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Systematic review of hydrogen, biomass, biogas, and solar photovoltaics in hybrid renewable energy systems: Advancements, challenges, and future directions

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ABSTRACT

Transitioning to Hybrid Renewable Energy Systems (HRES) is essential for a sustainable, low-carbon future. This systematic review evaluates progress in hydrogen, biomass, biogas, and solar photovoltaics (PV) and emphasizes their significance in hybrid energy frameworks. A thorough analysis of 174 research articles was performed using VOSviewer, categorizing the literature into seven themes: "Renewable Energy Technologies and Transition", "Advanced Bioenergy and Optimization", "Integrated Energy Systems and Hydrogen Technologies", "Energy Systems Management and Optimization", "Sustainable Energy Fundamentals", "Innovations in Hydrogen and Sustainable Energy", and "Biohydrogen and Biomass Technologies". The review results revealed that integrating hydrogen, advancing bioenergy, implementing AI-driven energy management, and utilizing hybrid storage solutions are crucial for enhancing energy efficiency and grid stability. High costs, intermittency challenges, and regulatory hurdles hamper large-scale implementation. Addressing these issues through policy initiatives and innovative technologies can expedite the rollout of HRES, promoting a clean, resilient, and energy-secure future.

1. Introduction

The global energy industry is experiencing a significant transformation driven by concerns over climate change, dwindling fossil fuel resources, and the rising demand for sustainable energy solutions. Long-lasting reliance on fossil fuels has led to significant environmental challenges, such as greenhouse gas (GHG) emissions, climate change, and air pollution [1]. Therefore, it is necessary to shift towards many new effective energy sources that are much more reliable and environmentally friendly. Renewable energy sources (RES) such as solar, hydrogen, biomass, and wind have become promising alternatives that can decarbonize energy production and improve energy security [2]. However, the unpredictable nature of solar and wind energy highlights the need to develop HRES that integrate various energy sources to guarantee a stable and continuous power supply [3]. Fig. 1a depicts the global electricity generation share by multiple sources. Among fossil fuels, coal plays the leading role in electricity generation at 35.1 %, followed by natural gas at 22.5 %. In contrast, renewable energies show hydropower at the top of the list with 14.2 %, while wind and solar exhibit promising growth rates of 7.8 % and 5.5 %, respectively. Nuclear energy stands at a steady 9.1 %, while oil and other renewables contribute smaller shares at 2.3 % and 2.6 %, respectively. The other non-renewables (0.8 %) category points to minor but existing dependencies [4].

Among the diverse renewable energy technologies, hydrogen, biomass, biogas, and solar photovoltaics (PV) have garnered significant attention for their potential to create an extremely efficient and sustainable hybrid power system [5]. Hydrogen is increasingly recognized as a clean energy carrier, generated from renewable sources through water electrolysis, biomass gasification, and photoelectrochemical

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methods. [6]. Its high energy compactness and long-term storage capability allow it to address solar and wind energy generation variability [7]. Biomass and biogas sourced from farm waste, organic residues, and purpose-grown energy crops represent another promising renewable energy source [8]. These resources facilitate carbon-neutral energy generation, decreasing reliance on fossil fuels while effectively utilizing waste materials [9]. Solar PV technology is in huge demand due to its falling costs and improved efficiency [10]. When combined with biomass and hydrogen storage, solar power can help create a balanced and robust energy system that meets diverse energy needs [11,12].

As an effective solution for fast increasing energy demand, HRES has been a great solution globally [13]. In contrast, single RES have several intermittency issues whereas HRES combines various RES to have a stable and secure energy supply [14]. HRES can have improved energy production, storage and utilization with minimized environmental impacts by integrating complementary energy technologies such as hydrogen, biomass/biogas, and solar PV, [15,16]. Thus, HRES enhances energy security, reduces dependence on fossil fuels, and supports a low-carbon energy economy [17]. The block diagram for HRES is shown in Fig. 1b illustrates multiple renewable energy sources.

Hydrogen is vital in HRES due to its dual role as an energy carrier and storage solution. It can be generated through electrolysis powered by surplus solar and wind energy, stored for long durations, and later converted into electricity using fuel cells [18]. This flexibility makes hydrogen ideal for balancing energy supply and demand in hybrid systems [19]. The block diagram of Hydrogen HRES is shown in Fig. 2a. There is enormous expansion in the solar PV market due to improvements in photovoltaic efficiency, battery storage integration, and grid-connected solar systems [20,21]. New technologies such as bifacial solar modules, floating solar parks, and perovskite solar cells enhance energy yields. Integrating solar PV with hydrogen and biomass systems is becoming increasingly prevalent, with ongoing research into multi-energy hybrid models that combine solar power, electrolysis, and biomass gasification for fully sustainable energy solutions [22,23]. The block diagram of solar (PV) HRES is shown in Fig. 2b.

Biomass and biogas are a stable and flexible energy sources, the energy flow chart for biomass and biogas is shown in Fig. 3a and b, respectively. Biomass and biogas mitigating the variability of solar and wind energy [24,25]. Hybrid systems utilizing biomass can transform organic waste into useable energy, benefiting waste management and supporting a circular economy [26]. Solar photovoltaic systems, commonly utilized as a renewable energy source, synergize with biomass and hydrogen technologies in daily clean electricity generation. Combining solar PV with energy storage solutions significantly boosts system efficiency and reliability, making it a key element of HRES [27].

HRES are renowned for their technological advancements and

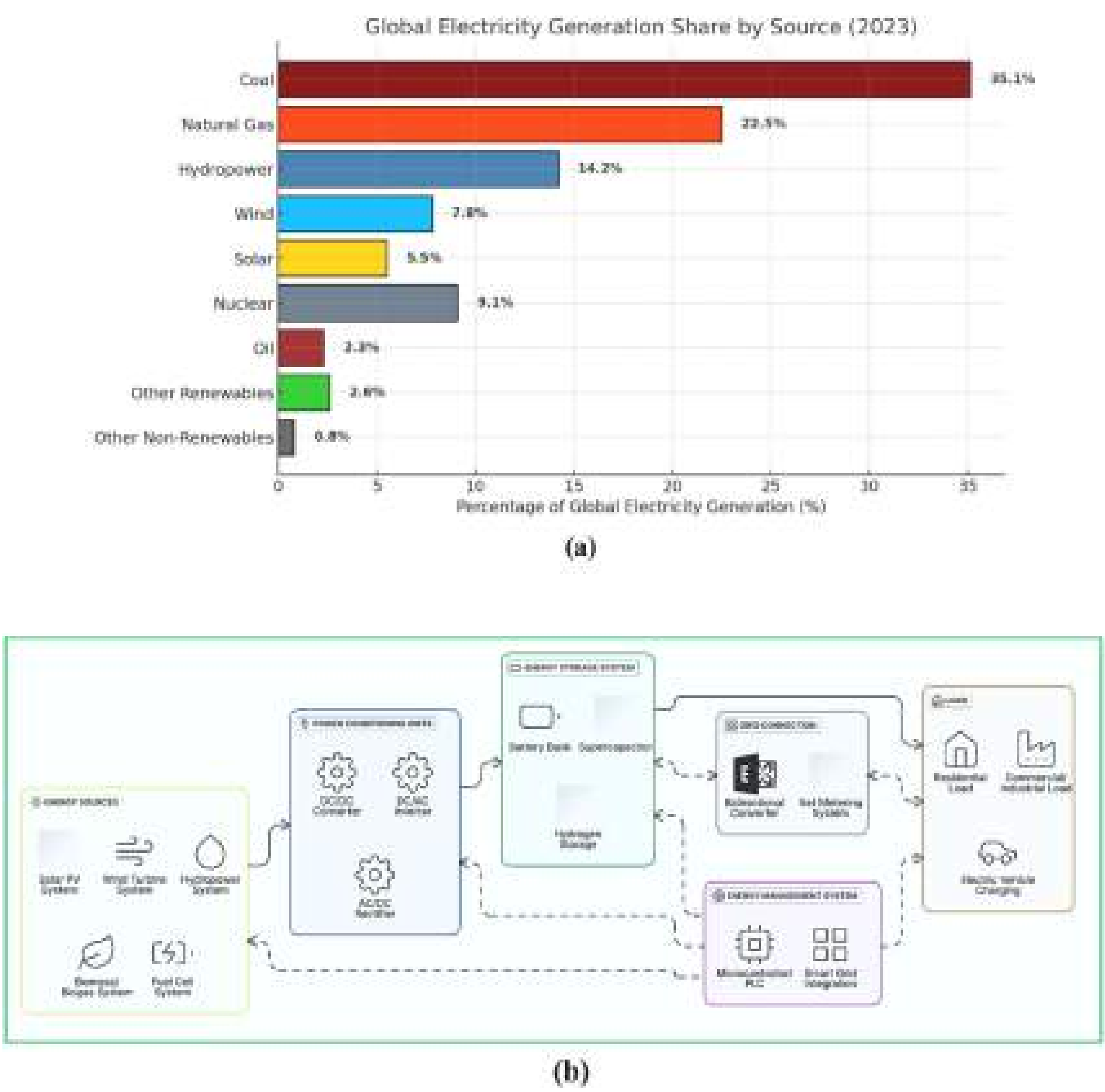


Fig. 1. (a) global electricity generation share by energy sources (2023), **(b)** block diagram for hybrid renewable energy System.

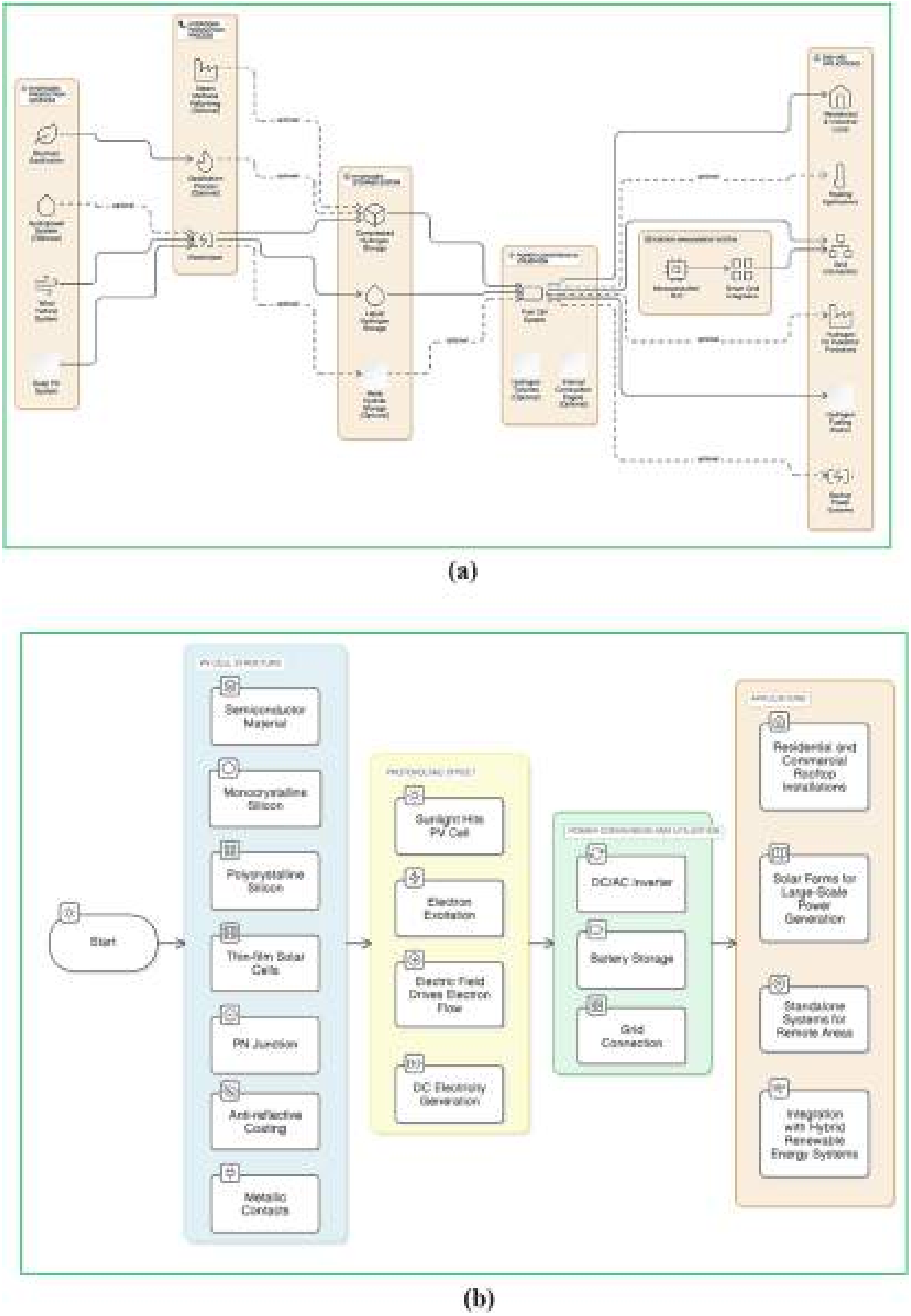


Fig. 2. Block diagram renewable energy System **(a)** hydrogen, **(b)** solar photovoltaic (PV) cell.

significant capacity to deliver economic and environmental benefits, particularly in rural and remote areas [28]. It will help create a much cleaner, more resilient global decarbonized, secure, and economically sustainable energy system [17]. Recent advances in HRES have occurred over the last few years, especially in integrating hydrogen, biomass/biogas, and PV [29]. These developments seek to boost system efficiency, reduce costs, and enhance the scalability of hybrid energy solutions [30].

Demand for hydrogen is increasing daily due to advancements in electrolysis technology, fuel cells, and hydrogen storage solutions [31].

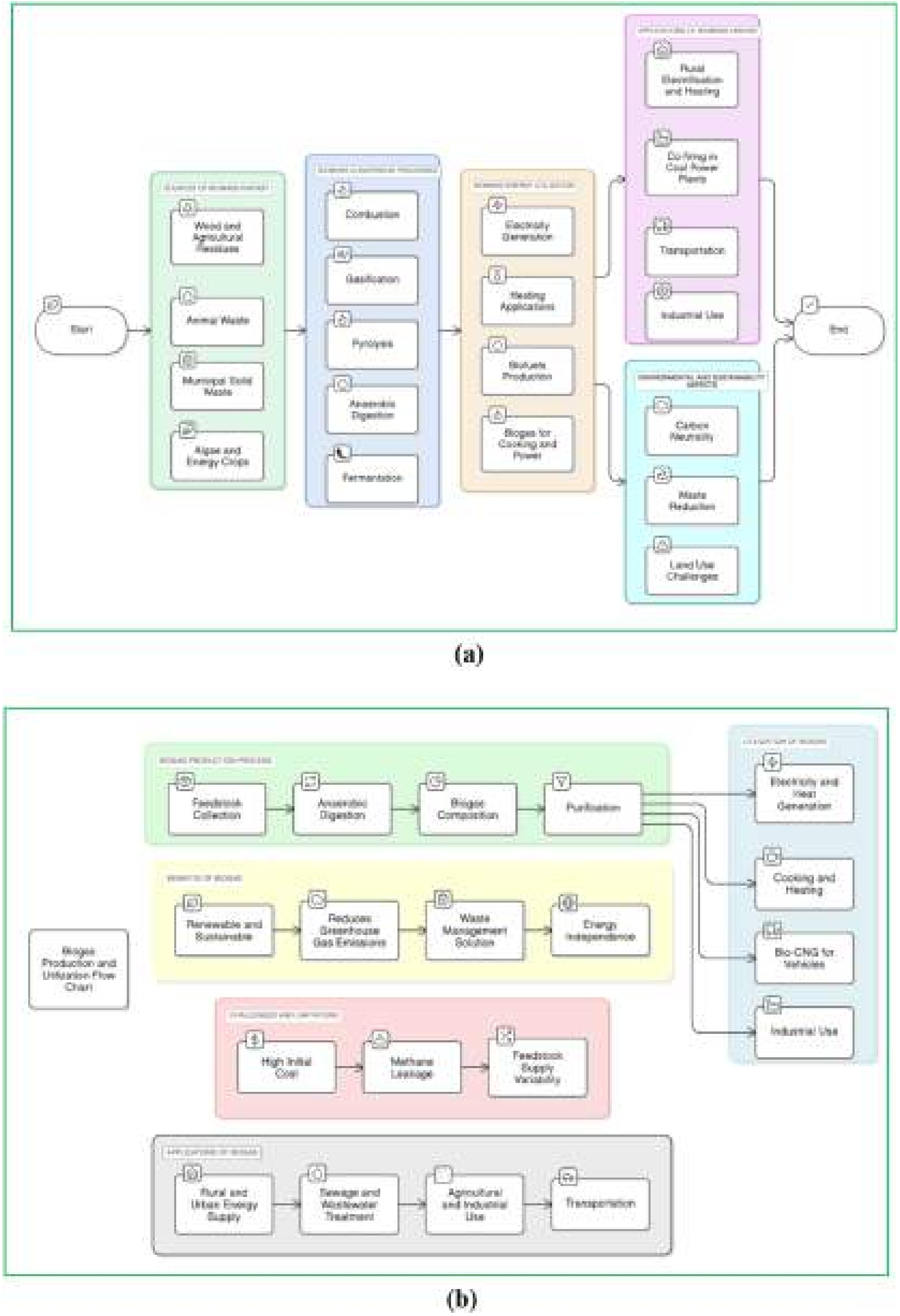


Fig. 3. Energy flow chart **(a)** biomass, **(b)** biogas.

Studies show that green hydrogen [32], generated from surplus solar or wind energy through electrolysis can function as a long-term energy storage solution, mitigating the intermittency of renewable energy sources [33,34]. Hydrogen-based power-to-gas (P2G) systems are being investigated to mix hydrogen with the current natural gas infrastructure, facilitating the transition to a hydrogen economy [35–37].

Recent progress in thermochemical [38] and biochemical conversion technologies have transformed the biomass and biogas sectors [39].

Greater hydrogen production efficiency from biomass can be achieved by using improved gasification techniques, leading to enhanced energy yields and reduced carbon emissions [40]. Additionally, developments in anaerobic digestion increase methane production from organic waste, endorsing decentralized power generation. Biogas and hydrogen fuel cells integrated to improve system efficiency and maintain consistent power supply [41]. Additionally, waste-to-energy initiatives are gaining momentum. These initiatives utilize agricultural and municipal waste to produce clean energy while supporting waste management and enhancing energy security [42].

The reviewed literature highlights various advancements and challenges in HRES systems, refer to Table 1. Research has investigated various hydrogen production methods, such as solar-driven, photocatalytic, photo-electrochemical (PEC), biomass-oriented, and biological approaches. However, these processes face many challenges, such as low conversion efficiency, higher costs, and energy-heavy processes. Similarly, HRES studies also focused on energy integration, storage, and cost-efficiency, highlighting the importance of hybrid energy storage solutions and the need for policy support.

While previous works have provided valuable insights, they are often limited to specific domains (e.g., nanotechnology, PEC, biomass gasification) without a complete, systematic review of hydrogen, PV, biomass and biogas in HRES in an unified manner. So, there is a need to fill this gap by systematic cluster analysis. This study analyzed 174 research articles to identify critical perceptions, trends, and future research directions. The uneven nature of past studies delays the comprehensive understanding of HRES regarding their efficiency, cost-effectiveness, and sustainability. The primary research problem is:

Table 1
Key research contributions of review articles: Hybrid renewable energy systems.

Ref.	Focus Area	Key Topics	Challenges and Trends	Publication Year/Citations	Type of Review
[43]	• Future of electricity generation	• Fossil fuel replacement, smart grids, renewables expansion	• Need for energy storage • Smart grids for balancing supply-demand	• 2011/876	• Broad review on electricity transition
[44]	• Photocatalytic hydrogen production	• Solar-driven hydrogen from water • Biomass derivatives	• Need for advanced photocatalysts • Optimization of reaction conditions	• 2011/572	• Short review on photocatalysis
[45]	• Hydrogen production from renewables	• Biomass gasification, electrolysis • Exergy efficiency	• Low efficiency of solar-based electrolysis • High energy demand for liquefaction	• 2012/645	• Exergy efficiency comparison
[46]	• PEC hydrogen production from biomass	• Biomass derivatives, water splitting • Photoanodes	• Thermodynamic efficiency advantage • Future material challenges	• 2014/367	• Review on PEC systems
[47]	• Nanotechnology in renewable energy	• Nanotech applications in solar, wind, biomass, tidal	• Limited studies in wind • Geothermal, tidal applications	• 2015/389	• Review on nanotech applications
[48]	• Clean energy solutions	• Renewable vs nuclear energy • Multigeneration systems	• Improvement potential for renewables • Economic and environmental trade-offs	• 2015/1024	• Comparative assessment
[49]	• Hydrogen production from renewables	• SCWG of biomass, solar-to-hydrogen efficiency • Hydrogen storage	• High cost of photovoltaic cells • Low solar-to-hydrogen efficiency	• 2016/512	• State-of-the-art review
[50]	• Hybrid renewable energy (HRE) systems	• Space heating, cooling • Power generation, hydrogen production	• Need for hybrid storage • Cost optimization • Policy support	• 2018/418	• Comprehensive review on HRE
[51]	• Photo-electrochemical (PEC) hydrogen production	• PEC water splitting, photocathodes • Photoanodes • Biomass upgrading	• Efficiency improvement, durability challenges • New material	• 2019/275	• Review on PEC developments
[52]	• Biological hydrogen production	• Photo-fermentation • Dark fermentation, photolysis • CO gas-fermentation	• Process integration, optimization of substrates and conditions	• 2020/192	• Comprehensive review on bio-hydrogen
[53]	• Power-to-gas with hydrogen	• Renewable energy sources, hydrogen production, efficiency comparison	• Intermittency of renewables, cost of hydrogen production	• 2021/179	• Comprehensive review
[54]	• Hybrid and polygeneration systems	• Renewable energy, hybrid energy systems, polygeneration	• Integration of multiple energy sources, scalability	• 2022/16	• Comprehensive review
[55]	• Biogas and methane mitigation	• Anaerobic digestion, methane capture, biogas upgrading	• Impurities in biogas, storage and grid integration	• 2022/97	• Comprehensive review
[56]	• Sustainable energy solutions	• Low-carbon technologies, energy storage, hydrogen-based systems	• Need for novel energy storage, hydrogen adoption challenges	• 2023/5	• Conference review
[57]	• Hydrogen generation and storage	• Electrolysis, gasification, storage methods	• Efficiency, cost of hydrogen storage	• 2023/145	• State-of-the-art review
[58]	• Green hydrogen system Configurations	• Electrolyzers, renewable energy sources, hydrogen storage	• System efficiency, technological maturity	• 2024/9	• Comprehensive review
[59]	• Solar thermal hydrogen production	• Solar collectors, steam reforming, thermochemical water splitting	• Efficiency improvements, scalability	• 2024/13	• Focused review
[60]	• Hydrogen as a clean energy carrier	• Hydrogen production from renewables, fossil fuel alternatives	• Infrastructure, cost, global transition	• 2025/0	• Comprehensive review
[61]	• Solar thermal hydrogen pathways	• PV-to-hydrogen, concentrated solar power	• Efficiency, cost-benefit analysis	• 2025/1	• Comparative review
[62]	• Wave energy converters	• Point absorber, oscillating water column, hydrodynamic modeling	• Performance optimization, deployment challenges	• 2025/1	• Comprehensive review
Present work	**• HRES** **• Solar, hydrogen, biomass and biogas**	**• Systematic review: Consortium 174 articles into clusters based on keywords**	**• Critical literature review of each cluster**	**• —**	**• Systematic literature review**

"How can a systematic review of HRES including hydrogen, PV, biomass and biogas deliver a comprehensive understanding of their interdependencies, challenges, and future research directions?"

