant for sectors that are difficult to electrify, where liquid fuels remain essential. Waste derived fuels therefore act as transitional energy carriers, enabling de-carbonization while maintaining compatibility with existing infrastructure [55, 56]. However, challenges remain in ensuring consistent feedstock quality, controlling emissions, and achieving stable product composition across varying waste streams.

### 4.2. Multi-dimensional evaluation of platform fuels

A complementary direction involves the production of platform fuels evaluated through integrated performance frameworks. The work on methanol synthesis is notable for incorporating energy efficiency, exergy analysis, economic feasibility, and environmental impact within a unified assessment [57, 58]. Such multi-criteria approaches represent a significant advancement over traditional single-metric evaluations. Methanol, in particular, serves multiple roles as a fuel, hydrogen carrier, and chemical feedstock making it a central component in integrated energy systems. Importantly, these studies signal a shift from laboratory-scale optimization toward system-level feasibility, where scalability, cost, and lifecycle impact are considered alongside technical performance.

### 4.3. Catalytic material design, stability, and regeneration

At the material level, catalytic systems are increasingly designed to align with sustainability and circularity principles. Mohammad et al. and Zia et al. demonstrated the use of lignin-derived heterogeneous catalysts for oxidative desulfurization under mild conditions, optimized via Box-Behnken design [59, 60]. This approach exemplifies the integration of catalyst development, process optimization, and waste valorization within a single framework. However, beyond catalytic activity, practical deployment is strongly influenced by catalyst stability, regeneration requirements, and sensitivity to impurities. Biomass-derived streams often contain sulfur, nitrogen compounds, and inorganic ash, which can lead to catalyst poisoning, deactivation, and reduced selectivity. Regeneration processes typically involving oxidation or thermal treatment restore activity but introduce additional operational costs and energy penalties. These factors must be incorporated into techno-economic assessments to ensure realistic evaluation of catalytic systems.

Compared to conventional fossil-based catalytic processes, biomass conversion presents additional complexity due to feedstock heterogeneity and impurity variability. While significant progress has been made in developing robust and low-cost catalysts, achieving long-term stability under real operating conditions remains a critical challenge for industrial implementation.

## 4.4. Expansion toward energy-environment integrated catalysis

Another emerging trend is the extension of catalytic systems beyond fuel production into the broader energy-environment interface. Recent studies include metal-organic framework (MOF) hybrids for oxygen evolution reactions, Zinc ferrite nanophotocatalysts for dye degradation, and nickel-impregnated ZnO systems for combined photocatalytic and sonocatalytic treatment of wastewater [61, 62]. Although often categorized under environmental remediation, these systems are fundamentally relevant to energy conversion due to shared mechanisms involving surface reactivity, charge transfer, and active-site engineering [63, 64]. For example, the oxygen evolution reaction remains a key kinetic limitation in water electrolysis, directly affecting hydrogen production efficiency. Similarly, photocatalytic systems demonstrate low-energy pathways for redox reactions, enabling sustainable chemical transformations under mild conditions [65,66].

Collectively, these developments indicate a shift toward multifunctional catalytic platforms capable of simultaneously addressing energy production and environmental challenges.

## 4.5. Feedstock process coupling and pretreatment dependency

The effectiveness of thermochemical and catalytic conversion is strongly dependent on feedstock characteristics and pretreatment strategies. Studies on cereal straw utilization and lignin-cellulolytic fungi demonstrate that biomass deconstruction and structural accessibility play a decisive role in determining conversion efficiency and product selectivity [67,68].

Key parameters such as lignin content, ash composition, moisture levels, and structural recalcitrance influence reaction pathways, catalyst stability, and reactor performance. This reinforces a fundamental system-level insight: conversion processes cannot be optimized independently of feedstock preparation, conversion efficiency. Instead, upstream pretreatment and downstream conversion must be co-designed to ensure consistent and efficient performance.

## 4.6. System-level implications and transition toward integration

Overall, thermochemical and catalytic conversion pathways are evolving toward integrated and adaptive systems characterized by feedstock flexibility, mild-condition catalysis, waste valorization, and multifunctional material design. This transition reflects a broader movement from isolated process optimization toward interconnected conversion platforms capable of responding to resource variability and environmental constraints.

At the system level, these developments enable the generation of not only fuels but also functional materials that can be directly integrated into energy storage and hybrid systems. This linkage is particularly important because the nature of conversion products, such as hydrogen, syngas, or liquid fuels, directly determines the requirements and compatibility of downstream storage technologies. **Figure 3** illustrates thermochemical (gasification, pyrolysis, plasma), chemical, biological, and coupled electrochemical/photocatalytic conversion routes. The figure highlights the transition from conventional biomass conversion to hybrid and integrated energy systems for sustainable fuel generation.

