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INTEGRATED RENEWABLE ENERGY SYSTEMS: A SYSTEMATIC REVIEW OF ARCHITECTURES, INTELLIGENT CONTROL, ENERGY MANAGEMENT, AND PERFORMANCE

By

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Abstract

Integrated renewable energy systems are increasingly important for achieving reliable low carbon energy supply, yet evidence remains fragmented across system architecture, enabling technologies, control, optimisation, and performance evaluation. This systematic review synthesised evidence on the design, operation, performance, and development of these systems. The literature search period spanned 2016 to 2026 and covered Scopus, Web of Science, ScienceDirect, Wiley, SpringerLink, Emerald Insight, IEEE Xplore, and Google Scholar. Studies addressing integrated renewable configurations, including solar photovoltaic, wind, biomass, hydropower, batteries, hydrogen, electric vehicles, and smart grids, were screened using eligibility criteria, structured data extraction, and thematic synthesis. A total of 67 studies were retained, comprising 45 primary studies and 22 background references. The evidence showed a progression from stand alone photovoltaic, wind, and battery systems toward grid connected, hybrid AC and DC microgrids and multi carrier hubs. Battery storage remained central to balancing and reliability, while hydrogen provided potential for long duration storage and sector coupling. Control strategies evolved from conventional and fuzzy approaches toward predictive, distributed, multi agent, and artificial intelligence based energy management. Integrated systems generally improved reliability, power quality, renewable utilisation, economic efficiency, emissions performance, and resilience when generation, storage, conversion, and demand were effectively coordinated. However, performance depended on architecture, uncertainty treatment, battery degradation, converter stability, communication, scalability, cybersecurity, and market conditions. Future progress requires benchmarks, digital twins, hardware in the loop testing, uncertainty aware optimisation, hierarchical distributed control, AI validation, battery and hydrogen integration, electric vehicle flexibility, and market mechanisms that value resilience and flexibility.

Keywords*: Integrated renewable energy systems; Renewable energy integration; Energy storage; Intelligent energy management; Smart grids*

1. INTRODUCTION

Integrated renewable energy systems are becoming central to the energy transition because the next phase of decarbonisation depends less on single technologies and more on how multiple renewable resources are coordinated as one operating system. Modern grids must absorb variable solar and wind output, balance demand in real time, and maintain reliability under increasing electrification, so the key issue is not only how much renewable power is installed, but how effectively generation, storage, conversion, and grid support functions are integrated (Zhang & Wei, 2022; Khalid, 2024). In practice, this means that renewable energy systems now have to perform as flexible networks rather than isolated assets, with storage, power electronics, and control logic

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working together to reduce curtailment, improve resilience, and support stable electricity supply (Zhang & Wei, 2022; Khalid, 2024).

For this review, integrated renewable energy systems refer to coordinated configurations that combine renewable generation, storage, energy conversion, supervisory control, and grid interfaces within a single functional architecture. Such systems may include solar photovoltaic units, wind turbines, biomass based generation, hydropower, geothermal resources, batteries, hydrogen pathways, and smart grid interfaces, depending on local resource conditions and demand profiles (Al Afif *et al.*, 2023; Kwon *et al.*, 2024). The defining feature is not the presence of one technology alone, but the way several technologies are sized, linked, and controlled so that their combined performance is better than any single component operating independently (Al Afif *et al.*, 2023; Kwon *et al.*, 2024).

The global transition context has made system level integration more urgent. Grid operators are increasingly facing flexibility gaps created by variable renewable generation, electrification of transport and industry, and rising expectations for reliable low carbon supply. Recent studies show that the practical value of integrated systems lies in their ability to pair storage with renewable generation, use hydrogen as a flexible energy carrier, and improve grid integration through coordinated dispatch and power balancing (Basnet *et al.*, 2024; Kwon *et al.*, 2024). Evidence from recent case studies also shows that hybrid renewable configurations can lower costs, reduce emissions, and support decarbonised electrification pathways when their operational design reflects local resource conditions and demand structure (Basnet *et al.*, 2024; Kwon *et al.*, 2024).

Although the literature on renewable energy integration has expanded rapidly, much of it still remains technology specific or method specific. Some studies focus mainly on storage sizing, some on grid integration, and others on hydrogen or optimisation methods, but fewer works connect architecture, control strategy, performance, and implementation constraints within a single synthesis (Mukelabai *et al.*, 2024). This fragmented pattern makes it difficult to compare design choices across systems or to identify which integration pathways are most effective under different operational settings. A systematic review is therefore needed to move beyond isolated findings and assemble a clearer system architecture to performance picture that can guide future research and deployment (Mukelabai *et al.*, 2024).

The aim of this systematic review is to examine integrated renewable energy systems in terms of their architectures, integration approaches, control and energy management strategies, performance outcomes, implementation challenges, and future research directions. The review contribution is organised around the six objectives of classifying system architectures, identifying enabling technologies, reviewing control strategies, evaluating performance, analysing challenges, and identifying future opportunities. Recent methodological work shows that stronger modelling practices, better treatment of uncertainty, and more rigorous integration of machine learning, hydrogen pathways, and storage dynamics are now shaping the next generation of renewable energy system studies (Mukelabai *et al.*, 2024; Zhao *et al.*, 2025). By synthesising these strands in one structured review, the present study seeks to provide a more coherent evidence base for designing integrated renewable energy systems that can support energy transition goals at scale (Zhao *et al.*, 2025).