This research aims to bridge knowledge gaps and support the transition toward a more efficient and sustainable hydrogen economy by addressing these aspects. The impetus for this research stems from the urgent need to design and optimize hybrid models of renewable energy that efficiently combine hydrogen, biomass, biogas, and solar PV. So, the following research objectives are laid.

- To systematically review and classify advancements in HRES by analyzing hydrogen, biomass, biogas, and solar photovoltaics integration.
- To identify key technological trends, challenges, and opportunities in energy storage, optimization, and hybrid renewable energy generation.
- To perform a cluster-based thematic analysis using VOSviewer while cataloging 174 research articles into seven clusters, allowing interconnections and research gaps.
- To evaluate the impact of AI-driven hybrid storage solutions, energy management, and policy frameworks on improving the scalability of HRES.
- To provide future research directions and policy developments that support the transition toward a sustainable, decarbonized energy economy.

This systematic review presents a detailed, cluster-based study of HRES, organizing 174 research articles into seven thematic clusters through VOSviewer. By assessing the integration of hydrogen, biomass, biogas, and PV, the research uncovers significant technological advancements, energy storage substitutes, and optimization techniques that improve grid stability and energy efficiency. It also highlights economic and policy issues that hinder large-scale implementation of innovative hybrid storage solutions, supportive regulations, and AI-based energy management techniques. The insights offer a strategic framework for researchers, policymakers, and industry leaders to enhance hybrid renewable energy solutions' scalability, commercialization, and long-term viability, by supporting sustainability and decarbonization efforts.

2. Materials and methods

2.1. Data search strategy

Data for this systematic review were collected from the Scopus database. The study employed the PRISMA (Preferred Reporting Items

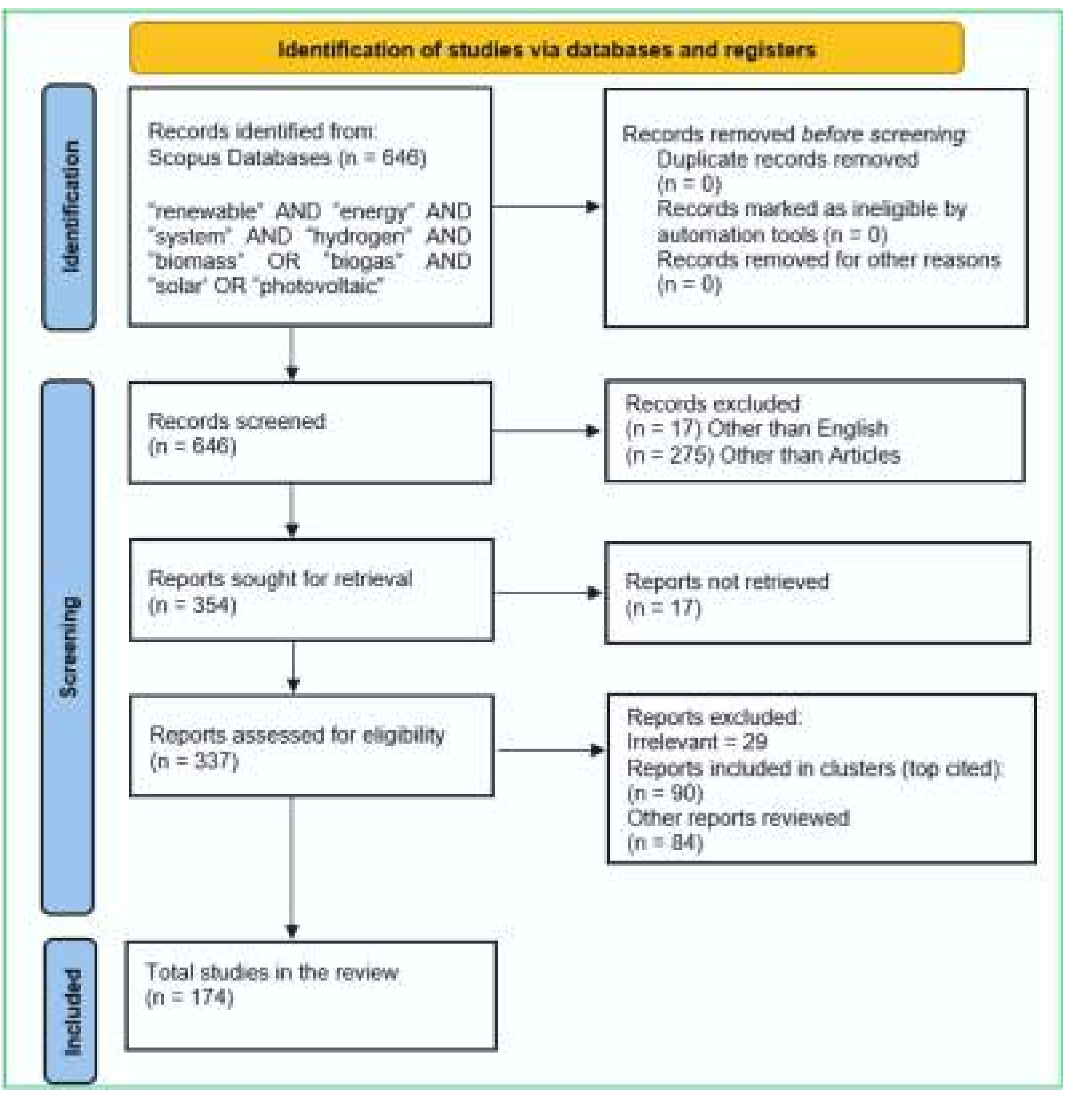


Fig. 4. Systematic review workflow illustrated by PRISMA

for Systematic Reviews and Meta-Analyses) framework to guarantee a structured and transparent method for conducting the systematic literature review [63,64] of hydrogen, biomass, and photovoltaic hybrid energy systems, refer to Fig. 4. A thorough search query was created using the following keywords:

(TITLE-ABS-KEY(renewable) AND (energy) AND (system) AND (hydrogen) AND (biomass) OR (biogas) AND (solar) OR (photovoltaic)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English"))

The PRISMA flow diagram in Fig. 4 illustrates identifying, screening, and selecting studies for a systematic review of hydrogen energy systems, including hydrogen, biomass, and photovoltaic sources. The identification stage began with retrieving 646 records from the Scopus database using search terms such as "renewable," "energy," "system," "hydrogen," "biomass," "biogas," "solar," and "photovoltaic."

At this stage, no duplicate records or ineligible studies were removed. During the screening phase, all 646 records were reviewed, excluding 17 studies for being in languages other than English and 275 records for not being journal articles, such as conference papers or book chapters, etc. This left 354 reports for retrieval, of which 17 could not be accessed, resulting in 337 studies being assessed for eligibility. After evaluating eligibility, 29 reports were excluded for irrelevance to study area. 90 Studies were identified as part of the most cited clusters and 84 additional reports were reviewed. A total of 174 studies were included in the final systematic review. This structured process ensures that only the most relevant and high-quality studies are considered, providing a strong foundation for the systematic review of hydrogen, biomass, and photovoltaic hybrid energy systems.

2.2. Cluster formation using VOSviewer

Cluster analysis using author keywords in VOSviewer depicts the latest trends and associated patterns, helping to recognize emerging areas and overriding themes. This systematic literature review tool can also quickly identify research gaps and future directions. This study utilized VOSviewer (version 1.6.20) for the systematic literature review. Author keywords were analyzed to produce clusters, categorizing 354 selected articles into seven thematic clusters. Each cluster was named based on relevant keywords. The VOSviewer analysis was conducted on a total of 1014 author keywords, from which 63 keywords met the threshold criterion, with a minimum occurrence of 4. Refer to Fig. 5a, it depicts a detailed visualization of the clusters and their allied author keywords, Fig. 5b represents the author keywords network diagram and Fig. 5c represents the author keywords density diagram.

Cluster names were assigned by carefully reviewing dominant author keywords and their co-occurrence links within each visualized group. Each cluster's label reflects the thematic concentration of the most frequently occurring keywords. It is validated by reviewing the titles, abstracts, and contexts of the top-cited articles in that cluster. This ensured that each cluster name accurately represented the underlying literature's prevailing research focus and technological scope.

2.3. Cluster-wise systematic literature review process

A systematic search was conducted once clusters were generated within the dataset of 354 articles. Cluster names were assigned based on author keywords, and each keyword was used as a filter to identify relevant articles in a particular group. However, since multiple author keywords were used for filtering, some articles appeared in various clusters. Repeated articles were systematically removed from overlapping clusters to maintain accuracy and avoid redundancy, ensuring each study was assigned to its most relevant category.

For example, in Cluster 7, the keywords "Biohydrogen" and "Biomass" were used to filter articles. Conditional formatting in Excel highlighted the top-cited articles from the dataset based on these author keywords. This search initially produced 93 articles, and those with over 30 citations were chosen for further critical review within the cluster. Cluster 7 includes 10 articles when duplicates were removed.

A similar process was repeated for all the clusters, achieving well-structured and non-redundant cluster categories. This critical review helps extract key insights and organize structured tables. These tables were examined to identify outlines, trends, and remarkable findings, leading to a more precise and comprehensive conclusion for each research domain.

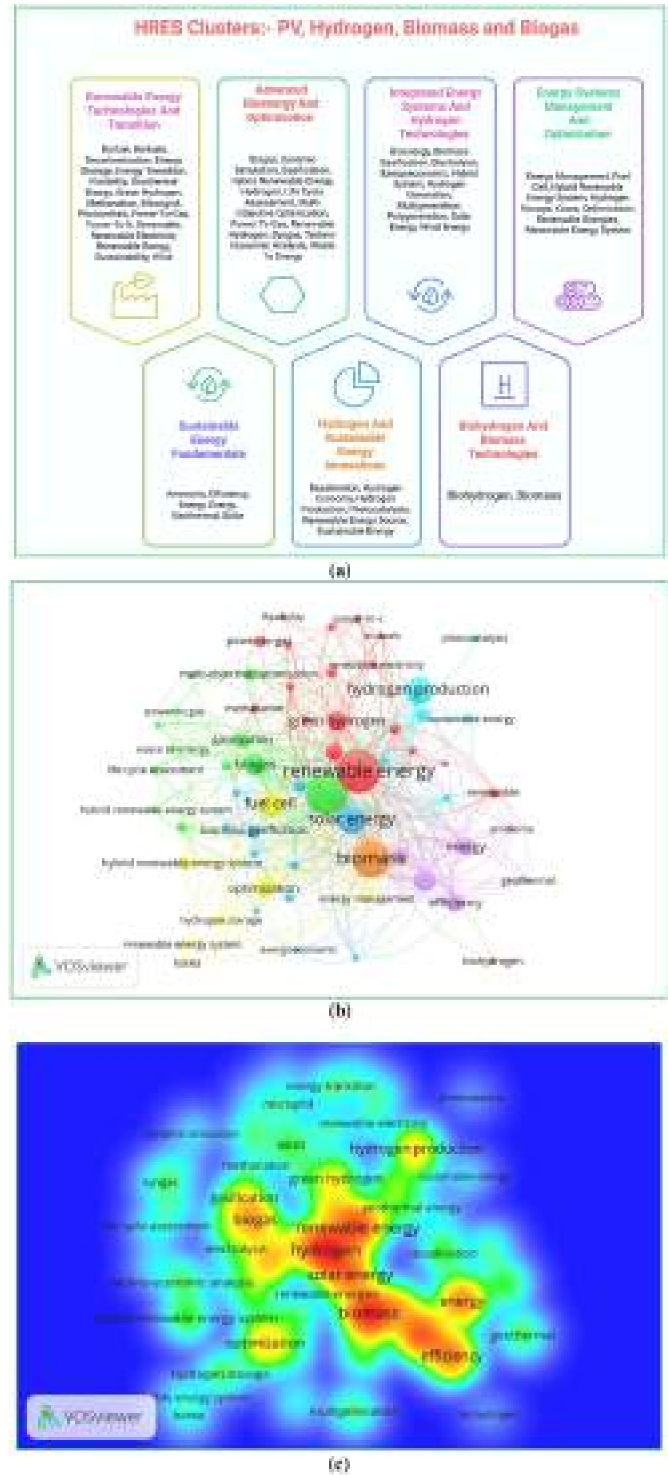


Fig. 5. (a) Formation of Different Clusters based on Keywords (b) Author Keywords Network Diagram (c) Author Keywords Density Diagram.

3. Cluster-wise critical review of literature

To fully grasp the recent progress in HRES, a cluster analysis was conducted using VOSviewer based on author keywords. This method classified 174 selected research articles into seven thematic clusters, each illustrating a distinct focus area within the HRES spectrum. The clusters showcase interconnected research paths, including renewable energy transition, bioenergy optimization, integrated hydrogen systems, and sustainable fuel innovations. Through a critical review of each cluster, the study uncovers the core technologies, significant findings, challenges, and future research avenues that influence the advancement of hybrid systems involving hydrogen, biomass, biogas, and solar PV. This organized review facilitates a focused assessment of contributions across various thematic areas, providing a comprehensive understanding of HRES.

3.1. Cluster 1: Renewable Energy Technologies and Transition

There is a need to shift towards renewable energy to achieve a sustainable, low-carbon future. Cluster 1, "Renewable Energy Technologies and Transition," surveys different renewable energy technologies, storage systems, and hybrid energy combinations for improving energy efficiency and minimizing environmental impact. Research in this cluster emphasizes the integration of the hydrogen economy, wind and solar power, biomass, and poly-generation systems to optimize the use of renewable energy, as shown in Fig. 6.

Table 2 depicts a detailed "Renewable Energy Technologies and Transition" research regarding Cluster 1. Many significant advancements and new innovative startegies were presented such as ice storage tanks, ground-source heat pumps, and wind turbines. Wind energy integration has decreased CO_2 emissions by up to 54 %, providing sustainable district energy systems and hydrogen applications in heating and cooling [65]. Recent methodologies like carbon capture and sequestration, involving amine scrubbing and photosynthetic bioreactors, reveal potential for sustainable CO_2 sequestration and economically feasible emission reduction [35]. Nanotechnology in PVs and biofuels boosts efficiency and lowers costs, aiding the shift towards alternative renewable energy sources [66].

Hydrogen production is being thoroughly investigated in developing countries in Pakistan, where biomass, solar PV, and municipal solid waste could yield 6.6 million tons annually, facilitating the establishment of a renewable hydrogen supply chain [67]. Enhancements in optimizing polygeneration systems integrating renewable and conventional sources have improved energy efficiency [68]. HRES, such as solar-integrated biodiesel production, demonstrate improved efficiency and lower NOx [69], while hybrid solar-methanol fuel cell systems operate at efficiencies exceeding 50 % [70]. Similarly, integrating PV modules with fuel cells enhances the performance of hybrid power generation systems by decreasing harmonic distortion [71]. The techno-economic viability of P2G processes, utilizing electrolysis and methanation with anaerobic digestion, has been confirmed, resulting in 100 % renewable methane production [72]. Incorporating energy storage with water management demonstrates the feasibility of producing hydrogen and oxygen through electrolysis while removing micropollutants [73]. Renewable hydrogen production efficiencies, primarily via biomass gasification, have reached top energetic and exergetic efficiencies of 53.6 % and 49.8 %, respectively [74]. Thermodynamic analyses of energy storage systems suggest pumped hydro storage efficiencies from 58 % to 94 %, while molten salt storage shows significant exergy destruction [75].

Hydrogen economy adoption strategies using fuzzy AHP-TOPSIS models, featuring significance of strategic decision-making in China have been assessed [76]. Poly generation techniques when integrated with HRES supports many new applications such as hydrogen production and desalination [77]. Hybrid optimization of RES, such as PV/wind/biogas/fuel cell (FC) systems, achieves a 100 % renewable energy share, showing cost-effective solutions for sustainable energy provision [78]. The Integrated Energy Production Unit concept boosts power system flexibility and emission reductions through the incorporation of PV power [79].

Educational insights reveal a lack of awareness regarding renewable energy and hydrogen technologies among teacher candidates, stressing education's role in advancing the energy transition [80]. Biomass-based multigeneration systems improve energy and exergy efficiencies by 4.8 % and 6.3 % when paired with cooling systems, making them suitable for off-grid residential applications [81]. Renewable-powered multigeneration systems using concentrated photovoltaic-thermal (CPVT) technology achieve energetic efficiencies reaching 71.06 %, providing

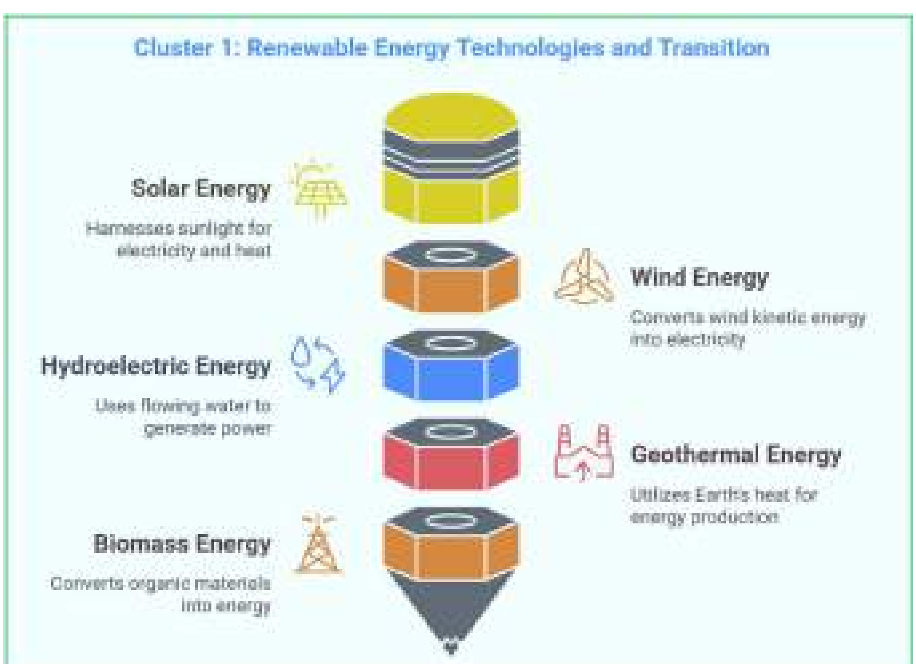


Fig. 6. Cluster 1: Renewable energy technologies and transition.

Table 2
Themes and insights on renewable energy technologies and transition: Cluster 1.

Ref.	Focus Area	Technology/Method	Key Findings	Potential Impact
[67]	• Wind energy	• Ice storage tanks • Ground-source heat pump • Wind turbines	• SPI: 1.06 • CO_2 emissions reduced: 54 %	• Supports sustainable district energy systems
[76]	• CO_2 capture • Sequestration	• Amine scrubbing • Photosynthetic reactions in bioreactors	• Photosynthetic reactions in controlled environments	• Development of economically and environmentally sustainable systems
[73]	• Nanotechnology	• Nanomaterials in PVs • Biofuels	• Improved efficiency and stability • Reduced cost of solar energy and biofuel systems	• Facilitates transition to alternative and RES
[88]	• Hydrogen economy in Pakistan	• Biomass • Solar PV • Municipal solid waste for hydrogen production	• 6.6 million tons/year hydrogen production potential	• Hydrogen supply chain development
[69]	• Optimization of polygeneration systems for energy efficiency	• Renewable and conventional sources	• Control strategies to optimize system performance	• Efficient production of power
[71]	• Design of HRES	• HRES with solar	• TES in TCR increased biodiesel production by 34.9 % • HRES emitted 12 % less NOx	• Integration of HRES
[78]	• Hybrid solar systems for residential energy generation	• Methanol-fed PEM fuel cells with solar collectors	• System efficiency above 50 % • Feasibility through bench test and prototype	• Efficient and cost-effective power generation for residential use
[65]	• Hybrid power generation system design and performance analysis	• PV modules with NF MPPT controller • Air-breathing fuel cells	• HPG system design reduces harmonic distortion	• Efficient hybrid systems for renewable energy integration
[35]	• Techno-economic analysis of P2G processes	• Electrolysis and methanation integrated with anaerobic digestion	• Economic feasibility demonstrated • 100 % renewable energy used for methane production	• Sustainable methane production
[66]	• Integration of energy storage with water management	• Micropollutant removal	• Electrolysis driven by renewable energy is feasible and sustainable for climate and water protection	• Integration of energy storage with wastewater treatment plants
[68]	• Renewable energy-based hydrogen production efficiencies	• Solar PV	• Biomass gasification had the highest energetic and exergetic efficiencies (53.6 % and 49.8 %)	• Efficient hydrogen production through renewable sources • Feasibility of multi-stage processes
[70]	• Thermodynamic analysis of energy storage systems	• Pumped-hydro	• Roundtrip efficiencies range from 58 to 94 % • Molten salt shows the highest exergy destruction	• Selection of efficient storage systems for renewable energy integration
[72]	• Evaluation of RES for hydrogen economy in China	• Fuzzy AHP-TOPSIS for RES evaluation	• Solar	• Strategic renewable energy adoption for hydrogen systems in China
[74]	• Renewable and conventional energy sources • Polygeneration	• Renewable and fossil fuel-fed advanced energy systems	• Focus on energy services integration	• Multi-energy vector systems with diverse applications • Hydrogen and desalination
[75]	• Optimization of hybrid RES	• PV/WT/BG/FC with hybrid optimization algorithms	• System achieved 100 % renewable energy fraction • ACS minimized using HFGA	• Standalone hybrid systems for cost-effective renewable energy supply
[77]	• Integrated energy production unit concept for power systems	• PV power	• IEPU concept enhances system flexibility with renewable energy integration	• Supports emission reduction goals and power system flexibility
[79]	• Educational perspectives • Renewable energy and hydrogen	• Qualitative research • Teacher candidates	• Awareness of renewable energy and hydrogen	• Role of education in promoting renewable energy adoption
[80]	• Development of renewable energy-based multigeneration systems	• Biomass	• Energy and exergy efficiencies increased by 4.8 % and 6.3 % with cooling system	• Comprehensive energy solutions for off-grid residential areas
[81]	• Renewable-powered multigeneration energy systems	• CPVT	• System achieved energetic efficiencies up to 71.06 %	• Environmentally friendly
[82]	• Integration of renewable energy with waste gasification technologies	• Hydrogen electrolysis	• Electric efficiencies ranged from 40 % to 43 % • Better performance than separate systems	• Efficient use of waste and renewable energy for power generation
[83]	• Hybrid power generation using biogas and renewable energy	• Biogas	• Carbon emissions reduced by 96 % • Cost savings of 28.42 % • THD of 4.53 %	• Cost-effective and sustainable hybrid systems for societal and industrial use
[84]	• Rural electrification using hybrid RES	• Hybrid PV/wind/biogas/fuel cell system	• Adding fuel cells increased costs by 33–37 % but improves system flexibility • On-grid energy costs 0.096–0.125 $/kWh	• Affordable and sustainable rural electrification solutions
[85]	• Liquid solar fuel production for transport applications	• Synthetic fuels from renewable energy	• Achievable process efficiency: ~50 % • Product cost: ~1 US$/liter for large-scale units	• Carbon-free synthetic hydrocarbon fuels for transport
[86]	• Solar biomass co-fired systems with hydrogen integration	• Hydrogen injection to reduce fossil fuel and CO_2 emissions	• CO_2 emissions reduced by 2 % • Exergy destruction cost lowered: 3.36 %	• Enhanced efficiency and sustainability in energy generation
[87]	• Hydrogen-based urban energy systems	• Hydrogen from surplus wind/solar power • Hydrogen-enriched biogas	• Exergy efficiency: 0.80 • Supports net-zero exergy districts	• Sustainable urban energy systems using hydrogen

environmentally sustainable energy options [82]. Hydrogen electrolysis, alongwith waste gasification, generates 40 %–43 % electric efficiencies [83].