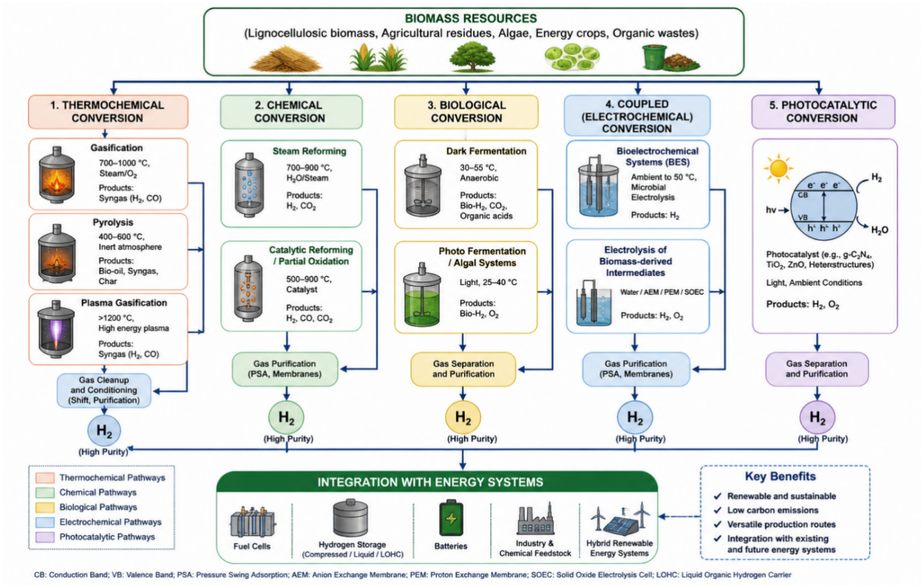


**Figure 3.** Integrated pathways for hydrogen production from biomass.

This evolving integration between conversion and storage systems forms the basis for the next stage of analysis, where electrochemical energy storage technologies are evaluated in terms of performance, scalability, and compatibility with biomass-derived energy streams.

## 5. Electrochemical energy conversion and storage: Materials, interfaces, and system integration

The effectiveness of biomass-derived energy systems ultimately depends on how efficiently converted energy carriers such as hydrogen, syngas, or electricity can be stored and delivered. As discussed in the previous section, the nature of conversion outputs directly determines storage requirements, making electrochemical energy storage a critical component in integrated energy systems. However, storage technologies differ significantly in terms of energy density, lifecycle performance, cost, and compatibility with biomass-derived streams.

### 5.1. Lithium-sulfur batteries: Opportunities and limitations

Lithium-sulfur (Li–S) batteries have attracted considerable attention due to their high theoretical energy density (~2,500 Wh $kg^{-1}$) and the abundance of sulfur. Practical systems typically achieve 300–500 Wh $kg^{-1}$, which remains significantly higher than conventional lithium-ion batteries. These characteristics make Li–S systems particularly attractive for highenergy applications and long-duration storage [69, 70]. Despite these advantages, several limitations hinder large-scale deployment. The polysulfide shuttle effect leads to capacity fading and reduced cycle life, while volume expansion during cycling affects structural stability. In addition, Li–S systems are sensitive to operating conditions and require advanced electrolyte and electrode engineering to maintain performance stability.

From a system perspective, Li–S batteries are well-suited for storing high-energy outputs from biomass-derived fuels and hybrid renewable systems. However, their current cost structure and durability challenges limit immediate commercialization, particularly in large-scale stationary applications.

### 5.2. Alternative storage technologies and comparative perspective

While Li-S systems offer high energy density, alternative storage technologies provide advantages in stability, cost, and compatibility with integrated energy systems. Sodium–sulfur (Na–S) batteries, for example, operate at elevated temperatures (300–350 °C) and offer energy densities of 150–240 Wh $kg^{-1}$. Their reliance on abundant sodium resources makes them economically attractive for grid-scale storage, although thermal management remains a challenge. Flow batteries, including vanadium redox systems, provide lower energy density (20–50 Wh $kg^{-1}$) but offer excellent scalability, long cycle life (>10,000 cycles), and independent control of power and energy capacity. These characteristics make them particularly suitable for coupling with intermittent renewable generation and biomass-based energy systems. Solid-state batteries represent another emerging class, offering improved safety and stability due to the absence of liquid electrolytes. However, they remain at an early stage of commercialization and face challenges related to cost and manufacturing scalability.

A comparative summary of major electrochemical storage technologies is provided in **Table 2** to highlight differences in performance, cost, and operational characteristics.

**Table 2.** Performance comparison of advanced electrochemical energy storage technologies highlighting energy density, cycle life, cost range, and operational constraints for integration into renewable and biomass-derived energy systems.

| Technology | Energy density (Wh/kg) | Cycle life | Cost (USD/kWh) | Key advantage | Limitation |
|---|---|---|---|---|---|
| Li–S | 300–500 | 200–1,000 | 150–300 | High energy density | Stability issues |
| Na–S | 150–240 | 2500–4,500 | 100–200 | Low cost materials | High |
| Flow | 20–50 | >10,000 | 200–500 | Long lifespan | Low energy density |
| Solid-state | 200–400 | 500–2,000 | >300 | Safety | Early stage |
| Li-ion | 150–250 | 1000–3,000 | 120–250 | Mature tech | Resource constraints |

Importantly, the compatibility of these systems with biomass-derived energy streams varies. Hydrogen-rich outputs from gasification processes are more naturally aligned with fuel cells and electrochemical conversion systems, whereas electricity generated from hybrid renewable systems can be directly stored in battery-based technologies. This highlights the need for system-level matching between conversion outputs and storage technologies.

## 5.3. Techno-economic considerations and deployment barriers

Beyond technical performance, economic factors play a decisive role in the deployment of energy storage systems. Current estimates suggest that lithium-based storage systems exhibit levelized costs of storage (LCOS) in the range of 0.10–0.25 USD $kWh^{-1}$, depending on system configuration and lifecycle assumptions. Flow batteries typically show higher initial capital costs but benefit from longer operational lifetimes, which can reduce overall lifecycle costs.