2. METHODS

2.1 Review design and research focus

This study was designed as a systematic review of peer reviewed journal articles and conference papers published between 1 January 2015 and 10 August 2026. The review focused on integrated renewable energy systems that combined two or more energy sources or support technologies within a single operating architecture, such as solar photovoltaic, wind, biomass, hydropower, geothermal energy, hydrogen, battery energy storage, electric vehicles, and smart grid interfaces. The emphasis remained on system level integration rather than on isolated component performance, because the earlier literature had already shown that the real engineering challenge lay not only in adding more renewable sources, but also in coordinating intermittency, storage, load balancing, and control in a stable and economically sensible way (Olatomiwa *et al.*, 2016). Work on renewable hybrid energy systems had also demonstrated that hydrogen backup, storage coordination, and operational scheduling were not peripheral issues but central design questions in integrated systems (Vivas Fernández *et al.*, 2018). In the same period, off grid and rural electrification studies showed that system topology, resource complementarity, and load matching strongly influenced feasibility, cost, and reliability, which justified a structured synthesis of primary studies rather than a simple descriptive narrative (Odou *et al.*, 2020).

The review question was therefore framed around four linked concerns. First, it examined how integrated renewable energy systems had been architected across stand alone, grid connected, and hybrid networked settings. Second, it traced how the different renewable sources and enabling components had been coupled in practice. Third, it examined the control and energy management strategies that had been used to coordinate generation, storage, demand, and grid exchange. Fourth, it assessed the performance indicators and implementation challenges reported in the primary studies. This focus made it possible to compare studies that were technically different but conceptually related, especially where they had dealt with intermittency, stability, resilience, and long term operational viability (Olatomiwa *et al.*, 2016; Vivas Fernández *et al.*, 2018; Odou *et al.*, 2020).

2.2 Search strategy

The literature search was carried out in Scopus, Web of Science, ScienceDirect, Wiley Online Library, SpringerLink, Emerald Insight, IEEE Xplore, and Google Scholar. The core search string was adapted to each database, but the same conceptual blocks were retained throughout: the first block

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captured the system concept, using terms such as integrated renewable energy system, hybrid renewable energy system, multi energy system, microgrid, and renewable integrated system; the second block captured the technical focus, using terms such as architecture, configuration, control, energy management, optimisation, performance, resilience, storage, hydrogen, battery, vehicle to grid, and smart grid; the third block captured the application context, using terms such as off grid, grid connected, stand alone, rural electrification, distributed generation, and networked microgrid. Boolean combinations were used to broaden or narrow the evidence base, for example: `(integrated renewable energy system OR hybrid renewable energy system* OR microgrid) AND (control OR energy management OR optimisation OR performance OR resilience)`.

Date limits were fixed from 2016 to 2026 in order to capture both the mature review literature and the most recent developments in artificial intelligence, distributed control, resilience analysis, and coupled electric vehicle integration. English language publications were retained because the review aimed for a transparent and reproducible screening process across multiple databases. Reference chaining was also used, especially for highly cited review papers that had mapped the field of hybrid renewable energy systems, because these papers had consistently identified the same core clusters of architecture, storage, optimisation, and operation while also pointing to newer directions such as hydrogen coupling, intelligent control, and smart grid coordination (Zebra *et al.,* 2021; Khan *et al.,* 2022; Thirunavukkarasu *et al.,* 2023).

The search terms were deliberately broad, because integrated renewable energy systems had been discussed in several overlapping research streams. Some studies had concentrated on mini grids and off grid electrification, while others had treated hybrid systems as control problems, optimisation problems, or resilience problems. The search strategy therefore had to be wide enough to capture the full design space, but focused enough to exclude papers that only mentioned renewable energy in passing. This balance was essential for keeping the review centred on hybrid system behaviour rather than on general renewable energy commentary (Zebra *et al.,* 2021; Khan *et al.,* 2022; Thirunavukkarasu *et al.,* 2023).

2.3 Eligibility criteria and review boundaries

Studies were included when they met four conditions. First, they had to address an integrated renewable energy system or a closely related hybrid architecture. Second, they had to report original system data, original modelling assumptions, original simulation settings, original optimisation outputs, or field specific performance results. Third, they had to provide enough technical detail to allow the architecture, energy mix, control logic, or performance indicators to be coded consistently. Fourth, they had to be peer reviewed journal articles or conference papers published within the selected time window. This meant that the review accepted empirical, simulation based, and design based studies as long as they described a concrete system rather than a purely conceptual discussion.

The exclusion criteria were defined just as carefully. Studies were excluded when they dealt only with one standalone technology, such as a single photovoltaic module, a single wind turbine, a battery chemistry, or a converter design, without linking that technology to a broader integrated system. Papers on component manufacturing, materials science, or device fabrication were also excluded, because they did not address system integration. In the same way, purely policy papers, market studies, or economic commentaries were excluded when they did not report an operational system topology or a measurable integration outcome. This boundary was important because the recent literature had shown that hybrid renewable energy systems were increasingly being studied as architecture problems, battery and storage coordination problems, and optimisation problems, rather than as single technology problems (Hassan *et al.,* 2023; León Gómez *et al.,* 2023; Ukoba *et al.,* 2024).

The review boundary was intentionally system centred. For example, papers on solar and wind combinations were retained when they went beyond a generic comparison and actually analysed configuration, storage, dispatch, or load balance. Likewise, papers on AI in renewable energy were retained only when the AI methods were tied to an operational system, such as forecasting, control, maintenance, dispatch, or sizing. This rule prevented the synthesis from drifting into a broad technology survey and kept it aligned with the review aim of understanding how integrated systems had been built and operated in practice (León Gómez *et al.,* 2023; Ukoba *et al.,* 2024).

2.4 Screening and study selection

The screening process followed four stages. In the first stage, duplicate records were removed after export into a reference manager and a spreadsheet based screening file. In the second stage, titles and abstracts were reviewed against the eligibility criteria. Records that clearly focused on a single technology, a non integrated policy discussion, or a non renewable subject were removed at this point. In the third stage, the full texts of the remaining studies were examined in detail. This allowed the review to check whether the paper truly reported an integrated system, whether the system had been adequately described, and whether the evidence was original rather than derivative. In the final stage, the studies that satisfied the criteria were retained for thematic synthesis.