Biogas and renewable energy together result in a 96 % reduction in carbon emissions and potential cost savings of 28.42 %. Thus, it is a sustainable and economically viable choice for industries and society [84]. Solutions for rural electrification utilizing hybrid PV/wind/biogas/fuel cell systems show that although incorporating fuel cells boosts costs by 33 %–37 %, it enhances system flexibility, with on-grid energy prices between $0.096 and $0.125 per kWh [85]. Liquid solar fuel production for transport applications achieves about 50 % process efficiency with an estimated cost of around $1 per liter for large-scale units, facilitating carbon-free synthetic hydrocarbons for transport [86]. Co-fired solar biomass systems with hydrogen injection lower CO_2 emissions by 2 % while decreasing exergy destruction costs by 3.36 %, thus improving energy generation sustainability [87].

Fig. 7 shows efficiency distribution across renewable energy technologies attained in different studies. Hydrogen production from biomass shows an energetic efficiency of 53.6 %, whereas electrolysis-based hydrogen production has a slightly lower efficiency of 49.8 % [74,83].

Hybrid solar systems consisting solar collectors with fuel cells having efficiency more than 50 % can be used mainly for residential purpose [70]. The P2G process for methane generation has 100 % efficiency [72]. Pumped-hydro energy storage with operating efficiency near 58 % are highly significant for integrating RES [75]. Liquid solar fuels having 50 % efficiency, is a workable substitute for conventional fossil fuels and mainly used for transportation purposes [86]. Biogas hybrid systems reduces carbon emissions up to 96 % and is a sustainable and cost-effective solution for industrial and societal applications [84]. Multigeneration systems utilizing biomass achieve an energetic efficiency of 71.06 %, illustrating their potential to enhance overall energy system performance [82]. Finally, solar biomass co-firing systems, combined with hydrogen injection, demonstrate an electric efficiency between 40 % and 43 %, further promoting low-carbon energy production [87].

3.1.1. Conclusion and future directions for cluster 1

Cluster 1, "Renewable Energy Technologies and Transition," highlighted the vital role of HRES, hydrogen technologies, and energy storage solutions for successful transition to sustainable and low-carbon energy systems. HRES along with energy storage and optimization algorithms, multi-energy integration, and hybrid systems offer advantages over single-source renewables. Technologies based on hydrogen, alongside P2G and Liquid Solar Fuel production, hold great promise and can improve the present renewable scenario and increase energy security.

Significant efficiency gains are observed with systems integrating solar with hydrogen and multigeneration technologies. Future research should improve these technologies to lower costs and boost performance, promoting their broader acceptance in global energy markets. Cluster 1 highlights that future research needs to concentrate on scaling up hydrogen production while looking into cost reductions and enhancing hydrogen storage infrastructure. Hydrogen-enriched biofuels integrated with district energy systems must focus on new developments. There is a need to optimize HRES, which comprises hybrid photovoltaic, wind, and fuel cell systems for rural electrification and grid stability.

3.2. Cluster 2: Advanced Bioenergy and Optimization

Cluster 2 "Advanced Bioenergy and Optimization" presents renewable energy production through bio-based technologies and advanced computational methods. It explores efficient biomass conversion, waste-to-energy solutions, and hybrid bioenergy systems integrated with renewables, solar and wind, refer to Fig. 8.

Table 3 presents a complete analysis of hydrogen production methods from renewable sources with a focus on different regions and technological approaches. Several studies explored that hydrogen production through biomass gasification, solar PV, geothermal, and electrolysis, improves efficiency, feasibility, and environmental benefits.

Ni et al. [89] depicted that 40 % of transportation energy demand and significant energy security with clean hydrogen production can be achieved in Hong Kong using wind-PV electrolysis and biomass conversion. Ishaq et al. [68] compared renewable hydrogen efficiencies and identified biomass gasification as the most efficient method with 53.6 %

Fig. 8. Cluster 2: Advanced bioenergy and optimization.

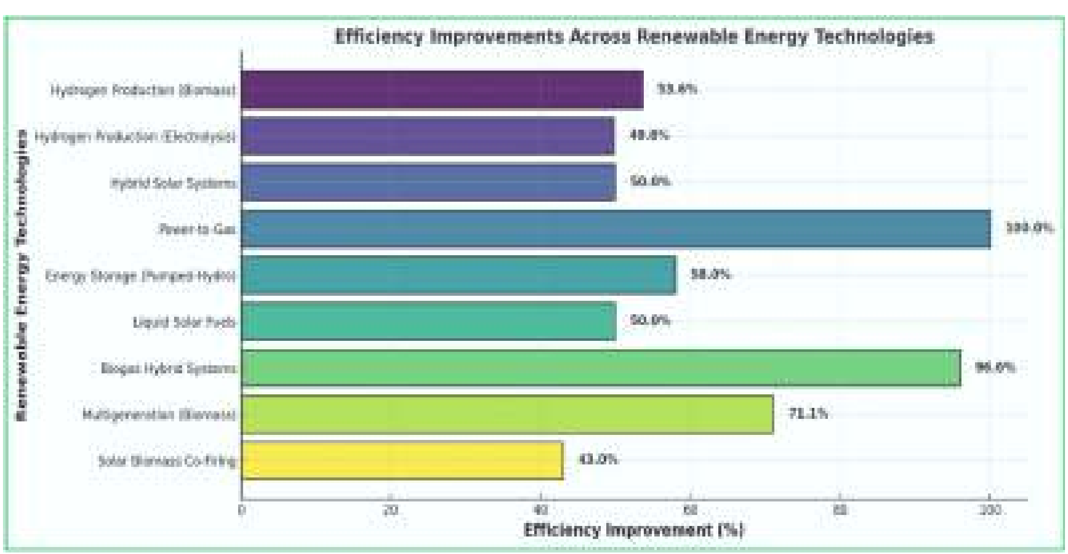


Fig. 7. Efficiency distribution across renewable energy technologies.

Table 3
Advanced bioenergy and optimization: Cluster 2.

Ref.	Focus Area	Technology/Method	Key Findings	Potential Impact
[89]	• Renewable hydrogen in Hong Kong	• Wind • PV • Electrolysis • Biomass conversion	• Renewable sources (solar, wind, and biomass can produce significant hydrogen) • 40 % of transportation energy demand achieved	• Enhances energy security and reduces fossil fuel dependency • Potential for clean hydrogen production from waste
[68]	• Renewable hydrogen efficiency analysis	• Solar PV • Geothermal • Biomass gasification	• Biomass gasification has the highest efficiency (53.6 % energetic, 49.8 % exergetic) • Solar PV and geothermal have lower efficiencies	• Optimized hydrogen production from various renewable sources • Biomass as the most efficient method
[90]	• Biological hydrogen production	• Green algae • Purple bacteria • Anaerobic fermentation	• Integrating different biological processes improves hydrogen yield and solar spectrum utilization	• Enhances biohydrogen production efficiency through combined biological systems
[88]	• Hydrogen economy in Pakistan	• Solar • Wind • Geothermal • Biomass • Municipal solid waste	• Biomass is the most feasible feedstock for hydrogen in Pakistan (6.6 million tons annually) • Solar PV (2.8 million tons) • Municipal solid waste (1 million tons)	• Lays the foundation for a hydrogen economy in Pakistan • Leveraging renewable resources for energy security
[91]	• Optimal hydrogen supply system in Jeju island, Korea	• Superstructure-based optimization • A mixed-integer linear programming MILP • Electrolysis • Biomass gasification	• MILP approach optimizes hydrogen production from renewable sources • Minimizes costs	• Integration of multiple renewable resources for cost-effective hydrogen production • Economic analysis for feasibility
[92]	• Biomass gasification for hydrogen	• Biomass gasification • Catalytic conversion • Solar-thermal integration	• Biomass gasification can be enhanced using concentrated solar energy	• Reduced carbon footprint by integrating solar energy
[94]	• Hybrid energy systems for households	• Wind-PV-diesel hybrid • Hydrogen utilization • Battery storage	• A wind-hydrogen-battery system is the most economical • Net present cost: $63,190 • Energy cost: $0.783/kWh	• Reduces dependence on fossil fuels • Clean energy solutions for residential use
[93]	• Renewable hydrogen for ammonia synthesis	• Biomass gasification • Biogas reforming • High-temperature water electrolysis	• Hydrogen from renewable sources • Promising solution for sustainable ammonia production (Haber-Bosch process)	• Enables fossil-free ammonia synthesis • Energy efficiency and sustainability of different hydrogen production methods
[95]	• Multi-renewable hydrogen production	• Biomass electrolysis • Powered by wind and solar	• Enhanced efficiency • Reduced electricity consumption	• Hydrogen fueling stations • On-site hydrogen production
[96]	• Environmental and economic impacts of hydrogen	• Photocatalysis • Photoelectrolysis • Biomass gasification	• Solar-hydrogen has near-zero emissions	• Sustainable hydrogen production • Reduced carbon footprint
[97]	• Off-grid energy system for rural areas	• Biogas-CHP-PV hybrid system	• Lowest capital and energy costs	• Rural electrification • Decentralized energy solutions
[98]	• Municipal solid waste (MSW) gasification	• MSW gasification with SOFC and stirling engine	• Increased efficiency (50 %) compared to waste incineration	• Waste-to-energy solutions • Reduced landfill dependency
[99]	• Solar thermal-based multi-generation system	• ORC • Absorption chillers • Electrolyzer • Belt dryer	• Produced electricity, heating, cooling, hydrogen, biomass	• Multi-output energy systems • Enhanced resource utilization
[105]	• Hydrogen and fuel cell applications	• Fuel cells • Hydrogen from renewables • Biogas reforming	• Hydrogen enables transportable zero-emission power	• Fuel cell applications • Hydrogen economy • Clean transportation
[100]	• Hydrogen production cost-benefit analysis	• AHP and fuzzy AHP applied to eight hydrogen production technologies	• Fossil fuel-based hydrogen production is cost-effective • Water splitting by chemical looping is the most promising among renewables	• Identifies cost-benefit trade-offs in hydrogen production • Highlights promising renewable hydrogen production methods
[101]	• Biogas-hydrogen engine optimization	• Simulation-based control of engine parameters	• Adding 20 % hydrogen to biogas improves engine efficiency • Increased NOx emissions by 10–15 %	• Boosted hybrid RES with optimized engine control
[102]	• Renewable methanol production	• Biomass gasification • Solar power • Alkaline water electrolysis	• A novel biomass gasification system coupled with a 50.4 MW solar plant	• Optimized model for large-scale integrated renewable power systems

energetic and 49.8 % energetic efficiencies.

Melis et al. [90] investigated biological hydrogen production by integrating green algae, purple bacteria, and anaerobic fermentation to improve hydrogen yields and solar spectrum utilization. On a regional scale, Jeju Island in [91] employed a mixed-integer linear programming (MILP) approach to optimize hydrogen supply, reducing costs and integrating multiple renewable sources. Advancements in biomass gasification are evident in studies [92,93], with solar-thermal integration enhancing efficiency and reducing land requirements. Hydrogen applications extended to household energy systems [94], and wind-hydrogen-battery hybrid system proved to be the most economical for residential use in Tehran.

Hydrogen plays a vital role in sustainable ammonia synthesis [93] and multi-renewable hydrogen production [95] making it highly applicable for industrial and energy sectors. Environmental and economic impacts [96] indicated that solar-based hydrogen has near-zero emissions, whereas coal has the highest, reinforcing the sustainability of renewable hydrogen. Off-grid solutions [97] and municipal solid waste (MSW) gasification [98] also offered decentralized energy solutions, reducing landfill dependency and capital costs.

Hydrogen's potential in multi-generation energy systems [99] and fuel cells [100] strengthened the case for its integration into clean transportation and decentralized power generation. Optimizing biogas-hydrogen engine parameters [101] improved efficiency and reduces emissions, while renewable methanol production [102] coupled biomass gasification with a large-scale solar plant for enhanced economic benefits.

Biomass gasification emerged as the most efficient hydrogen production method [68] with further improvements possible through solar-thermal integration [92]. Other methods like solar PV and geothermal exhibit lower efficiency but contribute to diversified hydrogen production.

MILP-based optimization in Jeju Island [91] and hybrid energy systems [101] provides the most optimized cost effective hydrogen solution. Trade-offs between fossil-based and renewable hydrogen, emphasized long-term economic and sustainability benefits [102,103]. According to studies conducted by Refs. [89,96], and [102], hydrogen from renewable sources can significantly reduce carbon emissions. Integrating solar, biomass, and electrolysis created a sustainable and decentralized hydrogen economy. Hydrogen has been proved to be highly versatile. Waste-to-energy solutions [104] and off-grid electrification [97] further expanded its applicability.

Fig. 9 outlines the efficiency (%) and cost ($/MWh) of various hydrogen production methods, emphasizing their trade-offs. Biomass gasification is the most efficient method at 53.6 %, with relatively low costs at $90/MWh ([74,92]). Electrolysis and fuel cells deliver moderate efficiency ranging from 45 % to 50 %, accompanied by higher costs of $110 to $120/MWh ([91,105]). Biological methods, such as fermentation and algae-based hydrogen production, demonstrate a lower efficiency of 40 % but hold promise for renewable hydrogen [90]. Meanwhile, photocatalysis shows the lowest efficiency at 35 % and the highest cost at $140/MWh, though it produces nearly zero emissions [96]. This analysis helps to identify ideal hydrogen production pathways that strike a balance between efficiency and cost.

The comparison in Table 4 shows the performance of different hydrogen production methods with respect to energy efficiency, production cost, CO_2 emission, and so on. Biomass Gasification proves to be the most energy-efficient renewable-based technology with an energy efficiency of 53.6 %, relatively moderate cost of about $90/MWh, and CO_2 emissions of 2.87 kg CO_2-eq/kg H_2. Though the emissions are slightly higher, it is well-balanced in efficiency and cost and therefore is a feasible renewable solution. Solar Electrolysis with PV has moderate efficiency (45–50 %) and low emission rates (1.45 kg CO_2-eq/kg H_2) but is restricted by its high cost of production (between $110 and $120/MWh), which keeps it from being economically viable for widespread application. Wind Electrolysis has the same efficiency (~50 %) but is better for the environment, having the lowest CO_2 emissions (1.29 kg CO_2-eq/kg H_2) and slightly lower production costs than solar, and is one of the cleanest approaches.

Methanol Electrolysis (MEP) offers the highest energy efficiency (~65 %) of all listed processes. Its cost is comparatively low at ~$80/MWh, and emissions are moderate (~2.00 kg CO_2-eq/kg H_2) based on methanol production. It uses less energy than traditional water electrolysis, indicating possible hybrid renewable-fossil applications. Biological approaches like algae-based and fermentation-based hydrogen are sustainable with low emissions but low energy efficiency (35–40 %) and very high costs ($130–140/MWh), so they are less practical to use for present industrial needs. Biogas Reforming is somewhere in the middle when it comes to cost (~$95/MWh) and efficiency (~48 %), but it has the highest level of emissions (3.61 kg CO_2-eq/kg H_2), which would call into question its sustainability even though it has cost benefits.

In general, the efficiency vs. cost vs. environmental balance is apparent. Solar and wind electrolysis are favored for clean hydrogen at higher costs, but methanol electrolysis and biomass gasification present a cost-performing balance depending on resource supply and environmental concern.

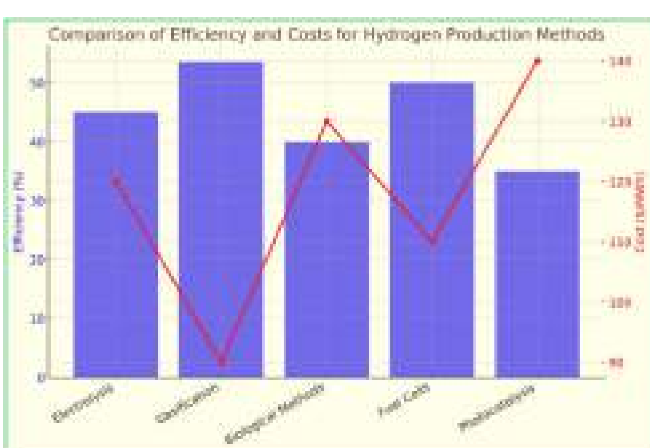


Fig. 9. Comparative analysis of efficiency and costs for hydrogen production methods.

3.2.1. *Conclusion and future directions for cluster 2*

The studies in cluster 2 collectively emphasized the growing feasibility of hydrogen as a clean energy carrier, with biomass gasification, electrolysis, and hybrid renewable systems leading the way. Cost and efficiency remain key challenges, but technological advancements and optimization models (e.g., MILP and chemical looping) offer promising solutions. Environmental benefits, particularly in reducing carbon footprints, solidified hydrogen's role in future energy landscapes.

Biomass gasification and electrolysis through AI-driven optimization and hybrid renewable integration must be the key areas to be focused on in the future. Hydrogen adoption becomes easier while developing economic incentives, subsidies, and financial models. Hydrogen fueling stations, storage solutions, and transportation applications should be further explored to enhance hydrogen's practical deployment.

3.3. *Cluster 3: Integrated Energy Systems and Hydrogen Technologies*

Cluster-3, "Integrated Energy Systems and Hydrogen Technologies," emphasizes innovative approaches for sustainable energy production and utilization. It includes bioenergy, biomass gasification, electrolysis, and hybrid systems for efficient hydrogen generation. The cluster scrutinizes multigeneration and polygeneration systems and also optimizes resources through exergoeconomic analysis, as illustrated in Fig. 10.

Table 5 explored various methodologies for sustainable hydrogen production and integrated energy systems. Hydrogen generation through electrolysis, biomass gasification, and advanced hybrid approaches are mainly focused to improve efficiency and sustainability. Comparative environmental impacts of different hydrogen production pathways, with wind-powered electrolysis in studies [106,107] shows lowest global warming potential. Similarly [104,108], highlighted large-scale renewable hydrogen initiatives in China and Japan, demonstrating the feasibility of transitioning towards self-sufficient energy systems.

Innovations in multigeneration and polygeneration systems are crucial for increasing efficiency and reducing emissions. Studies such as [81], and [109] illustrated integrated energy systems that simultaneously generate electricity, heating, cooling, and hydrogen. These systems achieve high energy and exergy efficiencies while reducing carbon footprints. Integrating solar power with biomass gasification, as shown in [103] optimizes land use and enhances system reliability. Hydrogen applications extend beyond energy production to transportation and household use. Research in Refs. [110,111] focused on renewable-powered EV charging infrastructure, demonstrating cost-competitive, grid-independent solutions. Meanwhile [112], explored the role of hydrogen as a clean cooking fuel, which could significantly reduce reliance on biomass in developing regions. Hybrid systems combining solar, wind, and biogas technologies, as seen in Refs. [113,114], optimized energy access for underserved communities.

Table 4
Comparative analysis of hydrogen production methods.

Hydrogen Production Method	Energy Efficiency (%)	Production Cost ($/MWh)	CO_2 Emissions (kg CO_2-eq/kg H_2)	Key Remarks
Biomass gasification	53.6 (energetic)	~90	~2.87	Most efficient renewable method
Solar electrolysis (PV)	45–50	110–120	1.45	Low emissions; high cost
Wind electrolysis	~50	~100	1.29	Lowest emissions
Methanol electrolysis (MEP)	~65	~80	~2.00* (dependent on methanol source)	Requires less energy than water electrolysis
Biological methods (Algae/ Fermentation)	35–40	~130–140	Low	Environmentally friendly, low efficiency
Biogas reforming	~48	~95	3.61	Highest emissions

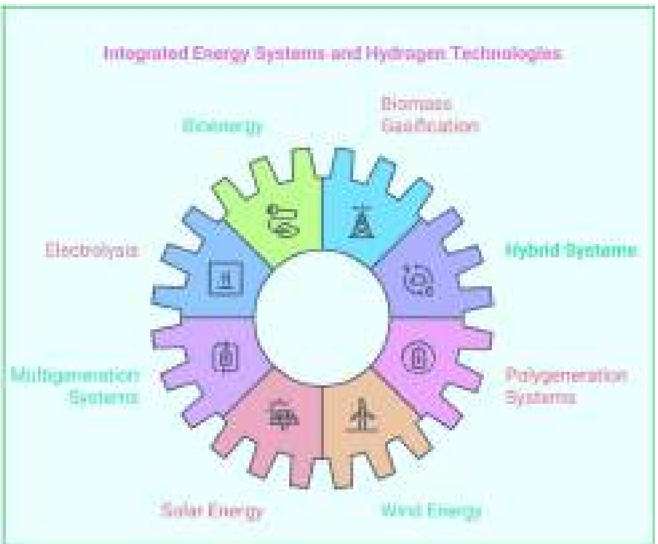


Fig. 10. Cluster 3: Integrated energy systems and hydrogen technologies.

The hydrogen production through wind and solar electrolysis offers the lowest environmental impact [107], while biogas reforming remains the least sustainable option due to high CO_2 emissions. Multigeneration systems [81], provide a versatile solution for increasing efficiency compared to standalone renewable technologies. Studies like [111,113] indicates that hybrid renewable systems can provide cost-effective energy access in developing nations. Another key comparison emerged between polygeneration and traditional energy systems. While polygeneration systems [115] demonstrate superior efficiency in utilizing biomass and renewables, their economic viability depends on district heating and infrastructure. Similarly, integrating renewables with fossil fuels for methanol production [116] reduces emissions but faces efficiency and cost competitiveness challenges.

Fig. 11 depicts the global warming potential of hydrogen production, showcasing CO_2 emissions (kg CO_2 eq/kg H_2) from various hydrogen production technologies, according to analysis by findings from [107]. Among the techniques analyzed, wind-powered electrolysis stands out as the most environmentally friendly, producing just 1.29 kg CO_2 eq/kg H_2. Solar electrolysis is a close second with emissions of 1.45 kg CO_2 eq/kg H_2. In contrast, biomass gasification has considerably higher emissions at 2.87 kg CO_2 eq/kg H_2 due to carbon released during conversion. Cho et al. [107], shows that biogas reforming has highest emissions, generating 3.61 kg CO_2 eq/kg H_2. The research indicates that renewable hydrogen production can lower emissions by 68–92 % compared to fossil-based hydrogen. Guo et al. [104] pointed China's commitment to large-scale solar hydrogen production, while Cheng et al. [108] highlighted Japan's significant potential for renewable energy integration. These developments jointly strengthen the shift toward cleaner hydrogen production with lower CO_2 emissions.

3.3.1. Conclusion and future directions for cluster 3

Cluster 3 emphasizes the growing role of hydrogen technologies and integrated energy systems in enabling a sustainable energy transition. While renewable hydrogen production advances, cost reduction and efficiency improvements remain critical. Multigeneration and hybrid systems offer viable pathways for maximizing renewable energy utilization, but their widespread adoption requires policy support, infrastructure investment, and economic incentives.

Future research should focus on optimizing energy storage solutions, improving the exergoeconomic performance of integrated systems, and enhancing hybrid renewable setups for continuous power supply. Nanotechnology and phase-change materials further improve energy efficiency and cost-effectiveness. Hydrogen is highly applicable in transportation, industry, and residential and will also be essential for achieving large-scale decarbonization. Integrating solar, wind, and bioenergy technologies with hydrogen systems can accelerate the transition towards a low-carbon economy, ensuring energy security and sustainability.