For hybrid energy systems integrating biomass conversion and renewable generation, additional economic barriers arise from system complexity, infrastructure requirements, and integration costs [71, 72]. These include:

- High CAPEX associated with multi-component systems,
- Operational variability due to feedstock fluctuations,
- Maintenance costs linked to catalyst degradation and storage system cycling.

These factors often limit large-scale deployment despite favorable technical performance. Therefore, techno-economic optimization must consider not only individual component efficiency but also system-level cost interactions. Representative techno-economic indicators for different energy systems are summarized in **Table 3** to provide a quantitative basis for comparison.

**Table 3.** Techno-economic indicators for biomass-based, solar-storage, and hybrid energy systems, summarizing capital cost (CAPEX), levelized cost of energy (LCOE), and levelized cost of storage (LCOS) for system-level evaluation and deployment feasibility.

| System type | CAPEX (USD/kW) | LCOE (USD/kWh) | LCOS (USD/kWh) |
|---|---|---|---|
| Biomass | 1,500–4,000 | 0.08–0.15 | - |
| Solar + Storage | 800–2,000 | 0.05–0.12 | 0.10–0.25 |
| Hybrid System | 2,000–5,000 | 0.07–0.18 | 0.12–0.30 |

## 5.4. Integration with hybrid renewable systems

Electrochemical storage technologies play a central role in enabling hybrid renewable architectures. By buffering variability in solar and biomass-derived energy supply, storage systems improve reliability, grid stability, and energy accessibility.

In integrated systems, storage units must operate under dynamic conditions, responding to fluctuations in energy generation and demand. This requires advanced control strategies, including digital optimization and real-time system monitoring. Machine learning-based approaches are increasingly being explored to optimize energy flow, predict system behavior, and enhance operational efficiency [73, 74]. The selection of storage technology within such systems is therefore not solely a function of energy density or cost, but also of flexibility, response time, and compatibility with upstream and downstream processes.

### 5.5. Comparative assessment and system-level implications

Overall, no single storage technology is universally optimal. Li–S batteries offer high energy density but face stability challenges; Na–S systems provide cost advantages but require thermal management; flow batteries excel in scalability but have lower energy density. This diversity underscores the importance of system-level design, where storage technologies are selected based on specific application requirements and their compatibility with biomass-derived energy streams. The integration of conversion and storage systems must therefore be approached as a coupled problem rather than independent optimization tasks [75, 76]. From a broader perspective, the transition toward integrated sustainable energy systems require alignment between resource characteristics, conversion pathways, storage technologies, and system-level optimization strategies. This interconnected approach forms the basis for the subsequent analysis of hybrid renewable architectures and the water-energy-environment nexus (**Table 4**).

**Table 4.** Cross-domain integration of biomass conversion, electrochemical storage, and hybrid renewable systems.

| Level | Component | Key processes/Technologies | Key constraints | Performance indicators | System role |
|---|---|---|---|---|---|
| Resource Level | Biomass/Waste Feedstocks | Agricultural residues, lignocellulosic biomass, algal systems | Seasonal variability, land-use competition, water dependency | Yield (t/ha), C/N ratio, moisture content | Primary carbon and energy input |
| Conversion Level | Thermochemical & Catalytic Systems | Pyrolysis, gasification, catalytic upgrading, photocatalysis | Feedstock heterogeneity, catalyst deactivation, tar formation | Conversion efficiency (30–75%), selectivity, energy yield | Converts biomass into fuels & intermediates |
| Energy Carrier Level | Hydrogen/ Syngas/ Electricity | Reforming, water splitting, biohydrogen production | Purity requirements, energy losses, storage instability | $H_2$ yield (kg/kg biomass), energy density | Intermediate energy transport medium |
| Storage Level | Electrochemical Systems | Li–S, Na–S, flow batteries, solid-state batteries | Cost, cycle life, thermal stability, material degradation | Energy density (20–500 Wh/kg), LCOS (0.1–0.25 USD/kWh) | Energy buffering and dispatch |
| System Level | Hybrid Renewable Systems | PV + biomass + storage + grid integration | Intermittency, integration cost, control complexity | Efficiency, reliability, capacity factor | Final energy delivery system |
| Control Layer | Digital Optimization | AI/ML forecasting, energy dispatch, predictive maintenance | Data quality, computational load | Response time, prediction accuracy | System stability & optimization |

### 5.6. System integration, operation, and economic considerations

At the system level, the effectiveness of electrochemical storage depends not only on material performance but also on operational strategy and integration within hybrid energy systems. Grid-connected photovoltaic-storage systems demonstrate that factors such as charge discharge scheduling, load balancing, renewable intermittency, and degradation management significantly influence overall system efficiency and lifetime [77, 78].

From a techno-economic perspective, storage systems remain a major cost component in hybrid energy architectures. While lithium-based systems offer high performance, their cost, material availability, and lifecycle limitations pose challenges for large-scale deployment. Alternative technologies may offer lower capital costs or longer lifetimes but require trade-offs in performance. These economic considerations represent a major barrier to widespread adoption and must be incorporated into system design and optimization.

In addition, resource constraints related to water availability and quality play a critical role in system integration. Biomass-based hydrogen production typically requires approximately 10–20 L of water per kWh, while electrochemical systems demand high-purity water with impurity levels below 5 ppm to prevent catalyst degradation. This creates a trade-off between resource accessibility and system performance, particularly when wastewater reuse is considered. The presence of residual contaminants such as sulfates, heavy metals, and organic compounds can significantly reduce electrolyzer efficiency and lifetime, necessitating additional pretreatment steps.