This process was made deliberately transparent so that the selection logic remained visible even without formal PRISMA labeling. The use of a staged screening process was particularly useful in this topic area because many papers used similar language but different technical meanings. For instance, some studies used the term microgrid in a narrow control sense, while others used it in a broader coupled generation and storage sense. Some papers treated energy management as a dispatch rule, whereas others treated it as a model predictive, stochastic, or artificial intelligence based optimisation process. The fuller screening stage was therefore

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essential for distinguishing superficial overlap from genuine relevance (Ibrahim, 2024; Nkambule *et al.*, 2025; Ojo *et al.*, 2025).

A further strength of the staged approach was that it allowed the review to preserve studies that were technically important even when they differed widely in scope. Studies on hybrid control, model predictive energy management, distributed intelligence, and small community level dispatch were all retained when they contributed original insights into operating modes or coordination strategies. This was especially relevant because the recent literature had shown that hybrid energy management systems were being shaped by centralised, decentralised, and distributed control logics, and that these logics had direct implications for scalability, resilience, and computational burden (Ibrahim, 2024; Nkambule *et al.*, 2025). The screening process therefore did not simply ask whether a study mentioned renewables; it asked whether the study added usable evidence to the integrated system question.

2.5 Data extraction and coding framework

Data extraction was completed with a structured coding sheet. Each retained study was coded for country or region, application setting, system topology, renewable mix, storage type, controller type, optimisation method, operating mode, and performance metrics. Additional notes were recorded for cost assumptions, reliability measures, emissions outcomes, sensitivity analysis, and any stated operational limitations. This approach ensured that the review worked from primary study outputs rather than from general claims. It also made it possible to compare studies across very different contexts, including residential mini grids, utility linked systems, remote areas, and hybridised multi energy platforms.

The coding framework was intentionally broad enough to capture the growing complexity of current integrated systems. Studies that involved electric vehicles, vehicle to grid interactions, or coupled energy networks were coded separately so that transport electrification could be examined as part of the energy transition rather than as a disconnected topic. Likewise, studies that used resilience metrics were coded for the presence of disturbances, recovery strategies, and backup logic, because resilience had become a major criterion in modern integrated system design. Recent work had shown that systems increasingly combined renewables with storage, demand flexibility, and grid interaction, while also beginning to treat electric vehicles and broader coupled energy infrastructures as part of the same operational landscape (Monie *et al.*, 2025; Saleh *et al.*, 2025; Al Hamzawi & Abed Al Sailawi, 2026).

Table 1 summarizes the domains and variables extracted from each included study, covering study profile, system topology, renewable mix, storage, control, optimization, operating mode, performance metrics, and implementation barriers. It shows how these variables were systematically coded to support consistent comparison of the reviewed integrated renewable energy systems.

Table 1. Data extraction and coding framework

Extracted domain	Variables coded from each study	Purpose of coding	Citation(s)
Study profile	Author, year, country or region, sector, application context	Allowed geographic and sectoral comparison	(Ibrahim, 2024; Nkambule *et al.*, 2025)
System topology	Stand alone, grid connected, hybrid AC, hybrid DC, AC DC coupled, multi energy	Distinguished integration architecture	(Zebra *et al.*, 2021; Khan *et al.*, 2022; León Gómez *et al.*, 2023)
Renewable mix	Solar photovoltaic, wind, biomass, hydropower, geothermal, hydrogen, EV interface	Identified technology combinations	(Hassan *et al.*, 2023; León Gómez *et al.*, 2023; Saleh *et al.*, 2025)
Storage and backup	Battery energy storage, hydrogen storage, pumped hydro, diesel backup, hybrid backup	Captured flexibility and reliability options	(Vivas Fernández *et al.*, 2018; Odou *et al.*, 2020; Monie *et al.*, 2025)
Control approach	Classical control, nonlinear control, MPC, distributed control, AI based EMS	Mapped coordination logic	(Ibrahim, 2024; Ukoba *et al.*, 2024; Nkambule *et al.*, 2025)
Optimisation method	Linear programming, heuristics, metaheuristics, stochastic, robust, hybrid AI	Compared design and dispatch methods	(Khan *et al.*, 2022; Thirunavukkarasu *et al.*, 2023; Al Hamzawi & Abed Al Sailawi, 2026)
Operating mode	Stand alone, grid linked, islanded, demand response, vehicle to grid	Clarified how the system was used	(Ojo *et al.*, 2025; Saleh *et al.*, 2025)
Performance metrics	LCOE, NPC, efficiency, emissions, reliability, resilience, unmet load	Standardised outcome comparison	(Hassan *et al.*, 2023; Monie *et al.*, 2025; Al Hamzawi & Abed Al Sailawi, 2026)

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Key barriers	Cost, intermittency, communication, policy, scalability, maintenance	Captured implementation constraints	(Zebra *et al.*, 2021; Nkambule *et al.*, 2025; Saleh *et al.*, 2025)

Abbreviations: MPC, model predictive control; AI, artificial intelligence; EMS, energy management system; LCOE, levelized cost of energy; NPC, net present cost; EV, electric vehicle. PV denotes photovoltaic; AC, alternating current; DC, direct current; V2G, vehicle to grid; LCOE and NPC represent the economic performance measures coded across the studies.

Figure 1 presents the sequential process used to identify, screen, assess, and retain studies for the review, beginning with database searches and duplicate removal. It further shows the progression from title and abstract screening to full-text eligibility assessment and the final inclusion of 67 studies, comprising 45 primary studies and 22 background or methodological references.