3.4. Cluster 4: Energy Systems Management and Optimization

Cluster 4, "Energy Systems Management and Optimization," examines advanced methods such as hybrid energy systems, multi-period modeling, and exergy analysis to enhance power generation and resource use, as shown in Fig. 12.

Table 6 depicts cluster 4 and the research works [118,119] focused on large-scale renewable energy transitions. The analysis by Lund et al. [118] presented a simulation-based approach to achieve 100 % renewable energy system in Denmark by 2050, emphasizing the importance of flexible energy system design, considering balancing electricity supply and demand. Investigation [119] expanded this concept to the European Union, using a multi-period mixed-integer programming model to examine a stepwise transition in the transport and power sectors.

Mousavi et al. [120] explored microbial fuel cells and electrolysis for clean energy and water treatment, with potential applications in hydrogen production and carbon sequestration. Dadak et al. [121] analyzed a solar-driven hydrogen co-generation system using solid oxide electrolysis cells (SOEC) with a biogas generator, achieving an annual hydrogen production of 29.2 tons. Additionally, Boulmrharj et al. [122] examined hydrogen cogeneration in buildings using photovoltaic (PV) panels, electrolyzers, and PEM fuel cells, demonstrating an electrical efficiency of 32 % and an overall system efficiency of 64.5 % when including thermal energy. These studies highlight the potential of hydrogen as a clean energy carrier, with applications in sustainable wastewater treatment, decentralized hydrogen production, and energy-efficient buildings as shown in Table 6.

Many researchers, such as Taheri et al. [123] evaluated a biomass and solar hybrid power system using a triple combined cycle with a PEM electrolyzer, achieving an exergetic efficiency of 30.44 % while reducing CO_2 emissions. Cao et al. [124] examined biomass gasification with SOFC and solar-powered hydrogen injection, reducing CO_2 emissions by 12.9 % and increasing power output by 8.7 %. Additionally, few studies integrated biogas reforming with a SOFC and hybrid renewable power to

Table 5
Integrated energy systems and hydrogen technologies: Cluster 3.

Ref.	Focus Area	Technology/Method	Key Findings	Potential Impact
[106]	• Hydrogen production from renewable sources	• Electrolysis • Biomass gasification • Pyrolysis • Fermentation • Photoelectrochemical water splitting	• Various hydrogen production methods from renewable sources are under development • Water electrolysis using wind/solar/biomass energy conversion	• Cost-competitive hydrogen production for passenger vehicles and sustainable energy systems
[107]	• Global warming potential of hydrogen production technologies	• Wind- and solar-powered electrolysis • Biomass gasification • Biogas reforming	• Wind electrolysis has the lowest global warming impact (1.29 kg CO_2 eq/kg H_2) • Biogas reforming has the highest (3.61 kg CO_2 eq/kg H_2) • Renewable hydrogen has 68–92 % lower emissions than fossil-based hydrogen	• Supports the transition to low-carbon hydrogen and integration into natural gas networks
[113]	• Hybrid energy for Cameroon	• PV • Fuel cell • Electrolyzer • Biogas hybrid system	• Optimal energy system designs found for various community sizes • Lowest LCOE was $0.071/kWh	• Energy access for underserved populations in Cameroon
[110]	• EV charging using renewables	• CPV/T • Wind • Biomass • H_2 and NH_3 fuel cells	• System can fast-charge 80 EVs daily • H_2 and NH_3 fuel cells ensure continuous operation	• Grid-independent EV charging using renewables and fuel cells
[112]	• Hydrogen as cooking fuel	• Solar-powered electrolysis	• Hydrogen cooking fuel reduces CO_2 impact	• Cleaner cooking fuel for biomass-dependent communities
[114]	• Flexible biogas production	• Demand-driven biogas system	• Flexible feeding reduces gas storage needs by up to 65 % without stability loss	• On-demand renewable power generation with reduced infrastructure needs
[104]	• Solar hydrogen production in China	• Solar-driven H2 production	• China focuses on large-scale solar hydrogen production • Sustainability and energy security	• Hydrogen as a future energy carrier for reducing emissions and increasing security
[108]	• Renewable energy integration in Japan	• Solar PVs • Offshore wind • Pumped hydro energy storage • High-voltage interconnection	• Japan has 14 times more solar and offshore wind resources than needed for 100 % renewable electricity • Cost of balancing 100 % renewable electricity is $20–27/MWh	• Demonstrates feasibility of self-sufficient renewable electricity system in Japan at competitive costs
[103]	• Polygeneration system for electricity and hydrogen	• Biomass gasification (direct/indirect) • Solar power tower • Rankine cycle • Brayton cycle • Water gas shift reactor	• Integration of indirect gasification, steam reforming, and Brayton cycle • Produces 340 MW electricity at €0.073/kWh and 97 kt/yr of hydrogen	• Supports year-long electricity and hydrogen production using biomass and solar power
[109]	• Multi-generation energy system	• Biomass combustor • PV thermal panels • Waste heat recovery • Absorption chiller • Ejector refrigeration • CO_2 capture • Organic Rankine cycle	• Produces 17.4–18.4 MW electricity • 4.1 MW heating • 1.2 MW cooling • 5.8–11.3 kg/h hydrogen • Captures 234.1 kg/s CO_2 with 90 % removal	• Enhanced sustainability by integrating power, heating, cooling, and CO_2 capture
[102]	• Methanol production from renewable energy	• Biomass gasification • Solar power plant • Alkaline water electrolysis • Syngas hydrogenation	• Optimized PV-biomass system achieves grid energy interaction of 0.60 kWh (Toronto) • 0.57 kWh (Crotone) per kWh required by the electrolyzer	• A scalable approach for renewable methanol production and energy storage
[111]	• Renewable energy for electric vehicle (EV) charging	• Solar • Wind • Biomass hybrid power • HOMER pro software optimization	• Biogas-PV system generates 3.9 GWh/yr electricity • 55.6 tonnes/yr hydrogen • CO_2 reduction of 460 tons/yr replacing 100 gasoline vehicles	• Supports sustainable EV adoption in sub-saharan Africa with renewable-powered charging infrastructure.
[116]	• Integration of renewables with fossil fuels for methanol production	• Biomass co-gasification • Solar hydrogen • Coal-based poly-generation	• Biomass reduces GHG emissions by 24.34 % • Lowers energy efficiency. • Solar hydrogen improves carbon utilization but negatively impacts efficiency and cost	• Evaluates trade-offs in renewable integration with fossil fuel processes for methanol production
[117]	• Sustainable multi-generation system	• Electrolytic hydrogen • Ammonia synthesis • Phase change material-based energy storage	• Energy efficiency: 28 % • Exergy efficiency: 18.9 % • Highest exergy destruction in MSF (25 MW) & Rankine cycle (32 MW)	• Sustainable remote area utility supply • 60 % carbon footprint reduction
[115]	• Biomass-based polygeneration system	• Biomass gasification • Electrolytic hydrogen • Bio-SNG storage	• Electricity efficiency: 46 % • Bio-SNG efficiency: 69 % • District heating: 85–90 % efficiency	• Smart energy system integration • Renewable energy transition • Economic feasibility dependent on district heating

improve off-grid energy solutions [125].

The transition to renewable energy in industrial sectors is examined by Ampah et al. [126] which investigated renewable electricity and hydrogen applications for coal mining in China. Many studies on large-scale renewable energy transitions [118,119] highlighted the feasibility of 100 % renewable energy systems, emphasizing the dominance of wind and solar by 2050. In contrast, hydrogen-based technologies [120–122] focused on decentralized hydrogen production, microbial fuel cells, and cogeneration systems, showcasing hydrogen's potential as a clean energy carrier for various applications, including wastewater treatment and energy-efficient buildings. Biomass and hybrid energy systems studies [115,123–125] provided solutions for

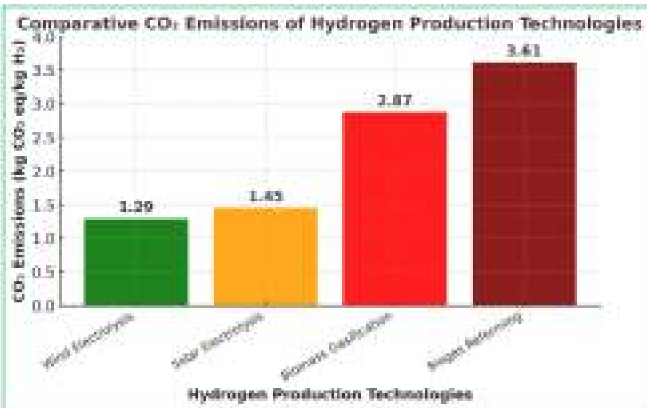


Fig. 11. CO_2 footprint of renewable versus biomass-based hydrogen.

stable and flexible renewable power, integrating biomass gasification, solar energy, and SOFC technologies to enhance efficiency and reduce emissions.

The analysis, based on studies ([118–126]) explores the relationships between energy efficiency, CO_2 reduction, hydrogen production, and exergy efficiency across various energy systems.

Fig. 13a analyzes the correlation between energy efficiency (%) and CO_2 reduction (%) for various energy technologies. More significant CO_2 reduction is generally linked to renewable-based and hybrid systems such as 100 % RES [118], EU carbon neutrality initiatives [119], and biomass hybrid power [123]. CO_2 emissions can be reduced by 12.9 % using biomass gasification with SOFC system [124] and further by 72 % using solar-driven hydrogen co-generation [121]. So, it can be concluded that solar energy is crucial for decarbonization initiatives.

Fig. 13b highlights the interaction between energy efficiency and hydrogen production across various energy models. Solar-driven hydrogen co-generation [121] and renewable energy for coal mining [126] the highest hydrogen output (29.2 and 15 tons/year, respectively). However, some systems, such as 100 % RES [118] and biomass-based polygeneration [115], do not prioritize hydrogen production, emphasizing their role in direct power generation. The trend suggests increased hydrogen production is attainable in renewable-integrated hydrogen production systems, but their efficiency trade-offs must be evaluated.

Exergy efficiency across the energy systems is shown in Fig. 13c. The hydrogen cogeneration system in buildings [122] demonstrates the highest exergy efficiency at 60 %, followed by solar-driven hydrogen co-generation [121] and biomass-based polygeneration [115], both around 50 %. Biomass gasification and SOFC [124] show lower exergy efficiency at 42 %, indicating that while biomass-based solutions contribute to sustainability, their energy conversion effectiveness is still evolving. This highlights the need for optimization in biomass and hybrid renewable power technologies to enhance their exergetic efficiency.

The heatmap presented in Fig. 13d provides a statistical overview of how energy efficiency, CO_2 reduction, and hydrogen production correlate. Energy efficiency and CO_2 reduction exhibit a positive correlation, implying that higher efficiency contributes to lower emissions as seen in Refs. [118,119], and [123]. Hydrogen production has a weaker correlation with energy efficiency, suggesting that some hydrogen-producing systems prioritize hydrogen yield over efficiency ([121,126]).

3.4.1. Conclusion and future directions for cluster 4

The studies of cluster 4 demonstrated the effectiveness of biomass integration in hybrid energy systems, which can enhance energy security, reduce emissions, and optimize resource utilization. The renewable-integrated systems, involving solar-driven hydrogen production [121] and hydrogen cogeneration [122] proved to be the most

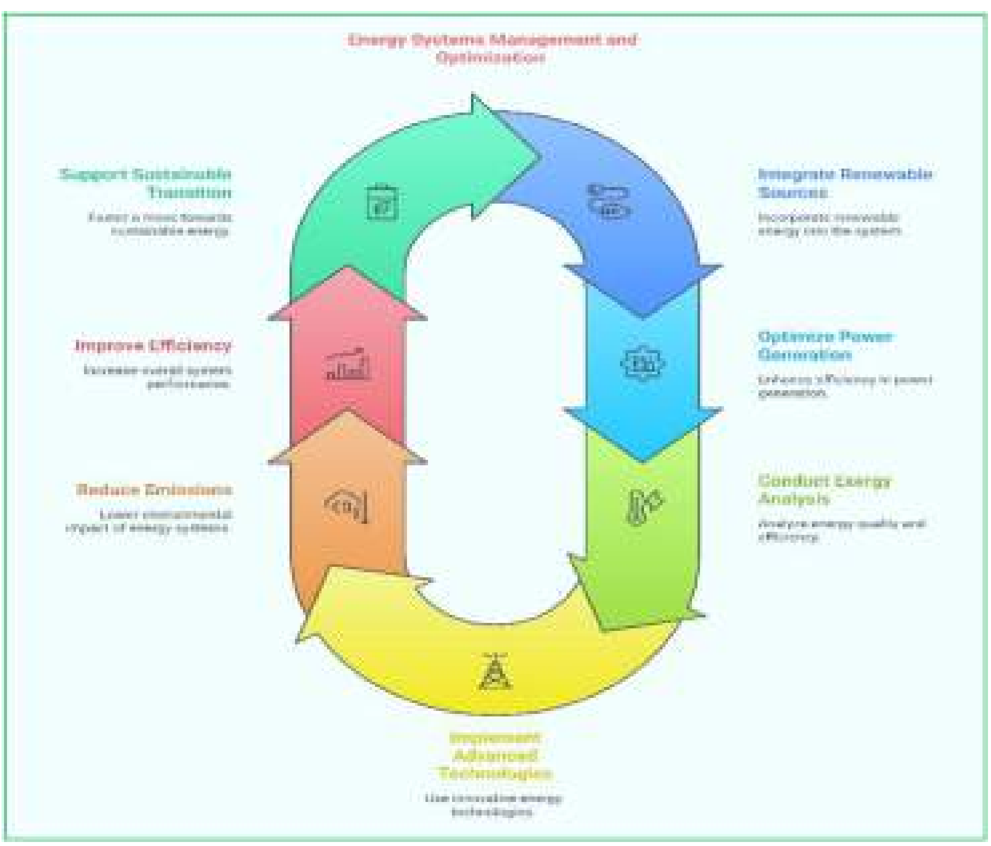


Fig. 12. Cluster 4: Energy systems management and optimization.

Table 6
Energy systems management and optimization: Cluster 4.

Ref.	Focus Area	Technology/Method	Key Findings	Potential Impact/Applications
[118]	• 100 % RES	• Hour-by-hour simulation	• Design of a flexible energy system balancing electricity supply and demand • 100 % renewable energy possible by 2050	• Denmark's transition to renewable energy • Policy implications for biomass vs. wind power reliance"
[119]	• EU carbon neutrality by 2050	• Multi-period mixed-integer programming	• Stepwise transition in transport and power sectors • Wind and solar dominate by 2050	• EU-wide renewable energy transition • Economic and social benefits, including 1.5 M new jobs
[120]	• Microbial fuel cells	• Microbial electrolysis • Desalination cells	• Utilization of microbes for clean energy and water treatment • Potential for hydrogen and carbon sequestration	• Sustainable wastewater treatment • Renewable hydrogen production
[123]	• Biomass & solar hybrid power	• Triple combined cycle with PEM electrolyzer	• Solar-based hydrogen reduced CO_2 emissions and biomass consumption • Exergetic efficiency: 30.44 %	• Decarbonization of power generation • Cost-optimized hybrid energy system
[115]	• Biomass-based polygeneration	• Bio-SNG from biomass gasification and electrolysis	• Electricity and bio-SNG production with high efficiency • District heating enhances feasibility	• Flexible energy production; supports 100 % renewable transition in Denmark
[125]	• Biogas-based SOFC system	• Biogas reforming for SOFC and hybrid renewable power	• Wind and solar hybrid power	• Off-grid renewable energy system • Decentralized hydrogen and power production
[121]	• Solar-driven hydrogen Co-generation	• SOEC with PV • Biogas generator	• Annual hydrogen production: 29.2 tons • Largest exergy destruction in SOEC reactor	• Decentralized hydrogen production • Optimization for various geographic locations
[122]	• Hydrogen cogeneration in buildings	• PV • Electrolyzer • PEM fuel cell	• Electrical efficiency: 32 % • Overall system efficiency reached 64.5 % with thermal energy	• Energy-efficient buildings • Distributed hydrogen energy applications
[124]	• Biomass gasification & SOFC	• Solar-powered hydrogen injection to SOFC	• Reduced CO_2 emissions by 12.9 % • Increases power output by 8.7 % at slight exergy efficiency loss	• Improved SOFC performance • Sustainable hydrogen-integrated biomass power
[126]	• Renewable energy for coal mining	• HOMER Pro-based PV, wind, diesel hybrid	• Renewable-based electricity and hydrogen for mining • Potential to replace diesel transport	• Carbon neutrality pathway for China's coal mining sector • On-site hydrogen refueling for trucks

efficient and sustainable technologies. Meanwhile, biomass-based technologies offer moderate performance and require further optimization to enhance their CO_2 reduction potential and exergy efficiency. Thus, it can be concluded that solar and hybrid renewable systems play a massive role in decarbonizing energy production while supporting hydrogen-based energy transition [115,124].

Many innovative technologies and storage solutions for wind and solar systems are essential for balancing supply and demand. Large-scale hydrogen production, storage, and transport into energy markets require adequate infrastructure. Decarbonizing mining, transportation, and heavy manufacturing industries is essential to achieving better renewable energy solutions.

3.5. Cluster 5: Sustainable Energy Fundamentals

Cluster 5 "Sustainable Energy Fundamentals" investigates the essential principles and technologies for shifting towards renewable energy. It prioritizes sustainability and efficiency, by examining energy production, storage, and conversion progress. This cluster showcases innovative solutions like biofuel production, hydrogen storage, and hybrid energy systems, illustrated in Fig. 14.

Table 7 provides valuable insights into renewable energy technologies and effective strategies for improving sustainable energy solutions. Bioelectrochemical systems [127] showed how bacteria can transform CO_2, H_2, and O_2 into biomass and alcohols, improving solar energy utilization. Storage and biofuel production. Liu et al. [128] demonstrated the biological production of ammonia from N_2 and H_2O using bacterial catalysis, with potential applications in biofertilizer production, emphasizing a distributed, sustainable approach to ammonia production.

When comparing the results, several common themes emerge. A recurring issue is the energy storage challenge, with studies like those by [129]. Pumped hydro and biomass are identified as the most viable solutions to this problem, with the need for diversified storage technologies highlighted as essential. The H_2RES energy system model [130] for island microgrids and the hybrid automata algorithm proposed by [131] showcased the importance of optimizing energy management and ensuring uninterrupted power supply in off-grid systems. Producing renewable fuels like hydrogen and DME (Dimethyl Ether) from solar energy and CO_2 [132] further emphasized the importance of CO_2 utilization in industrial-scale fuel production. Biohydrogen production through photoelectrocatalysis [133] offered promising avenues for clean fuel generation, but further efficiency improvements are required for large-scale implementation.

3.5.1. Conclusion and future directions for cluster 5

Cluster 5 adopts a multifaceted strategy integrating renewable energy sources, efficient storage systems, and advanced fuel production to achieve sustainable energy objectives. Many initiatives must be taken in the future to enhance the efficiency of renewable fuel production, especially in biofuels and hydrogen. Also, to mitigate the intermittent nature of RES, optimized energy storage technologies must be optimized.

3.6. Cluster 6: Hydrogen and Sustainable Energy Innovations

Cluster 6, "Hydrogen and Sustainable Energy Innovations," explored the most advanced techniques in hydrogen production, storage, and integration with RES. It focuses on innovative approaches like hybrid renewable systems, photocatalysis, and biomass-based technologies as shown in Fig. 15.

Table 8 shows research on hydrogen production, energy strategy, and integrated renewable energy systems. Many advanced methods such as photocatalysis, electrolysis, and gasification were studied to improve hydrogen production efficiency. Li et al. [138] highlighted that surface modifications can enhance efficiency using graphite-like carbon nitride (g-C_3N_4) for photocatalytic hydrogen generation. However, this methodology too faces challenges in achieving significant improvements. In contrast [117], suggested a multi-generation hydrogen system integrating ammonia synthesis with potable water and power production for remote areas. Cao et al. [139] revealed that injecting hydrogen powered by solar energy enhances the efficiency of biomass gas turbines, leading to lower CO_2 emissions and more significant power generation. Mousavi et al. [140] and Bozgeyik et al. [141] introduced multi-generation

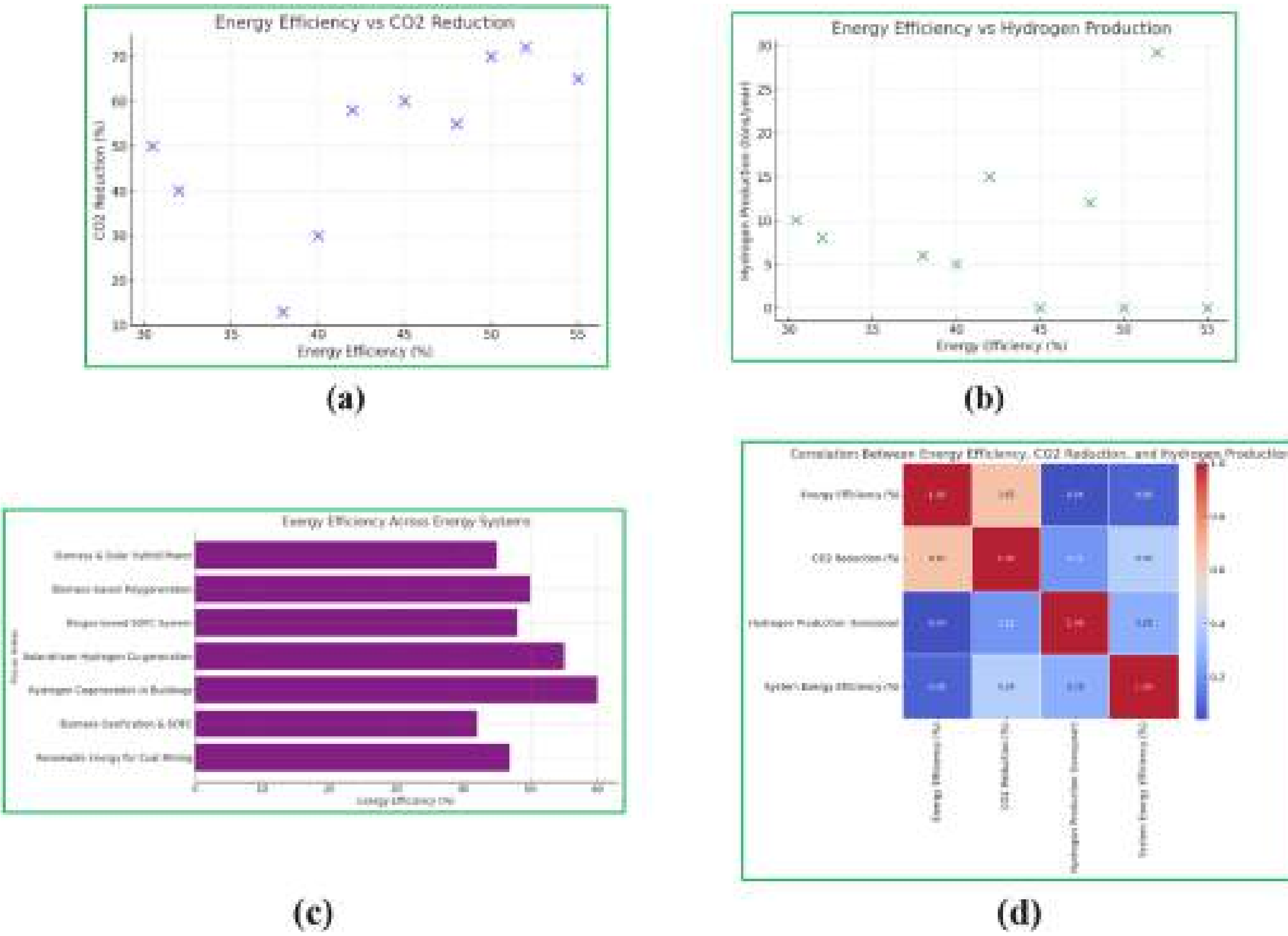


Fig. 13. **(a)** Energy Efficiency vs. CO_2 Reduction, **(b)** Energy Efficiency vs. Hydrogen Production, **(c)** Exergy Efficiency Across Energy Systems, **(d)** Correlation Between Energy Efficiency, CO_2 Reduction, and Hydrogen Production.