### 5.7. Digital optimization and intelligent energy systems

The integration of machine learning and data-driven optimization is transforming electrochemical energy systems from passive storage units into actively managed components of intelligent energy networks. Ahmad et al. and Bukhari et al. demonstrated machine-learning-assisted exergy prediction to optimize system performance under variable operating conditions [79, 80]. Such approaches enable predictive control, adaptive operation, and real-time decision-making, which are essential for managing the variability inherent in renewable energy systems. In practice, these tools enable more stable operation under fluctuating renewable inputs by coordinating storage dispatch, predicting degradation trends, and optimizing load balancing across integrated systems.

### 5.8. Integrated system design and deployment pathways

The preceding analysis highlights that the performance of electrochemical energy systems is governed not by individual component efficiency, but by the interactions between feedstock properties, conversion pathways, storage technologies, and operational strategies. Variability in biomass composition influences conversion efficiency, which in turn affects storage requirements and system stability. Similarly, catalyst degradation, electrolyte stability, and cycling performance introduce constraints that propagate across the system. From a deployment perspective, several bottlenecks remain critical. These include high capital costs associated with integrated systems, operational complexity arising from multi-component interactions, and infrastructure limitations related to feedstock logistics and grid integration. In addition, resource constraints, particularly water availability and land-use competition, further restrict large-scale implementation.

Addressing these challenges requires a shift toward system-level design approaches that prioritize flexibility, modularity, and compatibility across subsystems. Hybrid configurations integrating biomass conversion, electrochemical storage, and renewable generation offer a promising pathway, particularly when supported by advanced control and optimization strategies.

Overall, the transition toward sustainable energy systems depends on the ability to manage cross-domain interactions and align resource availability with technological performance. This integrated perspective provides the foundation for scalable deployment and informs the subsequent discussion on hybrid renewable systems and techno-economic optimization. **Figure 4** highlights interconnected routes including thermochemical, biological, and electrochemical hydrogen production, and their coupling with batteries, fuel cells, and hybrid renewable systems through advanced catalytic and interfacial engineering.


**Figure 4.** Integrated electrochemical energy conversion and storage framework linking biomass-derived hydrogen production pathways with electrochemical interfaces and energy storage systems.

These developments reinforce the central premise of this review: electrochemical systems must be understood not as isolated technologies, but as integral components of a broader resource–conversion-storage-system continuum. The nature of conversion outputs (e.g., hydrogen, liquid fuels, or electricity) directly determines storage requirements, while storage performance influences overall system efficiency and feasibility.

This integrated perspective provides a natural transition to the next section, which examines hybrid renewable energy systems, techno-economic optimization, and digital management strategies as key enablers of scalable and sustainable energy infrastructures.

## 6. Hybrid renewable energy systems, techno-economic optimization, and digital management strategies

Building on the integrated biomass conversion and catalytic-thermochemical pathways discussed in previous sections, the focus now shifts toward system-level implementation, where energy generation, storage, and utilization are coordinated within unified operational frameworks. At this stage, the primary challenge is no longer the optimization of individual technologies, but the coordinated performance of interconnected subsystems operating under dynamic, uncertain, and resource constrained conditions. In this context, hybrid renewable energy systems (HRES) have emerged as a key enabling architecture for achieving reliability, flexibility, and sustainability in modern energy infrastructures [81, 82].

A fundamental motivation for hybrid system design is the inherent intermittency of single renewable energy sources. Solar photovoltaic systems offer high scalability and declining costs, yet their output is strongly affected by temporal and weather-dependent variability. Electrochemical storage systems can partially compensate for these fluctuations; however, their degradation behavior, cost structure, and lifecycle limitations restrict standalone deployment. Hybrid configurations address these constraints by integrating complementary generation and storage technologies, thereby improving system reliability and operational stability.

## 6.1. Techno-economic feasibility and system-level design

Recent techno-economic studies demonstrate that hybrid systems must be evaluated not only in terms of energy output but also in terms of site-specific cost structures, operational constraints, and long-term performance degradation. The work by Choruma et al. and Ahmad et al. on grid-connected hybrid photovoltaic systems illustrates this transition toward deployment-oriented assessment frameworks [83, 84]. Such studies emphasize that system feasibility is determined by a balance between capital investment, operational efficiency, and resource availability rather than isolated component performance.

However, a key limitation in existing techno-economic assessments is the insufficient coupling between technical optimization and dynamic operational behavior. Most studies assume quasi-static conditions, which do not fully capture real-world variability in renewable generation and demand profiles. This gap highlights the need for integrated modeling approaches that combine economic evaluation with real-time system dynamics. **Figure 5** illustrates the hybrid renewable energy system architecture integrating multi-source power generation, electrochemical storage, and digital optimization frameworks.

## 6.2. Intelligent control and optimization frameworks

Beyond static economic evaluation, real-time control strategies play a decisive role in determining system performance. Intelligent optimization methods are increasingly being used to manage charge discharge scheduling, load balancing, and renewable dispatch prioritization. The study by Asif et al. and Shafiq et al. using dual predator optimization demonstrates how advanced algorithms can significantly enhance operational efficiency in hybrid systems [85, 86].

This reflects a broader transition in energy system design: performance is increasingly governed by system-level interaction dynamics rather than individual component efficiency [87, 88]. In this context, optimization algorithms are no longer auxiliary tools but core operational mechanisms that directly influence system stability, energy cost, and lifecycle performance.