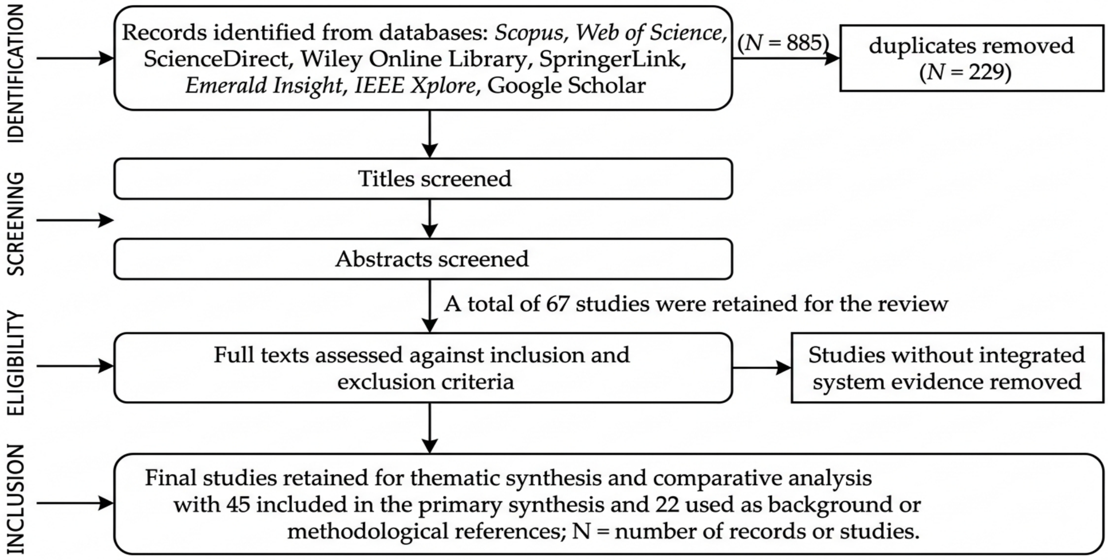

Figure 1. Literature Identification, Screening, Eligibility Assessment, and Study Selection Flow Diagram (Vivas Fernández *et al.*, 2018; Odou *et al.*, 2020; Zebra *et al.*, 2021; Khan *et al.*, 2022; Hassan *et al.*, 2023; León Gómez *et al.*, 2023; Thirunavukkarasu *et al.*, 2023; Ibrahim, 2024; Ukoba *et al.*, 2024; Monie *et al.*, 2025; Nkambule *et al.*, 2025; Ojo *et al.*, 2025; Saleh *et al.*, 2025; Al Hamzawi & Abed Al Sailawi, 2026).

Flow diagram showing records identified from Scopus, Web of Science, ScienceDirect, Wiley Online Library, SpringerLink, Emerald Insight, IEEE Xplore, and Google Scholar, followed by duplicate removal, title and abstract screening, and full-text assessment. Abbreviations: N, number of records or studies; the final 67 retained studies comprised 45 included in the primary synthesis and 22 used as background or methodological references.

3. RESULTS AND DISCUSSION

3.1 Evidence Base and Publication Patterns

The evidence base demonstrated a clear transition from relatively simple hybrid renewable energy configurations toward increasingly integrated, controllable and digitally coordinated energy systems. The reviewed primary studies covered different geographical settings, operating conditions, renewable resource combinations, storage technologies and control architectures. The earliest studies in the selected evidence base concentrated mainly on stand alone or weak grid applications involving combinations of photovoltaic generation, wind turbines and batteries, whereas later studies increasingly incorporated advanced power electronic interfaces, electric vehicles, hydrogen storage, energy hubs, demand response, distributed control and artificial intelligence (Canziani *et al.*, 2021).

A field based photovoltaic wind battery microgrid study in Peru demonstrated the practical orientation of rural electrification research, using the Laguna Grande site and locally measured or database derived resource information to develop a renewable microgrid configuration for remote electricity supply (Canziani *et al.*, 2021). The study illustrated an important characteristic of the evidence base: many integrated renewable systems had been designed around specific geographic and load conditions rather than as generic theoretical systems. This approach was important because the usefulness of an integrated configuration depended strongly on the resource complementarity of the location, the load profile, battery characteristics and the acceptable reliability threshold.

Research subsequently became more optimization oriented. In Zanjan, Iran, a stand alone photovoltaic wind battery system was optimized using real solar radiation and wind speed data, with system reliability represented through deficit power hourly interruption probability and economic performance expressed through net present cost (Moghaddam *et al.*, 2019). The inclusion of both resource conditions and reliability

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constraints showed that the design problem had gradually moved beyond simple capacity minimization. Similarly, an optimized photovoltaic wind microgrid study employed the Harris hawk optimizer to determine system capacities and demonstrated the continuing expansion of population based optimization methods in hybrid system design (Al-Shamma'a *et al.*, 2022).

The regional distribution of the evidence indicated strong research activity across Asia, Africa, Europe and Latin America. China and other Asian countries contributed substantial work on microgrid control, distributed optimization and multi energy systems, while African case studies emphasized rural electrification, grid extension alternatives and affordability. Latin American studies contributed field oriented microgrid investigations, while European research showed greater concentration on advanced predictive control, flexibility, interoperability and sector coupling. The evidence also showed a gradual shift from purely simulation based investigations toward hardware informed, monitored, field based and operationally constrained studies.

Methodologically, the evidence base was dominated by numerical simulation, optimization and digital experimentation, but these were increasingly combined with measured resource profiles, actual load data, real microgrid benchmarks and practical monitoring platforms. This represented a significant progression because integrated renewable systems had been evaluated not only for whether they could operate under idealized conditions, but also for how they responded to uncertainty, faults, price changes, load variation and grid disturbances. Overall, the publication pattern indicated that integrated renewable energy systems had evolved from a sizing problem into a coordinated energy infrastructure problem involving generation, storage, conversion, demand and communication.

Table 2 presents the principal characteristics of selected studies, including their locations, system configurations, methods used, and main reported outcomes. It provides a compact comparison of the geographical, technological, methodological, and practical features represented in the evidence base.