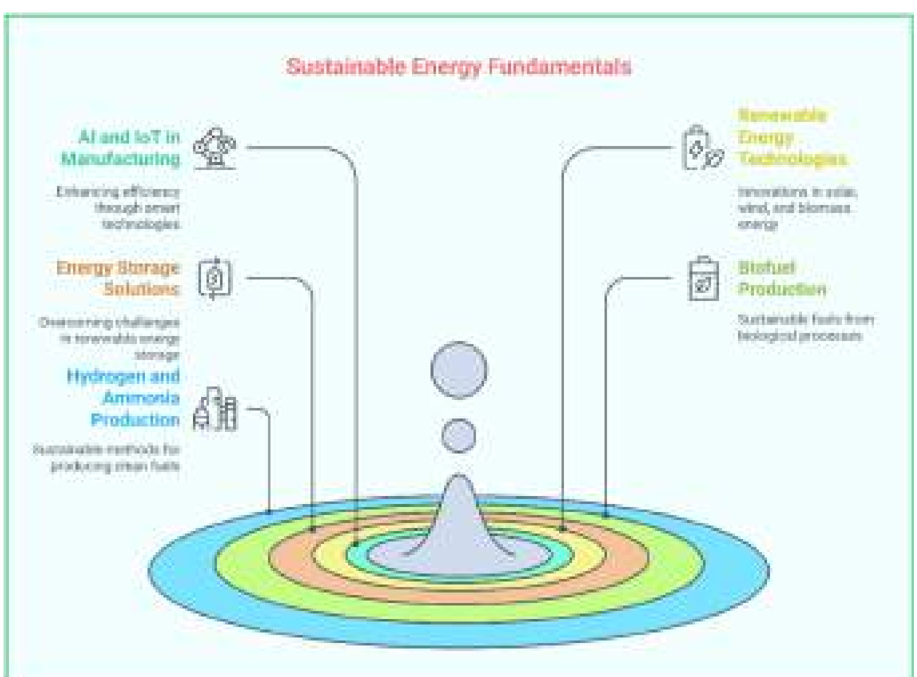


Fig. 14. Cluster 5: Sustainable energy fundamentals.

Table 7
Sustainable energy fundamentals: Cluster 5.

Ref.	Focus Area	Technology/Method	Key Findings	Potential Impact
[127]	• Solar-to-fuel storage	• Bioelectrochemical systems • Water splitting	• Bacteria convert CO_2, H_2, and O_2 into biomass and fusel alcohols, improving fuel yields	• Enhancing solar energy storage and biofuel production
[128]	• Sustainable ammonia production	• Bacterial catalysis, renewable electricity	• Biological NH_3 production from N_2 and H_2O, potential biofertilizer applications	• Distributed and sustainable ammonia production
[130]	• Renewable energy planning	• H2RES energy system model	• Model tested on multiple islands for 100 % renewable energy integration	• Energy planning tool for island and remote microgrids
[134]	• Energy transition and storage integration	• Solar, wind, and biomass • Storage systems (battery, hydrogen, methane, ammonia)	• Storage options are vital for stabilizing energy supply	• Supports orderly and efficient energy transition planning
[131]	• Off-grid renewable energy management	• Hybrid automata algorithm with batteries and hydrogen storage	• Uninterrupted power supply in islanded systems • Reducing fossil fuel use by 95.6 %–99.4 %	• Optimizes off-grid energy systems with diverse renewables
[129]	• Renewable energy storage challenges	• Biomass • Pumped hydro • Batteries and hydrogen	• Storage limitations hinder 100 % renewable power supply	• Need for diversified solutions
[135]	• Integrated biohydrogen refinery (IBHR)	• Hydrothermal hydrolysis • Biohydrogen fermentation • Fuel cell electricity	• 83–99 % waste destruction • 11x energy yield increase via electrodialysis	• Converts biomass waste into hydrogen and electricity efficiently
[136]	• Hybrid solar-biomass energy system	• Integrated gasification with solar tower • Reverse osmosis desalination	• 21.1 % exergy efficiency • Hydrogen/ammonia production of 20 g/s and 79 g/s	• Enhances renewable energy systems through waste heat recovery
[132]	• Year-round DME production from electrolytic hydrogen and CO_2 (Gulf of Cádiz, Spain)	• Solar PV • Wind • Electrolyzer • Gas purification • DME synthesis • Mathematical programming	• Solar and unreacted gas recycle optimal for 197 kt/year DME • Production cost: 1.4 €/kg	• Industrial-scale renewable fuel production, CO_2 utilization
[137]	• Hydrogen for north Europe	• Wind • Solar PV • Hydro storage • Fuel cells • Hydrogen storage • Temporal simulation	• Hydrogen supports stationary and transport sectors • Energy trade benefits renewables	• Hydrogen infrastructure development
[133]	• Hydrogen production via photo electrocatalytic degradation	• WO3 photoanodes • Solar energy • Photoelectrocatalysis	• Hydrogen production efficiency depends on organic additive • Solar-to-hydrogen efficiency: 2.35 %	• Clean fuel generation

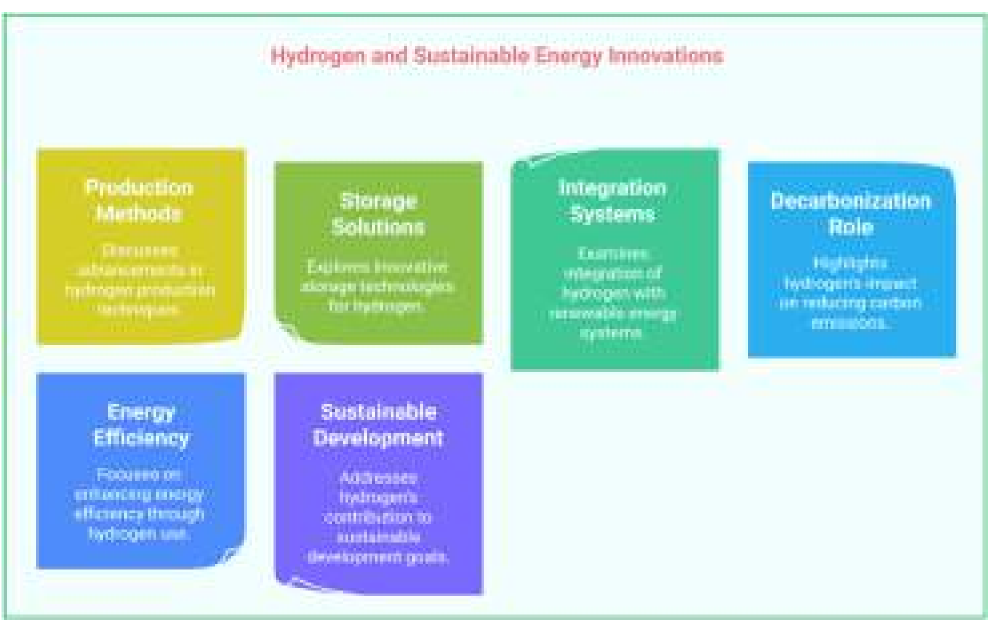


Fig. 15. Cluster 6: Hydrogen and sustainable energy innovations.

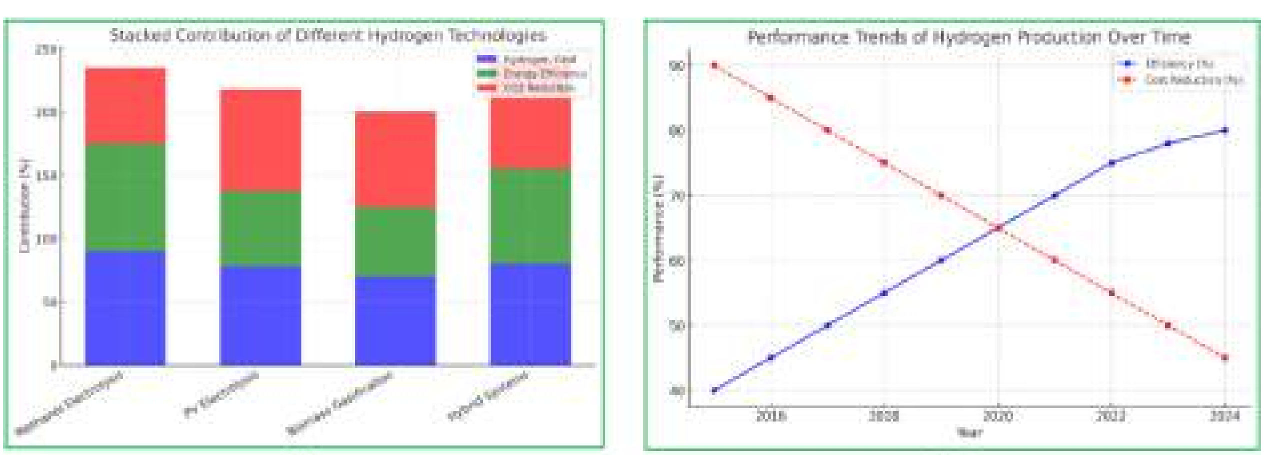
systems that utilize solar, biomass, and geothermal energy to produce hydrogen, electricity, cooling, and freshwater. Tebibel et al. [142] highlighted that methanol electrolysis requires significantly less energy than water electrolysis for hydrogen production, but further optimization is needed for large-scale applications.

Fig. 16a illustrates the combined contributions of various hydrogen production technologies toward three key performance metrics: hydrogen yield, energy efficiency, and CO_2 reduction. The technologies

Table 8
Hydrogen and sustainable energy innovations: Cluster 6.

Ref.	Focus Area	Technology/Method	Key Findings	Potential Impact
[138]	• Photocatalysis for hydrogen	• g-C_3N_4	• Surface modifications improve photocatalytic hydrogen generation but efficiency remains low (~2 %).	• Enhance solar-to-hydrogen conversion efficiency.
[130]	• Energy planning for hydrogen	• H2RES simulation model	• Modeling renewable hydrogen integration for island energy systems.	• Used for energy planning in multiple island case studies.
[139]	• Hybrid renewable hydrogen	• Biomass-solar • Hybrid system, • PEM electrolyzer	• Biomass gas turbine performance improved.	• Reduced CO_2 emissions • Increased power generation
[77]	• Integrated energy production	• PV electrolysis • CO_2-to-methanol	• CO_2 captured from biomass plants can synthesize fuels with hydrogen.	• Integrated systems for renewable energy and hydrogen production
[117]	• Multi-generation hydrogen system	• Ammonia synthesis from hydrogen • Wastewater electrolysis	• Integrated with potable water and power production.	• Sustainable energy supply for remote areas
[142]	• Methanol electrolysis for hydrogen	• Methanol electrolysis process (MEP) • PV electrolysis	• MEP requires 65 % less energy than water electrolysis	• Improved efficiency
[143]	• Photocatalysis • Nanocatalysts	• Pt-based photocatalysts • Benzaldehyde oxidation	• Enhanced hydrogen production efficiency.	• New approaches for photocatalytic hydrogen production
[144]	• Hydrogen strategy in EU	• Carbon capture for hydrogen • Wind-biomass hydrogen	• EU prioritizes renewables for hydrogen production	• Policy-driven transition towards hydrogen economy in EU
[145]	• Hydrogen from biomass-solar light	• TiO_2 nanotube arrays (TNTAs) with Pd quantum dots (Pd QDs) • Photoelectrochemical (PEC) system	• Hydrogen production 164.8 μmol cm^2 • 15x higher than pure water splitting	• Boosted PEC efficiency
[146]	• Solar-based rice husk gasification for hydrogen • Power • Cooling, and freshwater	• Thermodynamic analysis	• Hydrogen production rate = 0.0603 kg/s • Energy efficiency: 46.8 % • Cooling: 911.4 kW • Freshwater: 410.9 kg/s	• United energy systems for multi-output applications
[147]	• Co-combustion of H_2 and CH_4 in micro gas turbines	• Hydrogen-enriched methane/biogas blends • Combustion testing	• 20 % H_2/biogas blend reduced CO emissions by 29.8 % and NOx by 47.1 %	• Cleaner combustion for microturbines
[140]	• Biomass-solar-polygeneration for Kish island, Iran	• Kalina cycle • Gas turbine • Steam cycle • Organic Rankine cycle • Multi-effect desalination • PEM electrolyzer	• MSW is the most economical fuel • DPW has least environmental impact • MPW has best energy and exergy efficiency (41.68 % and 34.19 %)	• Waste-to-energy applications
[141]	• Solar, geothermal, and biomass-based multi-generation system	• Solar collectors • Rankine cycles • Absorption cooling • Gas turbine • Geothermal unit • Electrolyzer	• Hydrogen mass flow: 3.52 kg/h • Freshwater: 6.16 kg/s • Energy efficiency: 65.55 % • Exergy efficiency: 27.09 %	• Multi-generation systems for sustainable development
[148]	• Hybrid solar-biomass power and hydrogen production plant	• Biomass gasification • Aspen HYSYS simulation • Exergy analysis	• Hydrogen production: 7912.5 tons/year • Power output: 38.89 Mwe • Exergy efficiency: 55.8 % for hydrogen and 39.6 % for power	• High-efficiency renewable power and hydrogen production

discussed are Methanol Electrolysis (MEP), PV Electrolysis, Biomass Gasification, and Hybrid Systems ([77,139,141,142]). MEP [142] shows the highest hydrogen yield while using 65 % less energy than water electrolysis, making it an extremely efficient method. PV Electrolysis [77] offered lower energy efficiency and yield than MEP, but yielded reduced emissions. Further, reliance on fossil fuels can be reduced using



(a) (b)

Fig. 16. **(a)** Contribution of Hydrogen Technologies to Key Metrics **(b)** Efficiency vs. Cost Trends in Hydrogen Production (2015–2025).

biomass gasification [139] which turns biomass into hydrogen. Hybrid Systems [141]deliver balanced outcomes across all three metrics, aligning them as a sustainable option.

Fig. 16b illustrates the efficiency and cost reduction advancements of hydrogen production technologies from 2015 to 2025. The efficiency gains (blue line) showcase developments in renewable hydrogen production techniques, photocatalysis [143], biomass-solar hybrids [139], and enhanced electrolysis methods [142]. Over this period, efficiency has improved from 40 % to nearly 80 %, corresponding with innovations in single-atom catalysts [143] and biomass hybridization [139]. Methanol electrolysis [142] and hybrid systems [141], show a consistent drop in hydrogen production costs.

3.6.1. Conclusion and future directions for cluster 6

Hybrid renewable energy systems enhance sustainability by integrating multiple sources, improving energy efficiency, and addressing diverse energy needs. While advancements in hydrogen production and multi-generation systems are encouraging, challenges remain in maximizing efficiency, cost-effectiveness, and system integration, especially in remote communities.

Future research should focus on scaling these technologies, improving hydrogen production methods like photocatalysis and electrolysis, and merging waste-to-energy solutions. Strengthening energy system modeling, optimizing hydrogen integration, and enhancing policy support are crucial for fostering a hydrogen economy. Assessing environmental and social impacts will encourage wider acceptance and contribute to a stronger, more sustainable energy future.

3.7. Cluster 7: Biohydrogen and Biomass Technologies

Cluster 7 "Biohydrogen and Biomass Technologies," as shown in Fig. 17 mainly focuses on biological and biomass-based methods to create clean, renewable hydrogen and energy.

Table 9 show diverse cutting-edge technologies and approaches for merging hydrogen production with renewable energy frameworks. Qin et al. [116] examined the trade-offs between reducing greenhouse gas emissions and achieving energy efficiency in hybrid systems that integrate biomass co-gasification with solar hydrogen production. Boujjat et al. [149] pointed out the stability of syngas generation from hybrid solar/auto thermal gasification. Barbuzza et al. [36] examined hydrogen-to-methane processes for energy storage. Redwood et al. [135] concentrated on fermentative biohydrogen for electricity generation, illustrating waste-to-energy routes that transform organic matter into valuable energy. Siddiqui et al. [136,146] studied hybrid solar-biomass systems for hydrogen and energy production, highlighting how waste heat recovery and the use of agricultural waste can enhance energy generation. El Emam et al. [150] explored hybrid renewable energy systems that merge solar gas turbines with biomass SOFC, enabling dual-mode renewable power generation and boosting overall system efficiency.

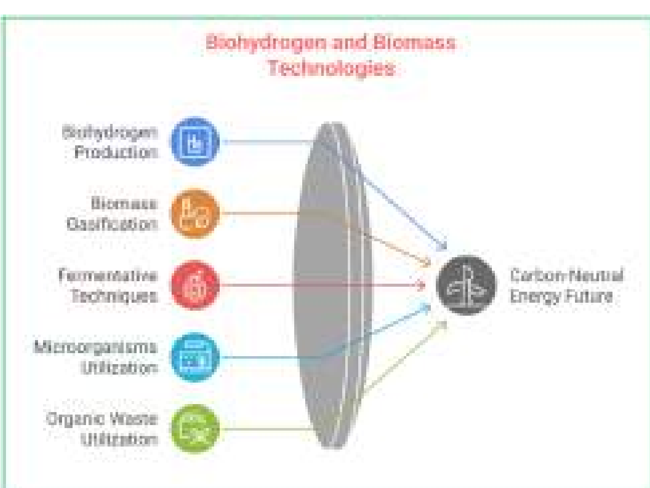


Fig. 17. Cluster 7: Biohydrogen and biomass technologies.

A recurring theme in these studies is optimizing hybrid systems that incorporate various renewable sources, boosting energy efficiency, reliability, and sustainability. Mousavi et al. [151] introduced a polygeneration system integrating biomass, solar energy, and a Kalina cycle to optimize fuel choices and advance multi-energy utilization. Burulday et al. [148] investigated the generation of high-purity hydrogen using biomass and solar energy to foster a sustainable hydrogen economy.

3.7.1. Conclusion and future directions for cluster 7

Cluster 7 shows that HRES, which combines solar, biomass, and hydrogen production, holds significant promise for addressing global energy challenges. These systems improve efficiency and reduce emissions while offering more reliable and sustainable energy solutions.

Future efforts should focus on incorporating such hybrid systems, particularly in energy storage, fuel production, and integrating waste-to-energy processes. Progress in hybrid hydrogen production and energy management technologies will be crucial for establishing a scalable, sustainable hydrogen economy and facilitating the transition to clean energy systems. Evaluating these systems' economic viability and scalability at an industrial level will help ensure their commercial success.

3.8. Cluster-wise Key Findings

This section will present insights specific to each cluster based on the seven thematic clusters identified through VOSviewer analysis.

Cluster 1: Renewable Energy Technologies and Transition.

- HRES mitigates intermittency issues and improves grid stability.
- Biogas hybridization in HRES can reduce carbon emissions by 96 %, demonstrating high sustainability potential.
- Solar-biomass hybrid systems lower CO_2 emissions by 2 % and reduce exergy destruction costs by 3.36 %.

Cluster 2: Advanced Bioenergy and Optimization.

- Biomass gasification has the highest hydrogen production efficiency (53.6 % energetic, 49.8 % exergetic).
- AI-driven modeling (MILP) optimizes hydrogen production costs in hybrid systems.
- Waste-to-energy solutions provide 50 % efficiency, a sustainable alternative to landfill disposal.

Cluster 3: Integrated Energy Systems and Hydrogen Technologies.

- Wind-powered electrolysis produces only 1.29 kg CO_2 eq/kg H_2.
- Japan's 100 % self-sufficient hydrogen economy can be proved using a large-scale renewable integration strategy
- Multigeneration systems combining hydrogen, power, heating, and cooling improve energy and exergy efficiencies.

Cluster 4: Energy Systems Management and Optimization.

- HRES efficiency and real-time energy distribution can be improved using AI-driven smart grids.
- Hybrid polygeneration systems with biomass and hydrogen achieve up to 60 % exergy efficiencies.
- Solar-driven hydrogen co-generation reduces CO_2 emissions by 72 %.

Cluster 5: Sustainable Energy Fundamentals.

Table 9
Biohydrogen and biomass technologies: Cluster 7.

Ref.	Focus Area	Technology/Method	Key Findings	Potential Impacts
[116]	• Coal-green energy integration	• Biomass Co-Gasification • Solar hydrogen	• GHG emission reduction vs. energy efficiency trade-offs	• Hybrid energy systems
[36]	• Renewable energy storage	• Wood Hydrogasification	• Hydrogen to methane process for energy storage	• Efficient renewable storage
[135]	• Biohydrogen	• Integrated biohydrogen refinery	• Fermentative biohydrogen for electricity generation	• Waste-to-energy solutions
[152]	• Cyanobacteria hydrogen	• Nickel-enhanced hydrogenase activity	• Optimized cyanobacteria hydrogen production	• Biological hydrogen pathways
[136]	• Solar-biomass hybrid	• Integrated gasification • Solar Tower	• Waste heat recovery improves efficiency	• Optimized multi-generation
[146]	• Rice husk gasification	• Solar-biomass hybrid system	• Renewable hydrogen and power production	• Agricultural waste utilization
[150]	• Hybrid renewable energy	• Solar gas turbine • Biomass SOFC	• Dual-mode renewable power generation	• Optimized hybrid energy
[149]	• Solar biomass gasification	• Hybrid solar/Autothermal gasification	• Stable syngas production despite solar variability	• Reliable renewable fuel production
[151]	• Polygeneration system	• Biomass • Solar • Kalina cycle	• Optimized biomass fuel selection	• Efficient multi-energy use
[148]	• Hybrid hydrogen production	• Solar power plant • Biomass gasification	• High-purity hydrogen production from biomass	• Sustainable hydrogen economy

- Bioelectrochemical systems enhance solar energy utilization by converting CO_2 into biofuels.
- Hybrid automata algorithms improve off-grid energy management and reduces fossil fuel use by 95.6 %–99.4 %.
- Renewable-powered ammonia synthesis provides a better alternative to fossil-based nitrogen fertilizers.

Cluster 6: Hydrogen and Sustainable Energy Innovations.

- Methanol electrolysis requires 65 % less energy than water electrolysis.
- Hybrid biomass-solar hydrogen production improves power generation efficiency, reducing CO_2 emissions.
- Multi-generation systems incorporating hydrogen, cooling, and desalination optimize renewable energy utilization.

Cluster 7: Biohydrogen and Biomass Technologies.

- Hybrid solar-biomass gasification ensures stable syngas production.
- Biohydrogen production from cyanobacteria and enzymatic fermentation increases yield efficiency.
- Polygeneration systems such as Kalina cycles, steam turbines, and biomass optimize energy efficiency.

3.8.1. *Cross-cluster insights*

Table 10 presents a comprehensive cluster-wise comparison of various HRES research themes, focusing on hydrogen production methods, efficiency metrics, core technologies, challenges, and future scope.

Cluster 1 concentrates on renewable transition through solar PV, wind, and power-to-gas (P2G) systems, employing biomass gasification and PV-electrolysis. It demonstrates strong energy performance with hydrogen efficiency at 53.6 % and multigeneration reaching 71.06 %. However, it faces significant challenges such as high initial capital investment and storage limitations. The future direction includes scaling up hybrid energy models and deeper integration of hydrogen into renewable grids.