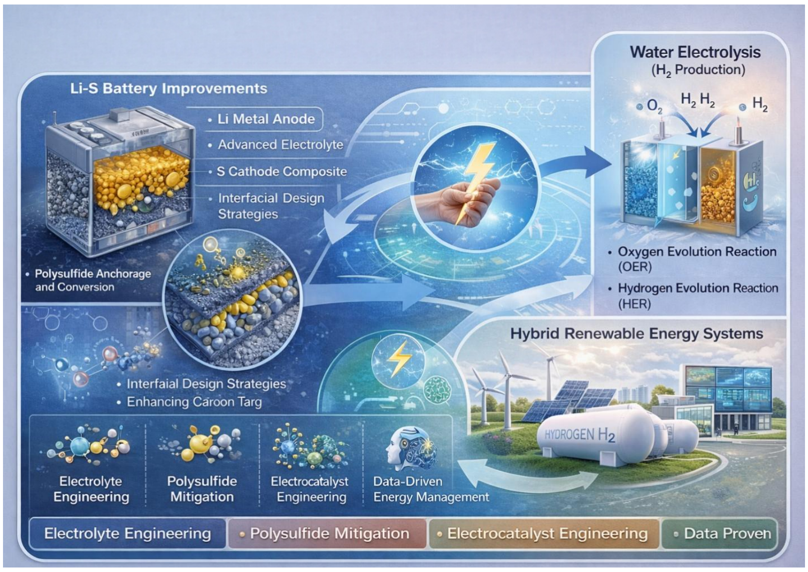


**Figure 5.** Hybrid renewable energy system architecture integrating multi-source power generation, electrochemical storage, and digital optimization frameworks.
Note: The system incorporates techno-economic evaluation, AI-driven energy management, and real-time control strategies to enhance reliability, efficiency, and cost-effectiveness under variable renewable conditions.

### 6.3. Data-driven and machine learning-based energy management

The integration of machine learning and data-driven methods further strengthens hybrid system adaptability under uncertainty. Waqas et al. and Shakoor et al. demonstrated machine-learning-assisted exergy prediction under variable operating conditions, highlighting the capability of predictive models to capture fluctuations in renewable generation and demand patterns [89, 90]. Unlike deterministic approaches, data-driven frameworks enable adaptive control, sensitivity analysis, and predictive optimization, making them particularly suitable for hybrid renewable environments characterized by variability in both supply and demand. These methods improve resilience by enabling anticipatory system adjustments rather than reactive control strategies.

### 6.4. Digital ecosystem and implementation constraints

Despite advances in optimization and control, the real-world performance of hybrid energy systems is strongly influenced by the surrounding digital and institutional ecosystem. Factors such as data availability, monitoring infrastructure, user engagement, and system interoperability significantly affect operational outcomes. Studies on digital transformation in energy and agricultural systems indicate that technological readiness alone is insufficient for successful deployment. Even highly optimized systems may underperform if digital infrastructure, data integration mechanisms, or operational expertise are lacking. This is particularly relevant in decentralized systems where energy, water, and agricultural resources are tightly coupled [91, 92].

### 6.5. Environmental and socio-economic constraints

Hybrid renewable systems must also operate within broader environmental and socio-economic boundaries. Constraints such as water scarcity, land-use pressure, and technology adoption barriers can significantly influence system feasibility. In biomass-integrated hybrid systems, water availability becomes a particularly critical limiting factor due to its impact on both feedstock production and conversion processes. Therefore, system design must extend beyond technical optimization to include environmental resource management and socio-economic feasibility. This reinforces the need for integrated sustainability frameworks that combine engineering performance with real-world constraints [93,94].

### 6.6. System-level synthesis and transition perspective

Overall, hybrid renewable energy systems are evolving from hardware-centric configurations into intelligent, adaptive, and socio-technically embedded platforms. Their performance depends on three interdependent dimensions:

(i) **Techno-economic design**, ensuring cost-effective and site-specific system configuration,
(ii) **Intelligent optimization**, enabling real-time adaptive control and operational efficiency, and
(iii) **Digital ecosystem integration**, supporting monitoring, data exchange, and user-level interaction.

This tri-dimensional structure links upstream resource availability, midstream conversion processes, and downstream storage technologies within a unified operational framework. Importantly, it demonstrates that sustainable energy systems cannot be optimized in isolation but must be designed as interconnected, data-driven, and context-aware infrastructures.

This integrated perspective also provides a natural transition toward the next section, which examines the water-energy-environment nexus and its role in defining the long-term sustainability limits of integrated energy conversion and storage systems.

## 7. Water energy environment nexus and resource circularity

The long-term viability of sustainable energy conversion and storage systems depends not only on technological efficiency, but also on their ability to operate within coupled environmental and resource constraints. In this context, the water-energy-environment (WEE) nexus has emerged as a critical analytical framework for evaluating system sustainability, as energy production, water use, and environmental impact are inherently interdependent. Energy systems require water for feedstock processing, cooling, electrochemical operation, and material synthesis, while simultaneously influencing water quality through emissions, effluents, and solid waste generation. Moreover, biomass-based energy systems are directly governed by hydrological conditions that determine feedstock availability and quality. As a result, the WEE nexus is increasingly recognized as a core design dimension rather than a secondary environmental consideration [95,96].