Table 2. Study characteristics and publication profile

Study	Location or study context	Primary system evidence	Main method	Main outcome	Citation(s)
Canziani *et al.*	Laguna Grande, Peru	PV, wind, battery microgrid	Case study and system simulation	Rural electrification assessment	(Canziani *et al.*, 2021)
Moghaddam *et al.*	Zanjan, Iran	PV, wind, battery	Improved crow search optimization	NPC and reliability based sizing	(Moghaddam *et al.*, 2019)
Al Shamma'a *et al.*	Hybrid microgrid	PV, wind, battery	Harris hawk optimization	Optimal hybrid capacity	(Al-Shamma'a *et al.*, 2022)
Datta *et al.*	Hybrid AC/DC microgrid	PV, wind, battery	Coordinated converter control	AC frequency and DC voltage coordination	(Datta *et al.*, 2021)
Chen *et al.*	AC/DC hybrid microgrid	PV, EV, heat pump and storage	P-ADMM distributed EMS	Distributed optimal scheduling	(Chen *et al.*, 2021)
Said *et al.*	Tumbatu Island, Zanzibar	Grid connected hybrid renewable system	HOMER Pro and sensitivity analysis	NPC about US$4.00 million; 3.79 year payback	(Said *et al.*, 2024)

Abbreviations: PV, photovoltaic; EV, electric vehicle; AC, alternating current; DC, direct current; P-ADMM, projection based alternating direction method of multipliers; EMS, energy management system; NPC, net present cost. PV/wind/battery refers to a system combining photovoltaic generation, wind generation, and battery storage, while HOMER Pro denotes the hybrid renewable energy system optimization and analysis software identified in the table.

3.2 Architectures and Configurations of Integrated Renewable Energy Systems

The reviewed studies showed that integrated renewable energy systems had been implemented through several architectural forms, with the choice largely determined by application scale, grid availability, energy carrier requirements and the type of loads being served. Stand alone systems remained important in remote areas where grid access had been limited, while grid connected systems were increasingly used in communities, buildings and distribution networks to exploit renewable generation while retaining

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access to grid support (Moghaddam *et al.*, 2019; Said *et al.*, 2024).

The stand alone architecture was typically characterized by renewable generators feeding local loads through one or more conversion stages, with battery storage providing balancing capacity. The Zanjan study used a photovoltaic wind battery arrangement connected through converters to a common DC interface and subsequently to the AC load through an inverter (Moghaddam *et al.*, 2019). This configuration reduced the mismatch between variable renewable generation and demand and provided a practical structure for remote power supply. The Peruvian microgrid followed a similar hybrid concept, combining PV and wind generation with battery storage to increase resource complementarity (Canziani *et al.*, 2021).

Grid connected systems added another operating layer by allowing energy import and export. The Tumbatu Island study demonstrated a grid connected hybrid system in which the renewable configuration was evaluated against technical and economic criteria using location specific resource and demand conditions (Said *et al.*, 2024). Such systems were advantageous because the external grid could absorb surplus generation or compensate for renewable shortages, thereby reducing the storage requirement compared with fully autonomous designs.

A major architectural development had been the emergence of hybrid AC/DC microgrids. Instead of forcing all sources and loads onto one electrical bus, these systems separated AC and DC resources according to their electrical characteristics and connected the two subsystems through power electronic converters. Datta *et al.* demonstrated a photovoltaic wind battery hybrid AC/DC microgrid in which AC frequency and DC voltage were coordinated, illustrating how different buses could be regulated while maintaining common energy balance (Datta *et al.*, 2021). Chen *et al.* further demonstrated a hybrid AC/DC energy management architecture using a projection based alternating direction method of multipliers, with independent scheduling of AC and DC subgrids and information exchange between them (Chen *et al.*, 2021).

Energy hub configurations extended the concept beyond electricity. In energy hub systems, electricity, heat, gas, cooling and other carriers were coordinated through conversion and storage equipment. Mou *et al.* developed an energy hub based multi energy network model that represented electricity, renewable generation, energy conversion units and storage devices through a coupled energy flow framework (Mou *et al.*, 2022). This architecture allowed renewable electricity to be redirected toward alternative energy services rather than being treated only as electrical generation.

The evidence therefore showed that no single architecture had emerged as universally superior. Stand alone arrangements had remained attractive where grid access was weak or absent; grid connected configurations provided flexibility and economic interaction; AC/DC systems reduced unnecessary conversion; and energy hubs enabled deeper sector coupling.

Table 3 classifies the main system architectures identified in the review according to configuration, operating mode, principal advantage, and representative evidence. It compares stand alone, rural hybrid, grid connected, hybrid AC/DC, distributed AC/DC, and energy hub arrangements.

Table 3. Classification of system architectures

Architecture	**Typical primary configuration**	**Main operating mode**	**Principal advantage**	**Representative study**	**Citation(s)**
Stand alone DC or AC	PV/wind/battery	Islanded	Energy autonomy	Zanjan PV/wind/battery	(Moghaddam *et al.*, 2019)
Rural hybrid microgrid	PV/wind/battery	Islanded or weak grid	Resource complementarity	Peru case study	(Canziani *et al.*, 2021)
Grid connected HRES	PV/wind/battery/grid	Grid connected	Import/export flexibility	Tumbatu Island	(Said *et al.*, 2024)
Hybrid AC/DC microgrid	PV/wind/battery/AC and DC loads	Islanded/grid connected	Reduced conversion	Datta *et al.*	(Datta *et al.*, 2021)
Distributed AC/DC microgrid	Multiple AC/DC subgrids	Coordinated	Privacy and scalability	Chen *et al.*	(Chen *et al.*, 2021)
Energy hub	Electricity plus thermal or other carriers	Multi energy	Sector coupling	Mou *et al.*	(Mou *et al.*, 2022)

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Abbreviations: PV, photovoltaic; HRES, hybrid renewable energy system; AC, alternating current; DC, direct current. PV/wind/battery indicates a system combining photovoltaic generation, wind generation, and battery storage, while AC/DC denotes coordinated alternating and direct current subsystems.

Figure 2 illustrates the progressive evolution of energy systems from stand-alone solar PV and wind systems through hybrid microgrids, grid-connected and AC/DC hybrid microgrids, to integrated multi-carrier energy hubs. It emphasizes increasing integration, controllability, and sector coupling through the coordinated conversion, storage, and utilization of electricity, heat, cooling, hydrogen, and other energy carriers.