Table 10
Cluster-wise comparative analysis of HRES research themes.

Cluster	Theme	Key Technologies	Hydrogen Production Methods	Efficiency Highlights	Challenges	Future Scope
1	Renewable energy technologies and transition	• HRES • Wind • Solar PV • P2G systems	• Biomass gasification • PV-electrolysis	• H_2: 53.6 % • Multigen: 71.06 %	• High initial costs • Storage limitations	• Scale-up of hybrid systems • Hydrogen integration
2	Advanced bioenergy and optimization	• Biomass • Biohydrogen • MILP models	• Gasification, biological • PV-electrolysis	• H_2: 53.6 % • Bio-H_2: ~40 %	• Cost-efficiency • Low conversion rates	• Off-grid optimization • Hydrogen fueling systems
3	Integrated energy systems and hydrogen technologies	• Multigen/ polygeneration • Solar + biomass	• Solar electrolysis • Wind electrolysis	• Wind electrolysis: 50 % • Exergy: ~60 %	• System complexity • Economic feasibility	• Urban HRES • Transportation • EV support
4	Energy systems management and optimization	• SOFC • Microbial fuel cells • HRES	• Solar/biogas electrolysis	• Exergy: 30–60 %	• Efficiency vs. cost • Infrastructure gaps	• AI-based optimization • Decarbonizing industry
5	Sustainable energy fundamentals	• Bioelectrochemical systems • Ammonia synthesis	• Photoelectrochemical • Fermentation	• PEC: 2.35 % • Ammonia: Emerging	• Low PEC efficiency • Limited scaling	• Distributed biofuels • DME synthesis
6	Hydrogen and sustainable energy innovations	• Photocatalysis • MEP • Hybrid hydrogen	• Methanol electrolysis • Biomass gasification	• MEP: ~65 % • Hybrid: ~60–70 %	• Low maturity • Material costs	• Scale-up of MEP and photocatalysis
7	Biohydrogen and biomass technologies	• Biohydrogen refinery • Solar-biomass	• Fermentation • Hybrid solar biomass	• Gasification: ~55 % • Hybrid: ~50–60 %	• Feedstock variability • Thermal instability	• Waste-to-H_2 • Rural deployment

Cluster 2 focuses on bioenergy and energy optimization techniques, particularly MILP-based modeling approaches. The primary hydrogen production methods include gasification, biological processes, and PV-electrolysis. While similar efficiencies (H_2 at 53.6 % and biohydrogen at ~40 %) are observed, this cluster is constrained by low conversion rates and cost-efficiency barriers. The research here is geared toward off-grid system development and creating practical hydrogen fueling infrastructure, especially in remote and underserved regions.

Cluster 3 emphasizes integrated systems, particularly polygeneration and urban HRES frameworks, employing solar and wind electrolysis. With exergy efficiencies around 60 % and wind electrolysis efficiency near 50 %, the systems offer decent performance but are hindered by their inherent complexity and uncertain economic feasibility. The cluster looks ahead to applications in smart urban energy planning and transportation systems, such as EV integration.

Cluster 4 revolves around energy system management, including solid oxide fuel cells and microbial fuel cells within HRES setups. Efficiency ranges from 30 % to 60 %, and the systems are oriented toward balancing performance with cost. The significant challenges are infrastructural gaps and cost-driven decision-making. This cluster holds promise for AI-based optimization strategies and industrial decarbonization.

Cluster 5 deals with fundamental research in sustainable hydrogen generation, featuring emerging technologies like photoelectrochemical (PEC) and ammonia synthesis. PEC efficiency is notably low at 2.35 %, and most technologies are at a low maturity level, limiting scalability. Nevertheless, future directions include the development of distributed biofuels and advanced DME synthesis for cleaner alternatives.

Cluster 6 is notable for investigating innovative hydrogen solutions such as photocatalysis, methanol electrolysis (MEP), and hybrid hydrogen production systems. With MEP reaching energy efficiency levels of ~65 % and hybrid methods up to 70 %, this cluster outperforms most in energy yield. Despite this, the technologies are underdeveloped, with high material costs being a limiting factor. Scaling these methods could significantly enhance the hydrogen landscape.

Cluster 7 is rooted in biomass and biohydrogen technologies, employing solar-biomass hybrid setups and fermentation-based hydrogen production. Efficiency values range between 50 and 60 %, with gasification methods achieving up to 55 %. Key barriers include feedstock inconsistency and thermal instability, yet this cluster shows strong potential for rural deployment and waste-to-hydrogen applications in decentralized settings.

The analysis reveals high-efficiency systems like those in Clusters 1 and 6 show technical promise, but real-world implementation still faces economic and infrastructural constraints. Emerging technologies in Cluster 5 offer long-term potential, while Clusters 2 and 7 may contribute significantly to decentralized and rural hydrogen applications. Cross-cluster interaction and targeted policy support will be essential to accelerate sustainable hydrogen deployment.

Thematic analysis of all seven clusters highlights converging technologies and recurring challenges in HRES. Key technologies, including hydrogen electrolysis, biomass gasification, and solar PV integration, consistently emerge across clusters, emphasizing their critical importance in sustainable energy transitions. Furthermore, multi-generation systems, AI-driven optimization, and hybrid storage solutions (e.g., battery–hydrogen) improve system efficiency and resilience. Identified challenges include substantial initial costs, insufficient standardized hydrogen infrastructure, feedstock availability for biomass, and uncertainties in policy and regulations, particularly in developing regions. Across all clusters, a common focus is scaling integrated systems, enhancing exergoeconomic performance, and advancing energy storage technologies for grid stability. Future research should aim to create scalable hybrid models, bolster supply chains, and integrate renewables with local socio-economic development, particularly focusing on rural electrification and waste-to-energy solutions. Provides a concise overview of technologies, hydrogen production methods, efficiency metrics, challenges, and future directions across the clusters.

Hydrogen presents great long-term storage and grid balancing possibilities but often entails significant capital costs and lacks adequate infrastructure. In contrast, solar PV is the most established and cost-effective technology, enjoying rapid cost declines and extensive implementation, although its intermittent nature requires additional storage or generating sources. Biomass and biogas, sourced from agricultural and organic waste, not only deliver dispatchable energy but also aid in waste management and rural electrification; however, their scalability is hindered by feedstock availability and emissions produced during combustion or gasification.

In hybrid systems, solar PV works well with hydrogen to utilize excess energy during the day, converting it into green hydrogen for later electricity generation. Biomass and biogas provide dependable base-load power and can generate biohydrogen or synthetic natural gas (SNG) when combined with hydrogen technologies. Each resource offsets the others' weaknesses solar ensures clean peak energy production, hydrogen offers long-term flexibility, and biomass/biogas guarantees base-load consistency, illustrating the importance of integrating multiple energy vectors in future renewable energy systems.

4. Challenges, Potential Solutions, Limitations, Policy Recommendations, and Future for Hybrid Renewable Energy Systems

Fig. 18 depicts integrating various RES, including solar, wind, biomass, and hydrogen, alongside power conditioning units, energy storage solutions, and grid connections. It illustrates the efficient energy flow from generation through conversion, storage, and distribution to meet demand. The Energy Management System (EMS) is vital in managing power fluctuations, ensuring grid stability, and addressing mismatches between demand and supply. Challenges such as intermittency, high costs, storage constraints, land use disputes, and regulatory obstacles were highlighted. Potential solutions like smart grids, AI-enhanced energy management, and hybrid storage systems were presented. It demonstrates the feasibility, reliability, and scalability of HRES in creating a sustainable energy future.

Table 11 presents significant challenges that HRES faces, including their causes and possible solutions. The variability in solar and wind energy highlights the need for energy storage and AI-driven forecasting. High investment costs may be alleviated through government incentives and collaborative partnerships. Limitations of batteries necessitate the development of advanced storage technologies and recycling efforts. Grid stability demand using smart grids and AI management can be achieved by integrating HRES. It includes floating solar panels and agrovoltaics to address land constraints. Maintenance efficiency can be improved through IoT-enabled predictive servicing. Environmental issues necessitate implementing sustainable battery and biomass solutions, while the challenge of demand-supply imbalances calls for smart energy management strategies to improve efficiency. It also includes peer-to-peer (P2P) energy trading [153], network cost and energy loss allocation for the P2P energy market [154].

4.1. Limitations of HRES deployment

Despite swift technological advances, the widespread adoption of HRES encounters notable economic and socio-political obstacles. A major challenge is the substantial capital investment required, particularly for technologies such as hydrogen electrolysis, advanced biomass gasification, and solar PV with integrated storage. The absence of scalable financing options, extended payback periods, and ambiguous tariff structures diminishes the financial appeal of these systems. Volatile energy prices and limited ways to monetize excess energy lead to unpredictable revenue streams. These economic challenges are exacerbated by fragmented policies, regulatory inconsistencies, and a lack of long-term planning, all undermining investor confidence and

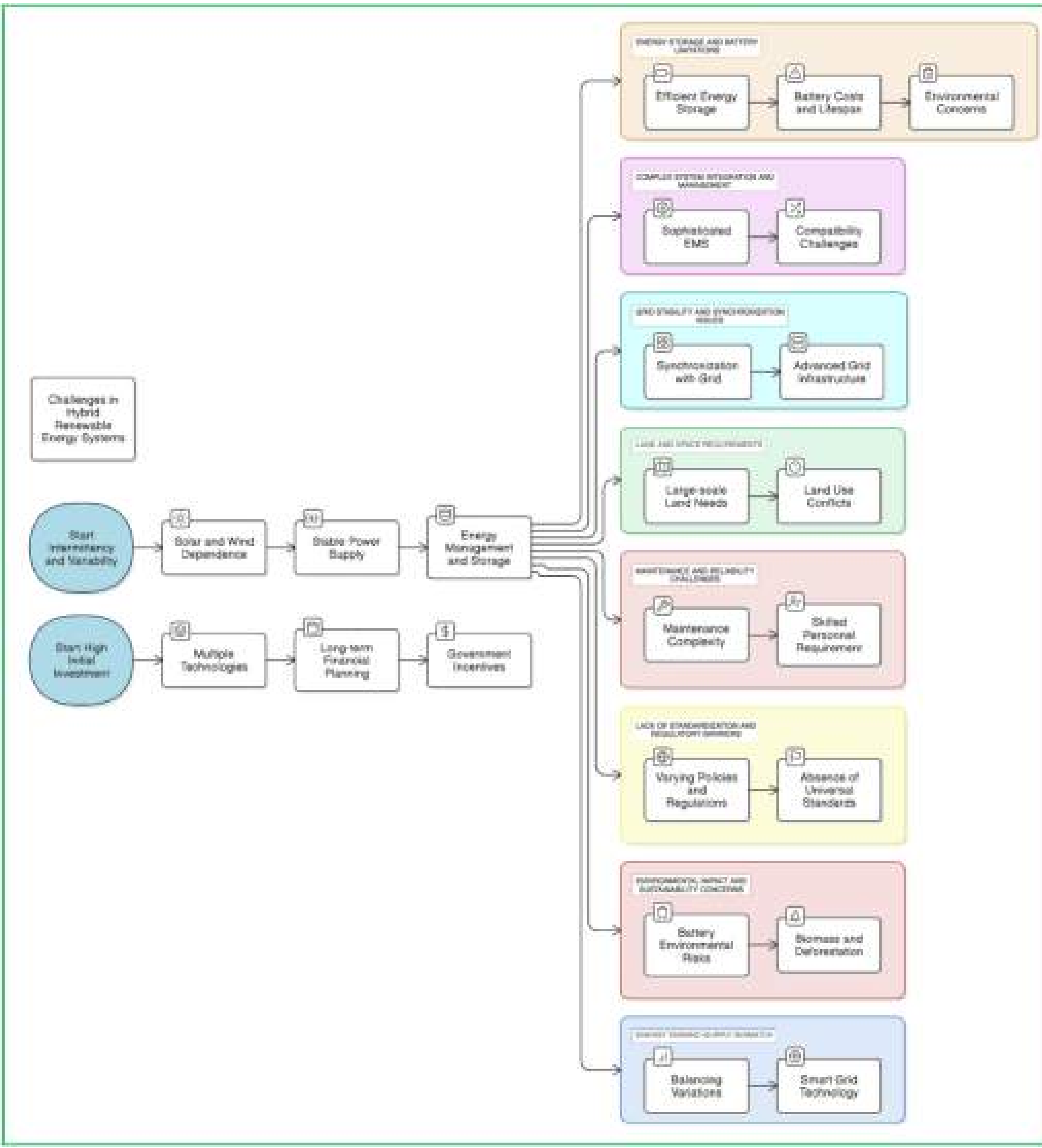


Fig. 18. Challenges in hybrid renewable energy systems.

hindering project scalability.

Socio-political challenges create obstacles for HRES adoption. Safety fears and environmental misunderstandings hinder the public's acceptance of hydrogen, biogas, and biomass technologies, especially in residential and rural areas. Many regions also lack the necessary infrastructure for decentralized hybrid energy systems, and collaboration among stakeholders-governments, utilities, investors, and communities-remains inadequate. Additionally, the reliance on essential raw materials like lithium, cobalt, and rare-earth elements adds vulnerabilities to the supply chain. Tackling these issues requires unified policy frameworks, targeted subsidies, public-private partnerships, awareness initiatives, and international collaboration to secure resilient, inclusive, and sustainable energy transitions.

4.2. Policy recommendations for improving HRES

As HRES continues to prove its ability to facilitate sustainable energy transitions, effectively designed and proactive policy frameworks are

Table 11
Challenges and potential solutions for hybrid renewable energy systems.

Challenge	Explanation	Potential Solutions
• Intermittency and variability	• Solar, wind, and hydropower depend on weather • Biomass and hydrogen need steady feedstock	• Energy storage (batteries, hydrogen) [155,156] • Hybridization [157,158] • AI-driven forecasting [140,159]
• High initial investment Cost	• Solar panels, wind turbines, storage, and grid infrastructure require high capital	• Government incentives [160] • Public-private partnerships [160–162] • Community projects [41,163,164]
• Energy storage and battery limitations	• High costs, limited lifespan, and environmental concerns impact battery efficiency	• Research on solid-state [165,166] • Sodium-ion batteries [167,168] • Hybrid storage solutions [169–171] • Recycling [172]
• Complex system integration and management	• Multiple power sources, converters, and controllers complicate system integration	• AI and IoT-based smart management [173–175] • Standardization [32,131,176,177] • Modular system design [142,178,179]
• Grid stability and synchronization issues	• Hybrid systems must sync with grids to prevent instability and power fluctuations	• Smart grids [115,180,181] • Grid-forming inverters [182–184] • Microgrid capabilities [131,185–188]
• Land and space requirements	• Large-scale projects need significant land, conflicting with agriculture and urbanization	• Floating solar [189,190] • Rooftop solar [191] • Agrovoltaics [192,193]
• Maintenance and reliability challenges	• Hybrid systems increase maintenance complexity and require skilled servicing	• Predictive maintenance with IoT sensors [194] • Technician training [195] • Modular components [196]
• Lack of standardization and regulatory barriers	• Policy inconsistencies across regions delay hybrid system adoption	• Harmonization of regulations [197,198] • Policy support [129,199,200] • Decentralized energy policies [78,201]
• Environmental impact and sustainability concerns	• Battery production, biomass use, and fossil-fuel-based hydrogen have environmental impacts	• Battery recycling [202–204] • Green hydrogen [22,196,205,206] • Sustainable biomass sourcing [179,207]
• Energy demand-supply mismatch	• Fluctuating energy demand leads to imbalances in supply and consumption	• Real-time pricing [208] • Peer-to-peer energy trading [205] • Demand-side management [209]

essential for tackling the current technological, economic, and infrastructure hurdles. This section presents practical and research-supported policy recommendations centered on three main areas: hydrogen regulation, reform of biomass subsidies, and rural electrification via HRES implementation [210].

4.2.1. Enhancing hydrogen regulation and infrastructure

To fully harness hydrogen's potential in HRES frameworks, national governments must set clear and consistent regulations covering hydrogen production, storage, distribution, and safety compliance [210]. This entails:

- Developing national hydrogen strategies that align with long-term decarbonization goals and set targets for renewable hydrogen production.
- Standardizing safety codes and technical guidelines for electrolyzers, hydrogen pipelines, fuel cell infrastructure, and transport mechanisms to reduce risk and improve public trust.
- Facilitating permitting and licensing processes for green hydrogen facilities to reduce bureaucratic delays.
- Supporting pilot-scale and demonstration projects through public-private funding to test hydrogen integration in multi-source HRES models, particularly in industrial and off-grid regions.

Governments should also prioritize investments in hydrogen infrastructure, such as hydrogen refueling stations and underground storage, and encourage international collaborations for cross-border hydrogen trade.

4.2.2. Reforming biomass subsidies and promoting waste-to-energy initiatives

Biomass and biogas are pivotal for reliable and dispatchable energy in HRES, especially in agricultural economies. However, many current subsidy schemes are fragmented or outdated. Policymakers are encouraged to [211]:

- Implement performance-based subsidies that reward efficient and low-emission biomass gasification and anaerobic digestion technologies.
- Expand eligibility for subsidies to include decentralized and community-level biomass systems, encouraging rural entrepreneurs and cooperatives to participate.
- Incentivize agricultural waste collection and supply chains, ensuring regular feedstock availability and reducing open-field burning.
- Introduce carbon credits or feed-in tariffs for verified biomass-derived electricity and hydrogen to make such systems more competitive.
- Promote circular economy models by integrating waste management with energy production, especially municipal solid waste, food waste, and crop residues.

Such reforms would improve biomass project bankability, reduce emissions, and create rural employment opportunities.

4.2.3. Promoting rural electrification through HRES

Energy poverty in rural and remote areas remains a significant barrier to equitable development. HRES particularly combinations of PV, biogas, and hydrogen storage—offer a scalable, clean, and cost-effective solution for rural electrification. To promote this, the following actions are recommended [212]:

- Deploy HRES-based mini-grids and microgrids under national rural electrification schemes with capital cost-sharing models involving government, NGOs, and private developers.
- Offer low-interest financing and soft loans for community-owned renewable energy systems with flexible repayment terms.
- Establish service-based tariffs and performance incentives to encourage long-term maintenance and operation of decentralized HRES infrastructure.
- Launch awareness campaigns and training programs to build local technical capacity in HRES installation, operation, and servicing.

- Encourage gender-inclusive energy policies that promote women's participation in renewable energy value chains, especially in rural biomass and solar micro-enterprises.

A coordinated and flexible policy framework is crucial for speeding up the global deployment of HRES. These policy recommendations focus on hydrogen regulation, reforming biomass subsidies, and achieving energy equity in rural areas, all of which aim to strengthen energy security, foster clean energy innovation, and guarantee the social sustainability of HRES.

4.2.4. Future scope

The fast-paced development of HRES, especially those that combine hydrogen, biomass, biogas, and solar PV, offers exciting opportunities for attaining global energy sustainability. Nonetheless, significant avenues remain to explore in research, innovation, and implementation. This section highlights the crucial future directions that have the potential to influence the next generation of hybrid energy systems greatly.

Future research should embrace a more integrated and interdisciplinary approach to HRES to hasten the global shift toward sustainable and resilient energy systems. There should be a strong focus on the large-scale adoption of optimization tools based on Artificial Intelligence (AI) and Machine Learning (ML) for real-time energy management and forecasting [213], PV power prediction while considering meteorological data [214]. Further investigation is warranted into hybrid energy storage solutions, especially those that combine hydrogen with new battery technologies to address intermittency issues, defect detection of photovoltaic modules [215], and application of fuzzy logic in HRES development [216], to explore a benchmarking framework [217]. Techno-economic assessments and lifecycle analyses must extend to encompass decentralized HRES deployments in rural, industrial, and urban settings. Formulating robust policy frameworks, investment models, and incentive structures will be essential for enabling commercialization.

- **Advancements in Hydrogen Technologies:** Future studies must focus on creating affordable and efficient hydrogen production techniques, particularly via water electrolysis utilizing excess renewable energy and biomass gasification. Advances in photocatalysis, methanol electrolysis, and microbial electrolysis are anticipated to considerably lower production costs and improve conversion efficiencies. Additionally, there is a critical need to investigate scalable hydrogen storage solutions like solid-state hydrides and underground storage, which can help stabilize energy systems reliant on significant renewable energy sources.
- **Integration with Artificial Intelligence and Digital Twins:** AI and digital twin technologies can significantly transform energy demand forecasting, energy dispatch optimization, and the real-time management of HRES. Future research should investigate reinforcement learning, predictive analytics, and cyber-physical integration to develop intelligent energy systems that dynamically adjust to resource variations, consumer habits, and grid conditions.
- **Techno-Economic Optimization and Lifecycle Analysis:** When designing and implementing HRES, lifecycle costs, carbon emissions, and long-term operational sustainability must be considered. Future efforts should develop multi-objective optimization models that harmonize economic, environmental, and technical considerations. Improved techno-economic evaluations, exergy analyses, and lifecycle impact assessments will be instrumental in pinpointing the most effective HRES configurations in diverse geographic and socio-economic environments.
- **Rural Electrification and Decentralized Energy Systems:** Expanding HRES in off-grid and underserved communities presents significant challenges and opportunities. Future initiatives should focus on creating modular and community-oriented HRES structures that align with local energy needs. Additionally, incorporating agro-industrial waste solutions, micro-hydro systems, and smart metering can improve energy access and foster economic inclusion.
- **Policy Innovation and Cross-Sectoral Interactions:** In addition to technical research, upcoming studies should focus on the policy tools and institutional structures that can foster a supportive environment for HRES. It is crucial to highlight the collaboration among sectors such as energy, agriculture, waste management, and transportation to create cohesive strategies that enhance the effectiveness of renewable hybrid systems.

Integrating various energy, agriculture, waste management, and transportation sectors can boost system efficiency and foster a circular energy economy. Finally, creating open-access databases and digital twins of HRES will facilitate improved system modeling, simulation, and validation in real-world scenarios. Innovative technologies like biohydrogen, methanol electrolysis, and multigeneration systems present significant opportunities for improving the efficiency and sustainability of HRES. Biohydrogen allows for clean energy generation from waste, while methanol electrolysis offers a more energy-efficient method for hydrogen production. Furthermore, multigeneration systems can optimize resource utilization in off-grid and remote regions. Future research should enhance these new technologies' efficiency, scalability, and integration into practical energy systems. The future of HRES research lies in multidisciplinary innovation that couples advanced technologies with inclusive policy frameworks. Strategic focus on hydrogen scaling, AI integration, decentralized systems, and cross-sector collaboration will be instrumental in transitioning toward a resilient, low-carbon energy future.

5. Concluding remarks

This systematic review examines the progress, challenges, and future perspectives in HRES, including hydrogen, biomass, biogas, and solar photovoltaics (PV). The review highlights new technologies, enhancements in efficiency, and economic viability, while highlighting sustainability and environmental effects.

VOSviewer organizes the literature into seven thematic clusters by systematically clustering 174 research articles that address various dimensions of renewable energy integration, energy storage, optimization strategies, and policy frameworks. HRES provides a robust and sustainable solution for tackling global energy issues and utilizes the synergistic advantages of different RES. Hydrogen enables long-term storage and proves to be a promising energy carrier. It also aids decarbonization across sectors, particularly when combined with solar PV and biomass gasification. Still, significant challenges, such as high upfront costs, limitations in energy storage, intermittent supply, and regulatory hurdles, hinder large-scale deployment. However, advanced computational techniques, AI-based optimization, and hybrid storage systems offer promising strategies to address these challenges. Various models enhance efficiency, reinforce grid stability, and enable carbon-neutral energy generation. Implementing policy measures, driving technological innovations, and offering economic incentives are essential to hastening the adoption of hybrid energy solutions and facilitating the shift towards a low-carbon, energy-secure future.