## 7.1. Water intensity and energy system coupling

A key dimension of the nexus is the water intensity associated with energy production pathways. Biomass conversion, hydrogen production, and electrochemical systems all exhibit significant dependence on water availability, particularly in pretreatment, reaction media, and cooling processes. In water-stressed regions, this dependency can become a limiting factor for scalability, particularly for decentralized bioenergy and hydrogen systems. Therefore, integrating water-efficient technologies and closed-loop water systems is essential for ensuring operational resilience and scalability of sustainable energy infrastructures [97,98].

## 7.2. Water reuse and decentralized resource recovery

Recent developments in water reuse technologies highlight the role of decentralized systems in reducing freshwater demand. Khaled [99] demonstrated a lamella-settler-based wastewater reclamation system for carwash stations, illustrating how low-cost treatment units can significantly reduce freshwater consumption in distributed applications. While such systems are traditionally outside the core energy domain, they play an enabling role in supporting energy technologies by reducing the indirect water footprint of industrial and processing operations.

More importantly, these approaches demonstrate a shift toward localized circular water systems, where wastewater is not treated as a disposal problem but as a recoverable resource stream. This concept is particularly relevant for biomass processing and hydrogen production systems, where water recycling can substantially improve sustainability metrics and reduce operational constraints in arid and semi-arid regions [99,100].

## 7.3. Convergence of energy conversion and environmental remediation

An emerging trend in the WEE nexus is the convergence of energy conversion technologies with environmental remediation processes. Advanced catalytic and photocatalytic materials used for pollutant degradation, dye removal, and wastewater treatment operate on principles similar to those used in electro-catalysis and energy conversion systems, including charge transfer dynamics, surface reactivity, and active-site engineering [101,102].

This convergence enables the development of dual-function systems capable of simultaneously generating energy and mitigating environmental pollution. For example, semiconductor-based photocatalysts and modified metal oxides can be engineered to serve both energy conversion and environmental detoxification roles, thereby increasing overall system utility and efficiency [103, 104]. This multi-functionality represents a critical step toward integrated energy environment platforms.

## 7.4. Upstream water constraints in biomass systems

Water availability also plays a decisive role at the upstream stage of biomass-based energy systems. Studies on irrigation efficiency, soil-plant-atmosphere interactions, and climate-driven hydrological variability demonstrate that biomass yield and composition are strongly dependent on water conditions [105, 106]. Water stress not only reduces biomass productivity but also alters structural characteristics such as lignin content, fiber composition, and moisture levels.

These changes propagate downstream, affecting pretreatment efficiency, catalytic performance, and overall conversion stability [107,108]. Therefore, biomass cannot be treated as an independent energy input; rather, it must be evaluated as a climate- and water-dependent resource whose performance is intrinsically linked to environmental conditions. This reinforces the need for integrated assessment frameworks that incorporate water-use efficiency, climate resilience, and land management alongside conventional energy metrics [109,110].

### 7.5. Resource circularity and waste valorization pathways

Beyond constraints, the WEE nexus also enables resource circularity through the transformation of waste streams into functional materials and energy carriers. Recent studies demonstrate multiple valorization pathways, including copper recovery from electronic waste, lignin-derived catalysts, biochar-based materials, and biomass derived thermal storage systems. These approaches convert waste into highvalue inputs for energy conversion and storage systems, reducing dependence on virgin materials and minimizing environmental burden [111,112].

From a systems perspective, circularity enhances not only environmental performance but also economic feasibility by reducing material costs and improving resource efficiency. However, the effectiveness of these approaches depends on their integration into broader energy-water-material networks rather than isolated implementation.

### 7.6. System-level integration challenges

Despite significant progress, most current studies evaluate water reuse, catalytic materials, or circular processes independently, without fully capturing cross-sector interactions. This fragmented approach limits the ability to assess cumulative environmental and system-level impacts. In contrast, real-world energy systems operate through tightly coupled water, energy, and material flows, where changes in one subsystem directly influence others.

Therefore, future research must move toward integrated assessment frameworks that simultaneously evaluate energy output, water consumption, material recovery, and environmental impact. Such frameworks are essential for translating laboratory-scale innovations into scalable and resilient energy infrastructures.

### 7.7. Transition toward integrated nexus-based energy systems

Overall, the literature indicates a clear transition from linear resource consumption models toward closed-loop, resource-efficient, and environmentally integrated energy systems. The WEE nexus provides a unifying framework for this transition by linking energy generation, water management, and environmental protection within a single system perspective.

Systems that incorporate water reuse, pollution control, and material circularity are inherently more adaptable to real-world constraints than those optimized solely for energy efficiency. This integrated perspective establishes the foundation for the final section of this review, which synthesizes key research gaps, system-level bottlenecks, and future directions required to advance sustainable energy conversion and storage toward practical deployment. **Figure 6** illustrates chemical, biological, thermochemical, and coupled electrochemical routes from biomass and water resources, highlighting system-level coupling between resource flows and energy conversion processes.