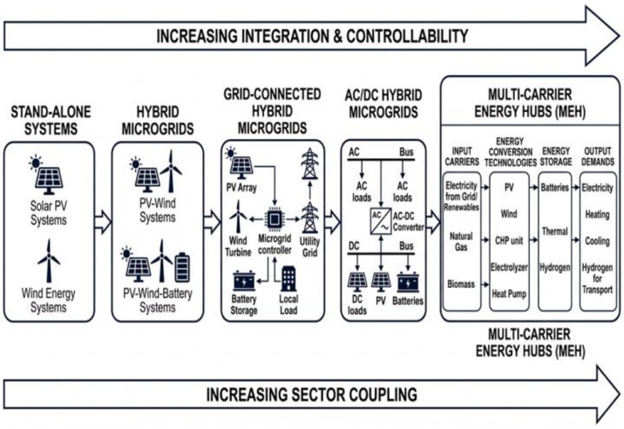

Figure 2. Progressive Integration of Renewable Energy Systems into Hybrid Microgrids and Multi-Carrier Energy Hubs (Moghaddam *et al.*, 2019; Canziani *et al.*, 2021; Chen *et al.*, 2021; Datta *et al.*, 2021; Mou *et al.*, 2022; Said *et al.*, 2024).

Schematic progression from stand-alone renewable energy systems to increasingly integrated and controllable energy architectures, showing solar PV, wind, battery storage, utility-grid interaction, AC/DC conversion, and multi-carrier energy conversion and storage. PV, photovoltaic; AC, alternating current; DC, direct current; AC-DC, alternating-current to direct-current converter; MEH, multi-carrier energy hub; CHP, combined heat and power; Bus, electrical connection/distribution bus.

3.3 Renewable Technologies and Enabling Components

The reviewed primary studies demonstrated that integrated renewable systems were rarely based on a single renewable technology. Photovoltaic generation remained the most frequently represented source because of its modularity, declining deployment barriers and compatibility with both AC and DC architectures. Wind generation was commonly paired with PV because the two resources had complementary temporal characteristics. The Peruvian case study incorporated both PV and wind with battery storage, while the Zanjan system used the same basic renewable combination to improve supply reliability (Moghaddam *et al.*, 2019; Canziani *et al.*, 2021).

Battery energy storage remained the most common enabling technology. In the Zanjan system, batteries compensated for renewable power deficits and absorbed excess generation, thereby improving supply continuity (Moghaddam *et al.*, 2019). Battery sizing was not treated only as a capacity issue; later research increasingly included battery lifetime and degradation. Zhang *et al.* explicitly incorporated battery lifetime into PV wind battery microgrid sizing, indicating that oversized or aggressively cycled storage could alter the economic attractiveness of an otherwise optimal configuration (Zhang *et al.*, 2021).

Hydropower and biomass appeared more strongly in systems serving locations with appropriate natural resource availability. Hybrid systems including biomass provided dispatchable renewable generation that complemented intermittent PV and wind. A 2025 optimization assessment of off grid hybrid systems incorporated PV, wind, biomass, diesel backup and battery storage and evaluated technical, economic and environmental trade offs (Sawle, 2025). This demonstrated that integrated systems were increasingly being constructed around a portfolio of renewable resources rather than a simple PV wind pairing.

Hydrogen represented a more recent enabling technology. Hydrogen based systems used an electrolyzer to convert surplus renewable electricity into hydrogen, storage tanks to retain the energy over longer durations, and fuel cells to reconvert hydrogen into electricity during periods of renewable deficit. A primary study on hydrogen based multi energy microgrid planning treated hydrogen storage as a long duration storage option in rural microgrid development and evaluated its economic and resilience effects (Shao *et al.*, 2023). Another study developed a green hydrogen power to gas service that used surplus renewable energy to produce hydrogen while coordinating the resulting storage service with multi energy microgrid operation (Qiu *et al.*, 2023).

Electric vehicles increasingly functioned as mobile energy storage assets rather than only loads. A primary V2G study integrated PV, wind, a conventional generator and EV based energy exchange into a microgrid representing approximately 1,000 households and assessed frequency regulation over a 24 hour operating cycle (Mahela *et al.*, 2022). This showed that EVs could become active components of integrated energy systems when bidirectional charging was coordinated with renewable generation and system conditions.

Power electronic interfaces had become equally important. Inverters, DC/DC converters, AC/DC converters, bidirectional battery converters and grid forming controls were required to integrate sources with different electrical characteristics. In hybrid AC/DC microgrids, the converter effectively became the bridge between electrical subsystems and therefore affected voltage stability, frequency control, protection and power sharing (Chen *et al.*, 2021; Datta *et al.*, 2021).

Demand side resources were also incorporated into the integrated system concept. Flexible loads, demand response, heat pumps and EV charging were increasingly treated as controllable resources rather than fixed demand. This

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development reduced the need to solve intermittency exclusively through additional generation and storage.

Table 4 summarizes the major renewable technologies and enabling components identified in the reviewed studies, together with their principal roles and observed applications. It highlights the contribution of solar PV, wind, battery storage, biomass, hydropower, hydrogen, electric vehicles, converters, and demand response to system integration.