Key Findings.

- HRES enhances energy security and sustainability by integrating solar PV, hydrogen, biomass, and biogas for improved efficiency.
- Hydrogen is crucial for long-term energy storage and decarbonization, with biomass gasification achieving the highest efficiency at 53.6 %.
- AI-driven energy management and hybrid storage solutions enhance system performance, reducing intermittency issues in solar and wind-based HRES.

- Multi-energy hybrid models integrating solar PV, hydrogen, and bioenergy achieve high efficiency, with biogas hybrid systems reducing carbon emissions by 96 %.
- Hydrogen-based power-to-gas (P2G) and waste-to-energy technologies provide scalable energy storage solutions, supporting grid stability and off-grid applications.
- Economic barriers remain challenging, but policy incentives, carbon pricing, and technological advancements can accelerate HRES adoption.
- Environmental benefits of renewable hydrogen production are significant, with wind electrolysis producing only 1.29 kg CO_2 eq/kg H_2, reducing emissions by 68–92 % compared to fossil-based hydrogen.
- Future research should optimize biomass gasification, expand hydrogen infrastructure, and incorporate AI-driven smart grids for an efficient hybrid energy transition.

5.1. Limitations of the review

This systematic review provides an extensive cluster-wise analysis of hydrogen, biomass, biogas, and solar PV integration within HRES. However, some limitations should be recognized. Firstly, the study is limited to English-language articles in the Scopus database, which may exclude important research from other sources or in different languages. Secondly, while clustering via VOSviewer can highlight thematic areas, manual filtering and categorization can introduce selection bias. Newer technologies that lack extensive literature may not be adequately represented. Future research could enhance findings using meta-analytical methods, incorporating real-world deployment data, and exploring a wider range of interdisciplinary sources.

CRediT authorship contribution statement

Swapandeep Kaur: Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis. **Raman Kumar:** Writing – review & editing, Validation, Supervision, Software, Project administration, Conceptualization. **Kanwardeep Singh:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Data curation. **Sehijpal Singh:** Visualization, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Aslam A, Bahadar A, Liaquat R, Muddasar M. Recent advances in biological hydrogen production from algal biomass: a comprehensive review. Fuel 2023;350.
[2] Ghorbani B, Monajati Saharkhiz MH, Li J. A novel integrated system for sustainable generation of hydrogen and liquid hydrocarbon fuels using the five-step ZnSI thermochemical cycle, biogas upgrading process, and solar collectors. J Clean Prod 2021;312.
[3] Yang M, Xu C, Bai Y, Ma M, Su X. Investigating black-box model for wind power forecasting using local interpretable model-agnostic explanations algorithm. CSEE Power Energy sys 2025;11:227–42.
[4] Statista. Distribution of electricity generation worldwide in 2023, by energy source. Statista Research Department. Statista Research Department. Statista; 2024.
[5] Liu K, Liu T, Fang Y, Zhan J, Han Z, Li P, et al. A hybrid solar-biomass hydrogen production system using chemical looping with negative carbon emissions and comprehensive performance evaluation. Energy Convers Manag 2024;322.
[6] Konrad J, Bernt AO, Hofmann P. Life cycle assessment of MHP (Mobile Hydrogen Powersupply), an off-grid system to charge battery electric vehicles. Int J Life Cycle Assess 2023;28:304–19.
[7] Zhao H, Zong Q, Zhou H, Yao W, Sun K, Zhou Y, et al. Frequency-voltage active support strategy for hybrid wind farms based on grid-following and grid-forming hierarchical subgroup control. CSEE Power Energy sys 2025;11:65–77.
[8] Kumar R, Channi HK. A PV-Biomass off-grid hybrid renewable energy system (HRES) for rural electrification: design, optimization and techno-economic-environmental analysis. J Clean Prod 2022;349.
[9] Popov SP. Methodological approach to the study of the electro-hydrogen system in Northeast Asia. Int J Hydrogen Energy 2022;47:13524–31.
[10] Alghool D, Bouden C, Haouari M, Trucco P. Harnessing enhanced solar efficiency for green hydrogen production: a comparative analysis of PV and PV-T systems. Int J Hydrogen Energy 2025;98:394–406.
[11] Guerra K, Welfle A, Gutiérrez-Alvarez R, Freer M, Ma L, Haro P. The role of energy storage in Great Britain's future power system: focus on hydrogen and biomass. Appl Energy 2024;357.
[12] Wang Z, Li B, Pipitone G, Liu Q, Yang T, Wang J, et al. Hydrogen production from biomass: a review combined with bibliometric analysis. Int J Hydrogen Energy 2025;117:271–91.
[13] Zhang M, Cai S, Xie Y, Zhou B, Zheng W, Wu Q, et al. Supply resilience constrained scheduling of MEGs for distribution system restoration: a stochastic model and FW-PH algorithm. IEEE Trans Smart Grid 2025;16:194–208.
[14] Zhang Z, Bu Y, Wu H, Wu L, Cui L. Parametric study of the effects of clump weights on the performance of a novel wind-wave hybrid system. Renew Energy 2023;219:119464.
[15] Channi HK, Singh M, Brar YS, Dhingra A, Gupta S, Singh H, et al. Agricultural waste assessment for the optimal power generation in the Ludhiana district, Punjab, India. Mater today proc. Elsevier Ltd; 2021. p. 700–8.
[16] Kumar P, Channi HK, Kumar R, Prakash C, Bhowmik A, Pandey S, et al. Efficient integration of photo voltaic and hydro energy technologies for sustainable power generation in rural areas: a case study. Mater Sci Energy Technol 2024;7: 297–308.
[17] Güven AF, Mengi OÖ. Assessing metaheuristic algorithms in determining dimensions of hybrid energy systems for isolated rural environments: exploring renewable energy systems with hydrogen storage features. J Clean Prod 2023; 428.
[18] Rabea K, Michailos S, Hughes KJ, Ingham D, Pourkashanian M. A new hydrogen production route through biomass gasification in a two-stage fixed bed reactor within the BECCS concept: a techno-economic and life cycle assessment study. Int J Hydrogen Energy 2025;124:140–52.
[19] Sani MM, Afshari H, Saif A. The role of long-term hydrogen storage in decarbonizing remote communities in Canada: an optimization framework with economic, environmental and social objectives. J Energy Storage 2025;105.
[20] Sharifishourabi M, Dincer I, Mohany A. Modeling of an advanced renewable energy system coupled with hydrogen production and liquefaction for sustainable communities. Energy Rep 2024;12:3386–404.
[21] Palanisamy S, Lala H. Optimal sizing of renewable energy powered hydrogen and electric vehicle charging station (HEVCS). IEEE Access 2024;12:48239–54.
[22] Ahang M, Granado PCD, Tomasgard A. Investments in green hydrogen as a flexibility source for the European power system by 2050: does it pay off? Appl Energy 2025;378.
[23] Zhu M, Ai X, Fang J, Cui S, Wu K, Zheng L, et al. Optimal scheduling of hydrogen energy hub for stable demand with uncertain photovoltaic and biomass. Appl Energy 2024;360.
[24] Hüner B. Feasibility and environmental analysis of biogas-based hybrid energy system using HOMER pro software: a case study for Hatay. Energy Convers Manag 2025;326.
[25] Alrbai M, Al-Dahidi S, Al-Ghussain L, Shboul B, Hayajneh H, Alahmer A. Assessment of the polygeneration approach in wastewater treatment plants for enhanced energy efficiency and green hydrogen/ammonia production. Process Saf Environ Prot 2024;192:803–21.
[26] Li Q, Jiang L, Huang G, Wang DW, Shepherd J, Daiyan R, et al. A ternary system exploiting the full solar spectrum to generate renewable hydrogen from a waste biomass feedstock. Energy Environ Sci 2023;16:3497–513.
[27] Modu B, Abdullah MPB, Alkassem A, Garni HZA, Alkabi M. Optimal design of a grid-independent solar-fuel cell-biomass energy system using an enhanced salp swarm algorithm considering rule-based energy management strategy. IEEE Access 2024;12:23914–29.
[28] Roy D, Bhowmik M, Roskilly AP. Technoeconomic, environmental and multi criteria decision making investigations for optimisation of off-grid hybrid renewable energy system with green hydrogen production. J Clean Prod 2024; 443.
[29] Kazakov AN, Dunikov DO, Romanov IA, Eronin AA, Allakhverdiev SI. An evaluation of the metal hydride hydrogen extraction efficiency from biological gas streams. Int J Hydrogen Energy 2024;110:317–23.
[30] Thirunavukkarasu M, Sawle Y. An examination of the techno-economic viability of hybrid grid-integrated and stand-alone generation systems for an Indian tea plant. Front Energy Res 2022;10.

[31] Abid H, Østegaard PA, Skov IR, Mathiesen BV. Comparative assessment of future hydrogen demand potentials in a decarbonised European energy system. Int J Hydrogen Energy 2025;122:82–96.
[32] Karthikeyan B, Praveen Kumar G. A comprehensive thermodynamic modeling, feasibility, and optimization study of a renewable energy powered system for sustainable cold chain applications – Cooling, power, heating, and green hydrogen production. Energy Convers Manag 2024;322.
[33] Takatsu N, Farzaneh H. Techno-economic analysis of a novel hydrogen-based hybrid renewable energy system for both grid-tied and off-grid power supply in Japan: the case of Fukushima prefecture. Appl Sci 2020;10.
[34] Shoukat K, Moazzam Khan M, Bukhari S, Abbas Shah SI, Bashir I, Alothman AA, et al. Study on oxygen evolution reaction efficiency demonstrated by Ce-E (E = S, Se and te) electrocatalyst. Int J Hydrogen Energy 2024;69:11–20.
[35] Leonzio G. Design and feasibility analysis of a Power-to-Gas plant in Germany. J Clean Prod 2017;162:609–23.
[36] Barbuzza E, Buceti G, Pozio A, Santarelli M, Tosti S. Gasification of wood biomass with renewable hydrogen for the production of synthetic natural gas. Fuel 2019;242:520–31.
[37] Manzoor S, Ali S, Mansha M, Safronova AV, Altaf F, Khan SA, et al. Boosting hydrogen production via alkaline water splitting: impact of Ag doping in Gd2O3 nanosheet arrays. Int J Hydrogen Energy 2024.
[38] Hai T, Chaturvedi R, Marjan RK, Almujibah H, Van Thuong T, Soliman NF, et al. Tri-objective optimization of electricity, fresh water, and hydrogen production in a biomass-driven trigeneration plant: thermoeconomic and environmental evaluation. Energy 2024;294.
[39] Ratnasiri J. Alternative energy - prospects for Sri Lanka. J Natl Sci Found Sri Lanka 2008;36:89–114.
[40] Yan Q, Zhang H, Sun B, Guo L. Effect of heating method on hydrogen production by biomass gasification in supercritical water. Adv Condens Matter Phys 2014:2014.
[41] Armoo EA, Mohammed M, Narra S, Beguedou E, Agyenim FB, Kemausuor F. Achieving techno-economic feasibility for hybrid renewable energy systems through the production of energy and alternative fuels. Energies 2024;17.
[42] Gungor B, Dincer I. Development of a sustainable community with an integrated renewable and waste to energy system for multiple useful outputs. J Clean Prod 2021;312.
[43] Armaroli N, Balzani V. Towards an electricity-powered world. Energy Environ Sci 2011;4:3193–222.
[44] Shimura K, Yoshida H. Heterogeneous photocatalytic hydrogen production from water and biomass derivatives. Energy Environ Sci 2011;4:2467–81.
[45] Christopher K, Dimitrios R. A review on exergy comparison of hydrogen production methods from renewable energy sources. Energy Environ Sci 2012;5:6640–51.
[46] Lu X, Xie S, Yang H, Tong Y, Ji H. Photoelectrochemical hydrogen production from biomass derivatives and water. Chem Soc Rev 2014;43:7581–93.
[47] Hussein AK. Applications of nanotechnology in renewable energies - a comprehensive overview and understanding. Renew Sustain Energy Rev 2015;42:460–76.
[48] Dincer I, Acar C. A review on clean energy solutions for better sustainability. Int J Energy Res 2015;39:585–606.
[49] Hosseini SE, Wahid MA. Hydrogen production from renewable and sustainable energy resources: promising green energy carrier for clean development. Renew Sustain Energy Rev 2016;57:850–66.
[50] Guo S, Liu Q, Sun J, Jin H. A review on the utilization of hybrid renewable energy. Renew Sustain Energy Rev 2018;91:1121–47.
[51] Tilley SD. Recent advances and emerging trends in photo-electrochemical solar energy conversion. Adv Energy Mater 2019;9.
[52] Akhlaghi N, Najafpour-Darzi G. A comprehensive review on biological hydrogen production. Int J Hydrogen Energy 2020;45:22492–512.
[53] Ozturk M, Dincer I. A comprehensive review on power-to-gas with hydrogen options for cleaner applications. Int J Hydrogen Energy 2021;46:31511–22.
[54] Homa M, Pałac A, Żołądek M, Figaj R. Small-scale hybrid and polygeneration renewable energy systems: energy generation and storage technologies, applications, and analysis methodology. Energies 2022;15.
[55] Farghali M, Osman AI, Umetsu K, Rooney DW. Integration of biogas systems into a carbon zero and hydrogen economy: a review. Environ Chem Lett 2022;20:2853–927.
[56] Chu W, Vicidomini M, Calise F, Duić N, Østergaard PA, Wang Q, et al. Review of hot topics in the sustainable development of energy, water, and environment systems conference in 2022. Energies 2023;16.
[57] Tang D, Tan GL, Li GW, Liang JG, Ahmad SM, Bahadur A, et al. State-of-the-art hydrogen generation techniques and storage methods: a critical review. J Energy Storage 2023;64.
[58] Abdelsalam RA, Mohamed M, Farag HEZ, El-Saadany EF. Green hydrogen production plants: a techno-economic review. Energy Convers Manag 2024;319.
[59] Singh SK, Tiwari AK. Solar-powered hydrogen production: advancements, challenges, and the path to net-zero emissions. Int J Hydrogen Energy 2024;84:549–79.
[60] Akpasi SO, Smarte Anekwe IM, Tetteh EK, Amune UO, Mustapha SI, Kiambi SL. Hydrogen as a clean energy carrier: advancements, challenges, and its role in a sustainable energy future. Clean Energy 2025;9:52–88.
[61] Hossain MS, Islam MN, Shahriar K, Mujtaba Hasan M, Hossain MS. The role of solar thermal hydrogen production technologies in future energy solutions: a review. Energy Convers Manag X 2025;25.
[62] Manan Jariwala A, Kumar Dash S, Sahu UK, Mohan HM. Performance optimization techniques on point absorber and oscillating water column wave energy converter: a comprehensive review. IEEE Access 2025;13:14743–59.
[63] Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Revista Panamericana de Salud Publica/Pan Am J Public Health 2022;46.
[64] Agyekum EB, Nutakor C, Khan T, Adegboye OR, Odoi-Yorke F, Okonkwo PC. Analyzing the research trends in the direction of hydrogen storage – a look into the past, present and future for the various technologies. Int J Hydrogen Energy 2024;74:259–75.
[65] Narasipuram RP. Optimal design and analysis of hybrid photovoltaic-fuel cell power generation system for an advanced converter technologies. Int J Math Model Numer Optim 2018;8:245–76.
[66] Gretzschel O, Schfer M, Steinmetz H, Pick E, Kanitz K, Krieger S. Advanced wastewater treatment to eliminate organic micropollutants in wastewater treatment plants in combination with energy-efficient electrolysis at WWTP Mainz. Energies 2020;13.
[67] Kılkış B. Exergetic comparison of wind energy storage with ice making cycle versus mini-hydrogen economy cycle in off-grid district cooling. Int J Hydrogen Energy 2017;42:17571–82.
[68] Ishaq H, Dincer I. Comparative assessment of renewable energy-based hydrogen production methods. Renew Sustain Energy Rev 2021;135.
[69] Calise F, de Notaristefani di Vastogirardi G, Dentice d'Accadia M, Vicidomini M. Simulation of polygeneration systems. Energy 2018;163:290–337.
[70] AlShafi M, Bicer Y. Thermodynamic performance comparison of various energy storage systems from source-to-electricity for renewable energy resources. Energy 2021;219.
[71] Tafavogh M, Zahedi A. Design and production of a novel encapsulated nano phase change materials to improve thermal efficiency of a quintuple renewable geothermal/hydro/biomass/solar/wind hybrid system. Renew Energy 2021;169:358–78.
[72] Liu R, Solangi YA. An analysis of renewable energy sources for developing a sustainable and low-carbon hydrogen economy in China. Processes 2023;11.
[73] Ramsurn H, Gupta RB. Nanotechnology in solar and biofuels. ACS Sustainable Chem Eng 2013;1:779–97.
[74] Calise F, Dentice D, Accadia M. Simulation of polygeneration systems. Energies 2016;9.
[75] Güven AF, Yörükeren N, Samy MM. Design optimization of a stand-alone green energy system of university campus based on Jaya-Harmony Search and Ant Colony Optimization algorithms approaches. Energy 2022;253.
[76] Stewart C, Hessami MA. A study of methods of carbon dioxide capture and sequestration - the sustainability of a photosynthetic bioreactor approach. Energy Convers Manag 2005;46:403–20.
[77] Zhou X, Zhao Q, Zhang Y, Sun L. Integrated energy production unit: an innovative concept and design for energy transition toward low-carbon development. CSEE Power Energy sys 2021;7:1133–9.
[78] Hotz N. Hybrid solar system for decentralized electric power generation and storage. J Solar Energy Eng Trans ASME 2012;134.
[79] Yüksel YE. Elementary science teacher candidates' views on hydrogen as future energy carrier. Int J Hydrogen Energy 2019;44:9817–22.
[80] Islam S, Dincer I, Yilbas BS. A novel renewable energy-based integrated system with thermoelectric generators for a net-zero energy house. Int J Energy Res 2020;44:3458–77.
[81] Bamisile O, Huang Q, Li J, Dagbasi M, Desire Kemena A, Abid M, et al. Modelling and performance analysis of an innovative CPVT, wind and biogas integrated comprehensive energy system: an energy and exergy approach. Energy Convers Manag 2020;209.
[82] Perna A, Minutillo M, Jannelli E. Hydrogen from intermittent renewable energy sources as gasification medium in integrated waste gasification combined cycle power plants: a performance comparison. Energy 2016;94:457–65.
[83] Anand K, Mittal AP, Kumar B. Cost-inclusive heuristic power management of hybrid power generation plant with ANN-regulated biogas plant. Sustain Cities Soc 2023;97.
[84] Rad MAV, Ghasempour R, Rahdan P, Mousavi S, Arastounia M. Techno-economic analysis of a hybrid power system based on the cost-effective hydrogen production method for rural electrification, a case study in Iran. Energy 2020;190.
[85] Trieb F, Moser M, Kern J. Liquid Solar Fuel – liquid hydrocarbons from solar energy and biomass. Energy 2018;153:1–11.
[86] Moharramian A, Soltani S, Rosen MA, Mahmoudi SMS, Bhattacharya T. Modified exergy and modified exergoeconomic analyses of a solar based biomass co-fired cycle with hydrogen production. Energy 2019;167:715–29.
[87] Kilkiş B, Kilkiş S. Hydrogen economy model for nearly net-zero cities with exergy rationale and energy-water nexus. Energies 2018;11.
[88] Gondal IA, Masood SA, Khan R. Green hydrogen production potential for developing a hydrogen economy in Pakistan. Int J Hydrogen Energy 2018;43:6011–39.
[89] Ni M, Leung MKH, Sumathy K, Leung DYC. Potential of renewable hydrogen production for energy supply in Hong Kong. Int J Hydrogen Energy 2006;31:1401–12.
[90] Melis A, Melnicki MR. Integrated biological hydrogen production. Int J Hydrogen Energy 2006;31:1563–73.
[91] Won W, Kwon H, Han JH, Kim J. Design and operation of renewable energy sources based hydrogen supply system: technology integration and optimization. Renew Energy 2017;103:226–38.