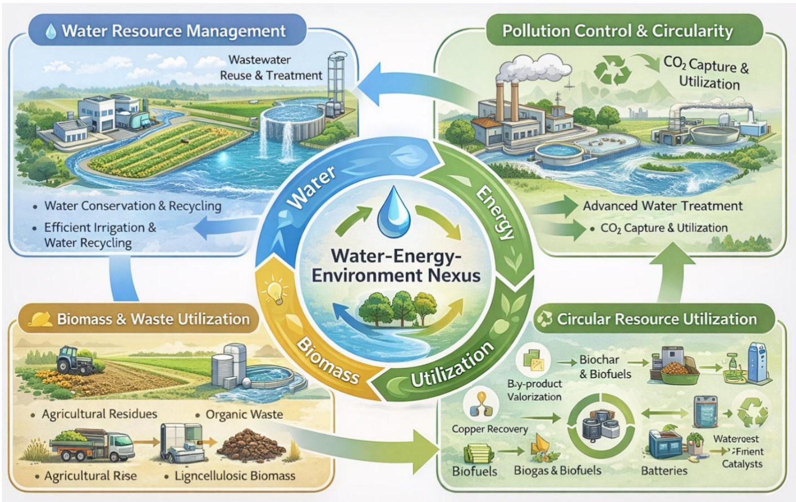


**Figure 6.** Integrated hydrogen production pathways within the water–energy–environment nexus.

## 8. Research gaps, integration challenges, and future directions

Despite substantial progress in biomass conversion, catalytic upgrading, electrochemical storage, and hybrid renewable systems, the current literature remains characterized by fragmentation across material, process, and system scales. While individual technological domains have achieved notable advancements, their development is largely decoupled, limiting the emergence of fully integrated and scalable sustainable energy systems. This lack of cross-domain integration represents the central barrier to system-level optimization.

### 8.1. Feedstock process decoupling and climate variability

A primary research gap lies in the weak coupling between biomass resource dynamics and conversion system design. Agricultural and environmental studies consistently show that biomass availability and quality are strongly influenced by climate variability, land-use change, and water scarcity [113, 114]. However, most conversion studies assume stable and idealized feedstock conditions, which do not reflect real-world variability.

As discussed in Section 3, parameters such as moisture content, lignin fraction, ash composition, and structural heterogeneity directly influence thermochemical behavior, catalytic stability, and overall system efficiency. The absence of climate-resilient feedstock modeling introduces significant uncertainty in scaling conversion technologies. Future research must integrate adaptive feedstock characterization and climate-responsive modeling into process design to improve robustness under variable conditions.

## 8.2. Limited circularity in material and catalyst systems

A second key gap concerns incomplete circularity in material design. Although promising advances such as lignin-derived catalysts, biochar materials, waste-derived fuels, and metal recovery systems have been reported, these are typically developed in isolation without lifecycle-level integration [115, 116]. What remains missing is a unified circular materials framework that systematically links:

- Waste streams → functional catalysts → energy products → recycling pathways.

As summarized in **Table 5**, current systems lack closed-loop integration across material flows. Future progress requires holistic material flow analysis where resource inputs, transformations, and outputs are co-optimized to minimize waste and improve system efficiency.

**Table 5.** System-level comparison of integrated biomass conversion, electrochemical storage, and hybrid renewable architectures, emphasizing cross-domain interactions, resource constraints, and deployment challenges in scalable energy systems.

| Domain | Key components | Representative technologies /Studies | Core function | Key challenges | Future opportunities |
|---|---|---|---|---|---|
| Biomass & Resource Base | Agricultural residues, algal biomass, waste oils, lignocellulosic feedstocks | Crop-residue valorization, algal hydrogen/biochar systems, climate-resilient biomass production | Provides renewable carbon source and energy carriers | Climate variability, water scarcity, inconsistent feedstock quality | Climate-resilient crops, residue-based systems, integrated biomass supply chains |
| Thermochemical Conversion | Pyrolysis, co-pyrolysis, gasification, biofuel upgrading | Waste oil → diesel-like fuel, biomass → syngas/bio-oil | Converts solid/liquid feedstocks into fuels | Product instability, process efficiency, tar formation | Catalytic-assisted pyrolysis, multi-feedstock reactors |
| Catalytic Systems | Heterogeneous catalysts, MOFs, biomass-derived catalysts | Lignin-derived catalysts, OER catalysts, photocatalysis | Enhances reaction efficiency and selectivity | Catalyst deactivation, cost, scalability | Circular catalysts (bio-derived), multifunctional catalytic platforms |
| Electrochemical Storage | Li–S batteries, electrolysis systems, advanced electrodes | Li–S electrolyte engineering, water electrolysis ($H_2$) | Stores renewable energy and enables conversion to fuels | Stability, polysulfide shuttle, degradation | Interface engineering, hybrid storage (battery + hydrogen) |
| Hybrid Renewable Systems | PV + storage + grid systems, hybrid power plants | Grid-connected hybrid PV, smart energy management | Balances intermittency and demand | Cost optimization, dispatch control, system complexity | AI-driven optimization, decentralized microgrids |
| Digital & Optimization Layer | Machine learning, control systems, smart grids | ML-based exergy optimization, energy management algorithms | Improves efficiency, reliability, and adaptability | Data availability, adoption barriers | Digital twins, real-time adaptive control |
| Water-Energy-Environment Nexus | Water use, wastewater reuse, pollution control | Wastewater reclamation, catalytic pollutant removal | Ensures environmental sustainability of energy systems | Water intensity, contamination risks | Integrated water–energy systems, low-water technologies |
| Circular Economy Integration | Waste recovery, biochar, recycled materials | Copper recovery, biochar systems, waste-to-energy | Reduces waste and improves resource efficiency | System integration, lifecycle assessment gaps | Closed-loop energy systems, zero-waste design |
| System Level Sustainability | Techno-economic + environmental assessment | Exergy analysis, hybrid system feasibility studies | Evaluates real-world viability | Multi-objective trade-offs (cost-carbon-water) | Integrated assessment frameworks |

### 8.3. Gap between digital optimization and real deployment

Recent advances in machine learning, smart grids, and predictive control have significantly improved energy system optimization. However, these approaches often remain disconnected from real-world implementation constraints such as data availability, infrastructure limitations, and institutional readiness.