Table 4. Technologies and enabling components included in the studies

Technology/component	Primary role	Evidence observed	Representative study	Citation
Solar PV	Variable renewable generation	Widely integrated	Peru, Zanjan and Tumbatu	(Moghaddam *et al.*, 2019; Canziani *et al.*, 2021; Said *et al.*, 2024)
Wind	Complementary generation	Frequently paired with PV	Peru and hybrid microgrids	(Moghaddam *et al.*, 2019; Canziani *et al.*, 2021)
Battery storage	Balancing	Charging/discharging for mismatch	PV/wind/battery studies	(Moghaddam *et al.*, 2019; Zhang *et al.*, 2021)
Biomass	Dispatchable renewable	Used with PV, wind and storage	Hybrid off grid	(Sawle, 2025)
Hydropower	Dispatchable renewable	Rural grid support	Hybrid rural system	(Hassan *et al.*, 2022)
Hydrogen	Long duration storage	Electrolyzer, storage and fuel cell	Hydrogen microgrid	(Qiu *et al.*, 2023; Shao *et al.*, 2023)
EV/V2G	Flexible storage and demand	Bidirectional exchange	1,000 household equivalent microgrid	(Mahela *et al.*, 2022)
Inverters/converters	Conversion/interface	AC/DC and DC/DC coupling	Hybrid AC/DC studies	(Chen *et al.*, 2021; Datta *et al.*, 2021)
Demand response	Load flexibility	Flexible loads in scheduling	Multi energy optimization	(Thang *et al.*, 2022)

Abbreviations: PV, photovoltaic; EV, electric vehicle; V2G, vehicle to grid; AC, alternating current; DC, direct current. EV/V2G refers to electric vehicle and vehicle to grid applications, while AC/DC refers to alternating and direct current conversion and coupling.

3.4 Integration Pathways and Coupling Mechanisms

The reviewed systems demonstrated four dominant integration pathways: electrical coupling, thermal or multi energy coupling, hydrogen coupling and hybrid combinations of these pathways. Electrical coupling remained the most mature pathway and involved connecting different renewable generators and storage devices through a common AC bus, DC bus or hybrid AC/DC network.

At device level, PV arrays generally required DC/DC conversion, wind turbines often required AC/DC conversion, and batteries used bidirectional converters. The resulting power streams were coordinated through inverters and energy management systems. The PV wind battery system in Zanjan clearly illustrated this pathway, with wind generation connected through an AC/DC converter and PV connected through a DC/DC converter before power was delivered to the load (Moghaddam *et al.*, 2019).

Hybrid AC/DC structures reduced unnecessary conversion by connecting DC loads and DC sources to the DC side while preserving AC compatibility for conventional loads and grid interfaces. Datta *et al.* demonstrated coordinated AC frequency and DC voltage regulation in a photovoltaic wind battery hybrid AC/DC microgrid, showing that the two electrical domains could be coordinated rather than independently optimized (Datta *et al.*, 2021). Chen *et al.* used distributed optimization to schedule AC and DC subgrids separately while exchanging the information required to reach a coordinated solution (Chen *et al.*, 2021).

Multi energy coupling provided a broader pathway. In energy hubs, renewable electricity could be directed toward heating, cooling, transport, hydrogen or other energy services. Thang *et al.* formulated a multi energy hub system linking electricity and gas networks while accounting for renewable uncertainty, demand response and emissions. Their case studies showed operation cost reductions of approximately 2.0% to 14.5% across analyzed cases, while combined renewable integration and demand response reduced carbon emissions by as much as 22.3% (Thang *et al.*, 2022).

Hydrogen created an additional conversion pathway through power to hydrogen and hydrogen to power. The electrolyzer

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acted as an electrical load during renewable surplus, while the fuel cell functioned as a dispatchable generator during shortages. This gave integrated systems a means of shifting energy across much longer time periods than conventional daily battery cycling.

The practical implication was that system integration had increasingly been defined by the management of energy interfaces rather than simply the addition of renewable generators. Every additional energy carrier introduced another conversion efficiency, operating constraint and control requirement. Effective integration therefore depended on minimizing unnecessary conversion, controlling losses and coordinating the timing of conversion between energy forms.

Table 5 compares the principal pathways used to connect renewable sources, storage, grids, and other energy carriers through appropriate interface devices and control arrangements. It shows how electrical AC, electrical DC, hybrid AC/DC, multi energy, hydrogen, and EV coupling pathways address different integration and coordination requirements.

Table 5. Integration pathways, interface devices and coupling methods

Pathway	**Coupled elements**	**Interface device**	**Main control issue**	**Representative study**	**Citation(s)**
Electrical AC	Wind, inverter, AC loads, grid	AC inverter	Frequency and voltage	Datta *et al.*	(Datta *et al.*, 2021)
Electrical DC	PV, battery, DC loads	DC/DC converter	DC voltage and SOC	Zanjan system	(Moghaddam *et al.*, 2019)
Hybrid AC/DC	AC and DC subgrids	Bidirectional converter	Coordinated exchange	Chen *et al.*	(Chen *et al.*, 2021)
Multi energy	Electricity, gas and other carriers	Energy hub converters	Joint dispatch	Thang *et al.*	(Thang *et al.*, 2022)
Hydrogen	Electricity, electrolyzer, tank, fuel cell	Electrolyzer/fuel cell	Conversion and timing	Hydrogen studies	(Qiu *et al.*, 2023; Shao *et al.*, 2023)
EV coupling	Renewables, EV batteries, grid	Bidirectional charger	SOC and availability	V2G study	(Mahela *et al.*, 2022)

Abbreviations: AC, alternating current; DC, direct current; PV, photovoltaic; SOC, state of charge; EV, electric vehicle; V2G, vehicle to grid. AC/DC indicates combined alternating and direct current subsystems, while SOC represents the stored energy level of a battery or other storage device relative to its usable capacity

3.5 Device Level Control Strategies

Device level control had represented the first control layer in integrated renewable systems because it determined whether individual generators, converters and storage units operated within acceptable electrical limits. The reviewed studies demonstrated a progression from classical proportional integral and droop techniques toward nonlinear, adaptive, robust and fault tolerant controllers.

Classical control remained important because of its simplicity and predictable implementation. The fuzzy logic microgrid study developed a PV wind battery system consisting of approximately 75 kW of PV generation, a 20 kW permanent magnet synchronous generator wind turbine and a 280 Ah lithium ion battery at 200 V. The proposed energy management and fuzzy control framework was implemented through MATLAB and Simulink and connected to a cloud monitoring platform (Al Sumarmad *et al.*, 2022). This demonstrated how relatively conventional control techniques could still support practical multi source operation when combined with appropriate monitoring.