[92] Nzihou A, Flamant G, Stanmore B. Synthetic fuels from biomass using concentrated solar energy - a review. Energy 2012;42:121–31.
[93] Frattini D, Cinti G, Bidini G, Desideri U, Cioffi R, Jannelli E. A system approach in energy evaluation of different renewable energies sources integration in ammonia production plants. Renew Energy 2016;99:472–82.
[94] Fazelpour F, Soltani N, Rosen MA. Economic analysis of standalone hybrid energy systems for application in Tehran, Iran. Int J Hydrogen Energy 2016;41:7732–43.
[95] Zhang D, Li Y, Chin KS. Photovoltaic technology assessment based on cumulative prospect theory and hybrid information from sustainable perspective. Sustain Energy Technol Assessments 2022;52.
[96] Acar C, Dincer I. Impact assessment and efficiency evaluation of hydrogen production methods. Int J Energy Res 2015;39:1757–68.
[97] Castellanos JG, Walker M, Poggio D, Pourkashanian M, Nimmo W. Modelling an off-grid integrated renewable energy system for rural electrification in India using photovoltaics and anaerobic digestion. Renew Energy 2015;74:390–8.
[98] Rokni M. Thermodynamic analyses of municipal solid waste gasification plant integrated with solid oxide fuel cell and Stirling hybrid system. Int J Hydrogen Energy 2015;40:7855–69.
[99] Almahdi M, Dincer I, Rosen MA. A new solar based multigeneration system with hot and cold thermal storages and hydrogen production. Renew Energy 2016;91:302–14.
[100] Thengane SK, Hoadley A, Bhattacharya S, Mitra S, Bandyopadhyay S. Cost-benefit analysis of different hydrogen production technologies using AHP and Fuzzy AHP. Int J Hydrogen Energy 2014;39:15293–306.
[101] Bui VG, Tu Bui TM, Ong HC, Nižetić S, Bui VH, Xuan Nguyen TT, et al. Optimizing operation parameters of a spark-ignition engine fueled with biogas-hydrogen blend integrated into biomass-solar hybrid renewable energy system. Energy 2022:252.
[102] Herdem MS, Mazzeo D, Matera N, Wen JZ, Nathwani J, Hong Z. Simulation and modeling of a combined biomass gasification-solar photovoltaic hydrogen production system for methanol synthesis via carbon dioxide hydrogenation. Energy Convers Manag 2020;219.
[103] Vidal M, Martín M. Optimal coupling of a biomass based polygeneration system with a concentrated solar power facility for the constant production of electricity over a year. Comput Chem Eng 2015;72:273–83.
[104] Guo LJ, Zhao L, Jing DW, Lu YJ, Yang HH, Bai BF, et al. Solar hydrogen production and its development in China. Energy 2009;34:1073–90.
[105] Brouwer J. On the role of fuel cells and hydrogen in a more sustainable and renewable energy future. Curr Appl Phys 2010;10:S9–17.
[106] Turner J, Sverdrup G, Mann MK, Maness PC, Kroposki B, Ghirardi M, et al. Renewable hydrogen production. Int J Energy Res 2008;32:379–407.
[107] Cho HH, Strezov V, Evans TJ. A review on global warming potential, challenges and opportunities of renewable hydrogen production technologies. Sustain Mater Technol 2023;35.
[108] Cheng C, Blakers A, Stocks M, Lu B. 100% renewable energy in Japan. Energy Convers Manag 2022;255.
[109] Jamali DH, Noorpoor A. Optimization of a novel solar-based multi-generation system for waste heat recovery in a cement plant. J Clean Prod 2019;240.
[110] Al Wahedi A, Bicer Y. Development of an off-grid electrical vehicle charging station hybridized with renewables including battery cooling system and multiple energy storage units. Energy Rep 2020;6:2006–21.
[111] Ampah JD, Afrane S, Agyekum EB, Adun H, Yusuf AA, Bamisile O. Electric vehicles development in Sub-Saharan Africa: performance assessment of standalone renewable energy systems for hydrogen refuelling and electricity charging stations (HRECS). J Clean Prod 2022;376.
[112] Schmidt Rivera XC, Topriska E, Kolokotroni M, Azapagic A. Environmental sustainability of renewable hydrogen in comparison with conventional cooking fuels. J Clean Prod 2018;196:863–79.
[113] Tiam Kapen P, Medjo Nouadje BA, Chegnimonhan V, Tchuen G, Tchinda R. Techno-economic feasibility of a PV/battery/fuel cell/electrolyzer/biogas hybrid system for energy and hydrogen production in the far north region of Cameroon by using HOMER pro. Energy Strategy Rev 2022;44:100988.
[114] Mauky E, Weinrich S, Jacobi HF, Nägele HJ, Liebetrau J, Nelles M. Demand-driven biogas production by flexible feeding in full-scale – process stability and flexibility potentials. Anaerobe 2017;46:86–95.
[115] Sigurjonsson HÆ, Clausen LR. Solution for the future smart energy system: a polygeneration plant based on reversible solid oxide cells and biomass gasification producing either electrofuel or power. Appl Energy 2018;216:323–37.
[116] Qin Z, Tang Y, Zhang Z, Ma X. Techno-economic-environmental analysis of coal-based methanol and power poly-generation system integrated with biomass co-gasification and solar based hydrogen addition. Energy Convers Manag 2021;228.
[117] Shahid UB, Bicer Y, Ahzi S, Abdala A. Thermodynamic assessment of an integrated renewable energy multigeneration system including ammonia as hydrogen carrier and phase change material energy storage. Energy Convers Manag 2019;198.
[118] Lund H, Mathiesen BV. Energy system analysis of 100% renewable energy systems-The case of Denmark in years 2030 and 2050. Energy 2009;34:524–31.
[119] Potrč S, Čuček L, Martin M, Kravanja Z. Sustainable renewable energy supply networks optimization – the gradual transition to a renewable energy system within the European Union by 2050. Renew Sustain Energy Rev 2021;146.
[120] Gude VG, Kokabian B, Gadhamshetty V. Beneficial bioelectrochemical systems for energy, water, and biomass production. J Microb Biochem Technol 2013;5.
[121] Dadak A, Mousavi SA, Mehrpooya M, Kasaeian A. Techno-economic investigation and dual-objective optimization of a stand-alone combined configuration for the generation and storage of electricity and hydrogen applying hybrid renewable system. Renew Energy 2022;201:1–20.
[122] Boulmrharj S, Khaidar M, Bakhouya M, Ouladsine R, Siniti M, Zine-dine K. Performance assessment of a hybrid system with hydrogen storage and fuel cell for cogeneration in buildings. Sustainability 2020;12.
[123] Taheri SI, Vieira GGTT, Salles MBC, Avila SL. A trip-ahead strategy for optimal energy dispatch in ship power systems. Elec Power Syst Res 2021;192.
[124] Cao Y, Dhahad HA, Abo-Khalil AG, Sharma K, Hussein Mohammed A, Anqi AE, et al. Hydrogen production using solar energy and injection into a solid oxide fuel cell for CO2 emission reduction; Thermoeconomic assessment and tri-objective optimization. Sustain Energy Technol Assessments 2022;50.
[125] Cozzolino R, Lombardi L, Tribioli L. Use of biogas from biowaste in a solid oxide fuel cell stack: application to an off-grid power plant. Renew Energy 2017;111:781–91.
[126] Ampah JD, Jin C, Agyekum EB, Afrane S, Geng Z, Adun H, et al. Performance analysis and socio-enviro-economic feasibility study of a new hybrid energy system-based decarbonization approach for coal mine sites. Sci Total Environ 2023;854.
[127] Torella JP, Gagliardi CJ, Chen JS, Bediako DK, Colón B, Way JC, et al. Efficient solar-to-fuels production from a hybrid microbial-water-splitting catalyst system. Proc Natl Acad Sci U S A 2015;112:2337–42.
[128] Liu C, Sakimoto KK, Colón BC, Silver PA, Nocera DG. Ambient nitrogen reduction cycle using a hybrid inorganic-biological system. Proc Natl Acad Sci U S A 2017;114:6450–5.
[129] Trainer T. Some problems in storing renewable energy. Energy Policy 2017;110:386–93.
[130] Krajačić G, Duić N, Carvalho MdG. H2RES, Energy planning tool for island energy systems - the case of the Island of Mljet. Int J Hydrogen Energy 2009;34:7015–26.
[131] Kafetzis A, Ziogou C, Panopoulos KD, Papadopoulou S, Seferlis P, Voutetakis S. Energy management strategies based on hybrid automata for islanded microgrids with renewable sources, batteries and hydrogen. Renew Sustain Energy Rev 2020;134.
[132] Martín M. Optimal year-round production of DME from CO2 and water using renewable energy. J CO2 Util 2016;13:105–13.
[133] Raptis D, Dracopoulos V, Lianos P. Renewable energy production by photoelectrochemical oxidation of organic wastes using WO3 photoanodes. J Hazard Mater 2017;333:259–64.
[134] Sánchez A, Zhang Q, Martín M, Vega P. Towards a new renewable power system using energy storage: an economic and social analysis. Energy Convers Manag 2022;252.
[135] Redwood MD, Orozco RL, Majewski AJ, Macaskie LE. An integrated biohydrogen refinery: synergy of photofermentation, extractive fermentation and hydrothermal hydrolysis of food wastes. Bioresour Technol 2012;119:384–92.
[136] Siddiqui O, Dincer I, Yilbas BS. Development of a novel renewable energy system integrated with biomass gasification combined cycle for cleaner production purposes. J Clean Prod 2019;241.
[137] Sørensen B. A renewable energy and hydrogen scenario for northern Europe. Int J Energy Res 2008;32:471–500.
[138] Li Y, Zhang M, Zhou L, Yang S, Wu Z, Ma Y. Recent advances in surface-modified g-c3n4-based photocatalysts for h2 production and co2 reduction. Wuli Huaxue Xuebao/Acta Phys - Chim Sin 2021;37.
[139] Cao Y, Dhahad HA, Togun H, Anqi AE, Farouk N, Farhang B. A novel hybrid biomass-solar driven triple combined power cycle integrated with hydrogen production: multi-objective optimization based on power cost and CO2 emission. Energy Convers Manag 2021;234.
[140] Mousavi Rabeti SA, Khoshgoftar Manesh MH, Amidpour M. Techno-economic and environmental assessment of a novel polygeneration system based on integration of biomass air-steam gasification and solar parabolic trough collector. Sustain Energy Technol Assessments 2023;56.
[141] Bozgeyik A, Altay L, Hepbasli A. Energetic, exergetic, exergoeconomic, environmental and sustainability analyses of a solar, geothermal and biomass based novel multi-generation system for production of power, hydrogen, heating, cooling and fresh water. Process Saf Environ Prot 2023;177:400–15.
[142] Tebibel H, Khellaf A, Menia S, Nouicer I. Design, modelling and optimal power and hydrogen management strategy of an off grid PV system for hydrogen production using methanol electrolysis. Int J Hydrogen Energy 2017;42:14950–67.
[143] Wang J, Huo J, Zhang S, Teng Y, Li L, Han T. Flexibility transformation decision-making evaluation of coal-fired thermal power units deep peak shaving in China. Sustainability 2021;13:1–16.
[144] Yolcular S. Hydrogen production for energy use in European Union Countries and Turkey. Energy Sources, Part A Recovery, Util Environ Eff 2009;31:1329–37.
[145] Zhang Y, Zhao G, Shi H, Zhang YN, Huang W, Huang X, et al. Photoelectrocatalytic glucose oxidation to promote hydrogen production over periodically ordered TiO2 nanotube arrays assembled of Pd quantum dots. Electrochim Acta 2015;174:93–101.
[146] Siddiqui O, Dincer I. Design and assessment of a new solar-based biomass gasification system for hydrogen, cooling, power and fresh water production utilizing rice husk biomass. Energy Convers Manag 2021;236.
[147] du Toit M, Engelbrecht N, Oelofse SP, Bessarabov D. Performance evaluation and emissions reduction of a micro gas turbine via the co-combustion of H2/CH4/CO2 fuel blends. Sustain Energy Technol Assessments 2020;39.
[148] Buruldy ME, Mert MS, Javani N. Thermodynamic analysis of a parabolic trough solar power plant integrated with a biomass-based hydrogen production system. Int J Hydrogen Energy 2022;47:19481–501.

[149] Boujjat H, Yuki Junior GM, Rodat S, Abanades S. Dynamic simulation and control of solar biomass gasification for hydrogen-rich syngas production during allothermal and hybrid solar/autothermal operation. Int J Hydrogen Energy 2020;45:25827–37.
[150] El-Emam RS, Dincer I. Assessment and evolutionary based multi-objective optimization of a novel renewable-based polygeneration energy system. J Energy Resour Technol Trans ASME 2017;139.
[151] Mousavi SA, Zarchi RA, Astaraei FR, Ghasempour R, Khaninezhad FM. Decision-making between renewable energy configurations and grid extension to simultaneously supply electrical power and fresh water in remote villages for five different climate zones. J Clean Prod 2021;279.
[152] Carrieri D, Ananyev G, Dismukes GC. Renewable hydrogen production by cyanobacteria: nickel requirements for optimal hydrogenase activity. Int J Hydrogen Energy 2008;33:2014–22.
[153] Zheng J, Liang ZT, Li Y, Li Z, Wu QH. Multi-agent reinforcement learning with privacy preservation for continuous double auction-based P2P energy trading. IEEE Trans Ind Inf 2024;20:6582–90.
[154] Xia Y, Huang Y, Fang J. A generalized Nash-in-Nash bargaining solution to allocating energy loss and network usage cost of buildings in peer-to-peer trading market. Sustainable Energy, Grids and Networks 2025;42:101628.
[155] Mohseni S, Brent AC, Burmester D. Off-grid multi-carrier microgrid design optimisation: the case of rakiura–stewart island, Aotearoa–New Zealand. Energies 2021;14.
[156] Wu H, Liu Q, Bai Z, Xie G, Zheng J. Performance investigation of a novel multi-functional system for power, heating and hydrogen with solar energy and biomass. Energy Convers Manag 2019;196:768–78.
[157] Altayib K, Dincer I. Development of a large-scale integrated solar-biomass thermal facility for green production of useful outputs. Energy 2024;313.
[158] Luo J, Abed AM, Salah B, Chohan MK, Yajid MSA, Mgm J, et al. Using green hydrogen as the supplementary fuel for a scheme of power/fresh water production: an application of AI for optimal energy management and emission reduction. Process Saf Environ Prot 2024;190:1273–89.
[159] Baseer MA, Kumar P, Nascimento EGS. Advancements in hydrogen production through the integration of renewable energy sources with AI techniques: a comprehensive literature review. Appl Energy 2025;383.
[160] Gupta S, Kumar R, Kumar A. Green hydrogen in India: prioritization of its potential and viable renewable source. Int J Hydrogen Energy 2024;50:226–38.
[161] Atzler F, Türck J, Türck R, Krahl J. The energy situation in the Federal Republic of Germany: analysis of the current situation and perspectives for a non-fossil energy supply. Energies 2023;16.
[162] Krah K, Ericson S, Li X, Olawale OW, Castillo R, Newes E, et al. Distributed clean energy opportunities for US oil refinery operations. Front Energy Res 2023;11.
[163] Khalil M, Dincer I. Investigation of a community-based clean energy system holistically with renewable and hydrogen energy options for better sustainable development. J Clean Prod 2024;440.
[164] Razaghi M, Rahdar MH, Aghamohamadi N, Mohammadi M, Ahmadi P. Biofuel, solar-biofuel or geothermal energy; which resource can better contribute to an integrated energy system for residential energy demands. Process Saf Environ Prot 2024;181:103–30.
[165] Du Y-L, Sun ZY, Fu Ba, Huang Q. Unleashing the power of hydrogen: challenges and solutions in solid-state storage. Int J Hydrogen Energy 2025.
[166] He Y, Guo J, Bi C, Hao Z, Li C, Wang Q, et al. Sandwich-like polyimide nanofiber membrane of PEO-based solid-state electrolytes to promote mechanical properties and security for lithium metal batteries. Int J Hydrogen Energy 2025;109: 1266–73.
[167] Kannadasan M, Sathiasivan K, Pandurangan I, Balakrishnan M. Synergistic nanocomposite polymer electrolytes for advanced all-solid-state sodium-ion batteries. Int J Hydrogen Energy 2024;78:634–41.
[168] Hussain A, Hussain M, Hussain A, Alam M, Khan A, Idrees M, et al. Improving the electrochemical performance of sodium-ion batteries with Zn1-xMnxO anode ($0 \leq x \leq 0.2$). Int J Hydrogen Energy 2024;71:894–902.
[169] Simbeck DR. CO2 capture and storage-the essential bridge to the hydrogen economy. Energy 2004;29:1633–41.
[170] Moura CHS, Silveira JL, Lamas WDQ. Dynamic production, storage, and use of renewable hydrogen: a technical-economic-environmental analysis in the public transport system in São Paulo state, Brazil. Int J Hydrogen Energy 2020;45: 31585–98.
[171] Li F-F, Xie J-Z, Fan Y-F, Qiu J. Potential of different forms of gravity energy storage. Sustain Energy Technol Assessments 2024;64:103728.
[172] Bringezu S. Carbon recycling for renewable materials and energy supply: recent trends, long-term options, and challenges for research and development bringezu carbon recycling. J Ind Ecol 2014;18:327–40.
[173] SaberiKamarposhti M, Kamyab H, Krishnan S, Yusuf M, Rezania S, Chelliapan S, et al. A comprehensive review of AI-enhanced smart grid integration for hydrogen energy: advances, challenges, and future prospects. Int J Hydrogen Energy 2024; 67:1009–25.
[174] Nnabuife SG, Udemu C, Hamzat AK, Darko CK, Quainoo KA. Smart monitoring and control systems for hydrogen fuel cells using AI. Int J Hydrogen Energy 2024; 110:704–26.
[175] Rong Q, Hu P, Yu Y, Wang D, Cao Y, Xin H. Virtual external perturbance-based impedance measurement of grid-connected converter. IEEE Trans Ind Electron 2025;72:2644–54.
[176] Modu B, Abdullah MP, Bukar AL, Hamza MF, Adewolu MS. Energy management and capacity planning of photovoltaic-wind-biomass energy system considering hydrogen-battery storage. J Energy Storage 2023;73.
[177] Rong Q, Hu P, Wang L, Li Y, Yu Y, Wang D, et al. Asymmetric sampling disturbance-based universal impedance measurement method for converters. IEEE Trans Power Electron 2024;39:15457–61.
[178] Aydın F, Öztürk D. Design and techno-economic analysis of hybrid power systems for rural areas: a case study of bingöl. Electricity 2024;5:562–84.
[179] Khoshgoftar Manesh MH, Davadgaran S, Mousavi Rabeti SA. New procedure for designing an innovative biomass-solar-wind polygeneration system for sustainable production of power, freshwater, and ammonia using 6E analyses, carbon footprint, water footprint, and multi-objective optimization. Renew Energy 2024;230.
[180] Dabirian M, Kheradmandi M, Sedighizadeh M. Determination of the optimal capacity of electric hybrid renewable energy systems using a smart optimization algorithm. IIOAB J 2016;7:336–43.
[181] Zhang T, Zhao W, He Q, Xu J. Optimization of microgrid dispatching by integrating photovoltaic power generation forecast. Sustainability2025.
[182] Dogan A. Analyzing flexibility options for microgrid management from economical operational and environmental perspectives. Int J Electr Power Energy Syst 2024;158.
[183] Rivera Y, Blanco D, Bastida-Molina P, Berna-Escriche C. Assessment of a fully renewable system for the total decarbonization of the economy with full demand coverage on islands connected to a central grid: the balearic case in 2040. Machines 2023;11.
[184] Thai C, Brouwer J. Decarbonizing a solar PV and gas turbine microgrid with hydrogen and batteries. Energy Convers Manag 2023;292.
[185] Żołądek M, Kafetzis A, Figaj R, Panopoulos K. Energy-economic assessment of islanded microgrid with wind turbine, photovoltaic field, wood gasifier, battery, and hydrogen energy storage. Sustainability 2022;14.
[186] Żołądek M, Figaj R, Kafetzis A, Panopoulos K. Energy-economic assessment of self-sufficient microgrid based on wind turbine, photovoltaic field, wood gasifier, battery, and hydrogen energy storage. Int J Hydrogen Energy 2024;52:728–44.
[187] Ishraque MF, Shezan SA, Shafiullah GM, Muyeen SM, Alharbi T, Alenezi AH, et al. Operational assessment of solar-wind-biomass-hydro-electrolyser hybrid microgrid for load variations using model predictive deterministic algorithm and droop controllers. E-prime - advances in electrical engineering, electronics and energy, vol. 9; 2024.
[188] Rong Y, Xu Z, Liu J, Liu H, Ding J, Liu X, et al. Du-bus: a realtime bus waiting time estimation system based on multi-source data. IEEE Trans Intell Transport Syst 2022;23:24524–39.
[189] Saitov K, Jiang Z. Advancing offshore solar energy generation: numerical modelling and calibration of a floating solar array against model tests. Sol Energy 2025;288.
[190] Anam MZ, Bari ABMM, Basak D, Foysal MA, Raihan A, Islam ARMT. An integrated fuzzy optimal location selection model for setting up floating solar photovoltaic plant: implications for energy sustainability in Bangladesh. Results Eng 2025;25.
[191] Kumar R, Saha R, Simic V, Dev N, Kumar R, Kumar Banga H, et al. Rooftop solar potential in micro, small, and medium size enterprises: an insight into renewable energy tapping by decision-making approach. Sol Energy 2024;276:112692.
[192] Jain P, Raina G, Sinha S, Malik P, Mathur S. Agrovoltaics: step towards sustainable energy-food combination. Bioresour Technol Rep 2021;15.
[193] Roxani A, Zisos A, Sakki GK, Efstratiadis A. Multidimensional role of agrovoltaics in era of EU green deal: current status and analysis of water–energy–food–land dependencies. Land 2023;12.
[194] Wellsandt S, Klein K, Hribernik K, Lewandowski M, Bousdekis A, Mentzas G, et al. Hybrid-augmented intelligence in predictive maintenance with digital intelligent assistants. Annu Rev Control 2022;53:382–90.
[195] Wirtz M, Remmen P, Müller D. EHDO: a free and open-source webtool for designing and optimizing multi-energy systems based on MILP. Comput Appl Eng Educ 2021;29:983–93.
[196] Madi H, Lytvynenko D, Schildhauer T, Jansohn P. Decarbonisation of geographical islands and the feasibility of green hydrogen production using excess electricity. Energies 2023;16.
[197] Winter CJ. Solar hydrogen energy trade. Energy Policy 1991;19:494–502.
[198] Obregon L, Valencia G, Duarte J. Study on the applicability of sustainable development policies in electricity generation systems in Colombia. Int J Energy Econ Pol 2019;9:492–502.
[199] Moreno Rocha CM, Florian Domíngue ED, Díaz Castillo DA, Vargas KL, Guzman AAM. Evaluation of energy alternatives through FAHP for the energization of Colombian insular areas. Int J Energy Econ Pol 2022;12:87–98.
[200] Song C, Zhao C, Liu Z, Ma X, Yuan Y, Han X. Unveiling energy transition strategy: a deep dive into China's ambitious renewable energy policy and its impact on carbon emission dynamics. J Clean Prod 2024;475.
[201] Su L, Wu S, Zhu W, Liang B, Zhang X, Yang J. Enhanced geopolymerization of MSWI fly ash through combined activator pretreatment: a sustainable approach to heavy metal encapsulation and resource recovery. J Environ Manag 2024;370: 122870.
[202] Machala ML, Chen X, Bunke SP, Forbes G, Yegizbay A, de Chalendar JA, et al. Life cycle comparison of industrial-scale lithium-ion battery recycling and mining supply chains. Nat Commun 2025;16.
[203] Jiang R, Wu C, Feng W, You K, Liu J, Zhou G, et al. Impact of electric vehicle battery recycling on reducing raw material demand and battery life-cycle carbon emissions in China. Sci Rep 2025;15.
[204] Kordloo M, Khodadadmahmoudi G, Barati MR, Rezaei A. Effect of leaching media on selective precipitation of Al, Ni, Co, and Mn in the NMC battery recycling process. Separ Purif Technol 2025;363.

[205] Fadhil MFSA, Liew PY, Zaharuddin HH, Mah AXY, Ho WS, Woon KS. Hydrogen supply chain optimisation with green electricity generation for energy trading between industrial parks. Chem Eng Trans 2024;114:541–6.
[206] Karthikeyan B, Praveen Kumar G. Thermoeconomic and optimization approaches for integrating cooling, power, and green hydrogen production in dairy plants with a novel solar-biomass cascade ORC system. Energy Convers Manag 2023;295.
[207] Goh QH, Zhang L, Ho YK, Chew IML. Modelling and multi-objective optimisation of sustainable solar-biomass-based hydrogen and electricity co-supply hub using metaheuristic-TOPSIS approach. Energy Convers Manag 2023;293.
[208] Chavhan S, Gupta D, Alkhayyat A, Alharbi M, Rodrigues JJPC. AI-empowered game theoretic-enabled dynamic electric vehicles charging price scheme in smart city. IEEE Syst J 2023;17:5171–82.
[209] Ma K, Yu Y, Yang B, Yang J. Demand-side energy management considering price oscillations for residential building heating and ventilation systems. IEEE Trans Ind Inf 2019;15:4742–52.
[210] Yazdi M, Zarei E, Pirbalouti RG, Li H. A comprehensive resilience assessment framework for hydrogen energy infrastructure development. Int J Hydrogen Energy 2024;51:928–47.
[211] Chowdhury P, Mahi NA, Yeassin R, Chowdhury N-U-R, Farrok O. Biomass to biofuel: impacts and mitigation of environmental, health, and socioeconomic challenges. Energy Convers Manag X 2025;25:100889.
[212] Dadjiogou KZ, Ajavon ASA, Bokovi Y. Enhancing energy access in rural areas: intelligent microgrid management for universal telecommunications and electricity. Cleaner Energy Sys 2024;9:100136.
[213] Zhang H, Yue D, Dou C, Hancke GP. PBI based multi-objective optimization via deep reinforcement elite learning strategy for micro-grid dispatch with frequency dynamics. IEEE Trans Power Syst 2023;38:488–98.
[214] Yang M, Jiang Y, Zhang W, Li Y, Su X. Short-term interval prediction strategy of photovoltaic power based on meteorological reconstruction with spatiotemporal correlation and multi-factor interval constraints. Renew Energy 2024;237:121834.
[215] Jia Y, Chen G, Zhao L. Defect detection of photovoltaic modules based on improved VarifocalNet. Sci Rep 2024;14:15170.
[216] Fu L, Wang J, Fu X, Zhao G. Finite-time Pade-based adaptive FNN controller implementation for microbial fuel cell with delay and multi-disturbance. Int J Hydrogen Energy 2025;98:1034–43.
[217] Xu X, Liu Z, Liu W, Pei C, Wu X, Nie Z. A sustainable development benchmarking framework for energy companies based on topic mining and knowledge graph: the case of oil and gas industry. Renew Sustain Energy Rev 2024;196:114350.