This creates a critical gap between theoretical optimization and deployable solutions. Future research should combine techno-economic modeling with digital readiness assessment to ensure that AI-driven optimization strategies are not only efficient but also practically implementable across diverse socio-technical environments.

### 8.4. Underdeveloped water-energy-environment integration

Although water use, wastewater treatment, and environmental remediation have been studied independently, they are rarely integrated into energy system design [117, 118]. This is a significant limitation, particularly for biomass conversion, hydrogen production, and electrochemical systems, where water availability directly affects performance and sustainability. Future frameworks must incorporate:

- Water consumption per energy unit,
- Contamination thresholds for reuse,
- Environmental impact across lifecycle stages.

Such integration is essential for aligning energy systems with real environmental constraints rather than treating them as external considerations.

### 8.5. Lack of unified system-level frameworks

A broader structural gap exists in the absence of unified frameworks connecting:

Resource availability → conversion technologies → storage systems → distribution networks.

As a result, many laboratory-scale innovations fail during scale-up due to mismatched system assumptions. Bridging this gap requires interdisciplinary integration across materials science, process engineering, environmental analysis, and systems modeling.

### 8.6. Future research directions

To address the above challenges, future research should focus on developing integrated resource–materials systems frameworks capable of capturing cross-domain interactions. Such frameworks should incorporate:

- Climate-resilient biomass supply models.
- Circular material and catalyst design.
- Advanced thermochemical and catalytic conversion systems.
- Electrochemical storage integration.
- Hybrid renewable system optimization.
- Water-energy-environment constraints.
- uncertainty aware and data-driven modeling approaches.

The combination of these elements will enable more realistic and scalable system design under dynamic operating conditions.

### 8.7. Transition toward integrated energy systems

Overall, the next phase of sustainable energy research will be defined by a shift from isolated technological development toward system-level integration. The most impactful advancements will not arise from improving individual components alone, but from aligning feedstock, conversion, storage, and digital control within a unified operational framework. This transition marks a move from component optimization to system orchestration, where resilience, scalability, and environmental compatibility are co-optimized.

The findings of this study align with the broader role of science and technology in driving innovation. Technological innovations, global collaboration, comprehensive data integration, and scientific discoveries collectively accelerate progress in energy storage research (**Figure 2**). Incorporating these strategies can enhance the efficiency, scalability, and sustainability of renewable energy systems. Beyond technical integration, sustainable energy advancement is increasingly driven by the convergence of scientific innovation, digital technologies, and global collaboration, as summarized in **Figure 7**.

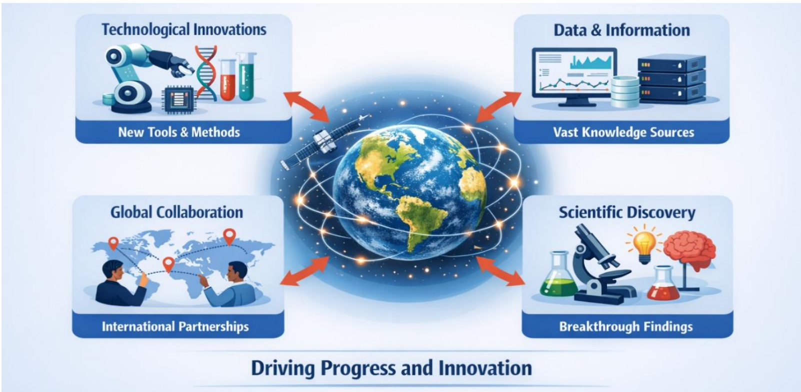


**Figure 7.** The role of science and technology in advancing research and innovation.
Note: **Figure 7** highlights technological innovations, data and information, global collaboration, and scientific discoveries as drivers of sustainable energy progress.

## 9. Conclusion

Sustainable energy conversion and storage is evolving from a set of independent technological domains into an interconnected and system-oriented research field. The literature analyzed in this review demonstrates that progress is no longer defined solely by improvements in individual components such as fuel yield, catalytic efficiency, or battery capacity, but rather by the ability to integrate these components within coherent, scalable, and environmentally compatible systems. Recent developments in biomass valorization, thermochemical conversion, catalytic upgrading, lithium–sulfur batteries, oxygen evolution electro catalysis, and hybrid renewable systems collectively indicate a shift toward a multifunctional and flexible energy platform. However, the analysis also reveals persistent limitations arising from feedstock variability, catalyst instability, storage degradation, and lack of system-level integration. A key finding of this review is that technological performance alone is insufficient to ensure real-world sustainability. Factors such as climate-resilient biomass supply, water-energy interactions, circular material utilization, and digital system management play equally important roles in determining system viability. Technologies that perform well under controlled conditions may fail under real operational constraints if these external dependencies are not considered. To address these challenges, this study proposes an integrated resource-material-systems framework which connects biomass feedstocks, conversion pathways, electrochemical storage, hybrid system operation, and sustainability constraints within a unified structure. This framework enables a more realistic representation of energy systems by capturing interdependencies that are typically overlooked in conventional studies. Overall, the future of sustainable energy systems will depend on the convergence of climate-adaptive feedstocks, efficient conversion technologies, circular material design, advanced storage systems, and intelligent system optimization. Moving from isolated component optimization toward integrated system design is essential for achieving scalable, resilient, and environmentally sustainable energy solutions capable of supporting a low-carbon future.

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