Sliding mode control was used where robustness against model uncertainty was important. Ge *et al.* developed a frequency coordinated control strategy for a microgrid containing a hybrid energy storage system composed of a battery and ultracapacitor. The study coordinated the power response of different sources and used fuzzy logic to determine the hybrid storage power threshold before applying sliding mode control for frequency regulation (Ge *et al.*, 2021). This approach allowed the fast response of the ultracapacitor to complement the energy capacity of the battery.

Fault tolerant control represented another important development. Shahzad *et al.* developed a robust sliding mode observer for a voltage source converter based microgrid and evaluated simultaneous and individual sensor faults involving magnitude, phase and harmonic disturbances. The observer used an optimization based gain design and was combined with PI based voltage and frequency control to maintain operation under faulty measurement conditions (Shahzad *et al.*, 2022).

Predictive control was also increasingly deployed at device level. Nair *et al.* applied model predictive control in a PV based microgrid to reduce grid congestion while also minimizing battery degradation. The controller explicitly accounted for battery use rather than treating storage as an unrestricted balancing device (Nair *et al.*, 2021). This

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indicated a broader change in device control objectives from immediate stability toward lifecycle aware operation.

Table 6 compares control techniques used at the device level according to their applications, operating variables, and reported areas of use. It covers conventional, droop, fuzzy, sliding mode, observer based, predictive, and coordinated converter control approaches used in integrated systems.

Table 6. Device level control techniques and application domains

Control technique	Device/application	Operating variable	Evidence of use	Citation(s)
PI control	Converter regulation	Voltage/frequency	Conventional layer	(Shahzad *et al.*, 2022)
Droop control	Inverter source	Voltage/frequency	AC/DC microgrid operation	(Datta *et al.*, 2021)
Fuzzy control	Hybrid storage and EMS	Power threshold	Battery plus ultracapacitor	(Ge *et al.*, 2021)
Sliding mode	Frequency control	Frequency/power	Robust response	(Ge *et al.*, 2021)
Sliding mode observer	Fault diagnosis	Current/voltage	Fault tolerant VSC	(Shahzad *et al.*, 2022)
Model predictive control	PV microgrid/storage	Power exchange	Congestion and degradation	(Nair *et al.*, 2021)
Coordinated converter control	Hybrid AC/DC	AC/DC variables	Cross bus coordination	(Datta *et al.*, 2021)

Abbreviations: PI, proportional integral; EMS, energy management system; PV, photovoltaic; AC, alternating current; DC, direct current; VSC, voltage source converter. AC/DC represents alternating and direct current variables or subsystems, while PI denotes the proportional integral control strategy used for converter regulation.

3.6 Supervisory and Hierarchical Control

Supervisory control operated above individual converters and sources and coordinated energy allocation among multiple components. The principal finding was that the increasing number of devices in integrated systems had made purely local control insufficient. Higher level controllers were therefore used to determine power references, operating modes, source priorities and storage schedules.

Marín *et al.* developed a two level hierarchical energy management system for microgrid operation using robust model predictive control. The upper layer optimized energy usage and established a power reference, while the lower level tracked that reference through real time control (Marín *et al.*, 2019). This architecture separated slower energy management decisions from fast device regulation and thereby reduced the burden placed on individual controllers.

A physical 6 kW smart microgrid study involving wind, PV and battery storage also demonstrated the usefulness of hierarchical coordination. The system combined master slave and hierarchical control with a battery state of charge based energy management strategy. Several operating modes were evaluated, including direct renewable supply, grid energy feedback, battery supply, grid supply and load limitation (Liu *et al.*, 2018). The range of tested operating modes showed that supervisory control had effectively acted as an operating mode manager as well as an energy optimizer.

Hierarchical control became particularly important when the system could operate in both grid connected and islanded modes. Mode transitions required the supervisory layer to decide when renewable sources, storage, grid supply and flexible loads should be prioritized. This was necessary because a control policy that was economically appropriate under normal grid operation could become inappropriate during islanding or supply interruption.

Another important finding concerned the relationship between forecasting and supervisory control. Supervisory controllers performed better when they had access to short term information about renewable output, electricity price and demand. However, forecast information introduced uncertainty, and robust or stochastic optimization was therefore increasingly incorporated into the supervisory layer.

Table 6 summarizes supervisory control architectures according to their functions, dispatch principles, strengths, and representative evidence from integrated renewable systems. It contrasts hierarchical, master slave, state of charge based, robust, and hybrid supervisory energy management approaches.

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Table 7. Supervisory control architectures and dispatch logic

Architecture	Supervisory function	Dispatch principle	Main strength	Representative evidence	Citation(s)
Two level hierarchical EMS	Upper optimization plus lower tracking	Cost and self consumption	Separated timescales	Marín *et al.*	(Marín *et al.*, 2019)
Master slave control	Operating state	Source priority and bus conditions	Straightforward coordination	6 kW smart microgrid	(Liu *et al.*, 2018)
SOC based supervision	Storage dispatch	SOC limits	Protects storage	Smart microgrid	(Liu *et al.*, 2018)
Robust hierarchical EMS	Optimization under uncertainty	Worst case/uncertainty sets	Robustness	Marín *et al.*	(Marín *et al.*, 2019)
Hybrid supervisory EMS	Renewables, storage, grid	Rule plus optimization	Multi mode flexibility	Integrated systems	(Liu *et al.*, 2018; Marín *et al.*, 2019)

Abbreviations: EMS, energy management system; SOC, state of charge. SOC based supervision refers to storage dispatch governed by state of charge limits, while EMS denotes the higher level system used to coordinate generation, storage, grid exchange, and operating modes.

Figure 2 illustrates a hierarchical control architecture linking grid or market coordination, supervisory energy management, source and storage controllers, and device-level components through measurement signals and dispatch commands. It depicts bidirectional communication and control among transmission and distribution operators, renewable-energy controllers, battery and superconducting storage systems, SCADA systems, and individual generation/storage devices.

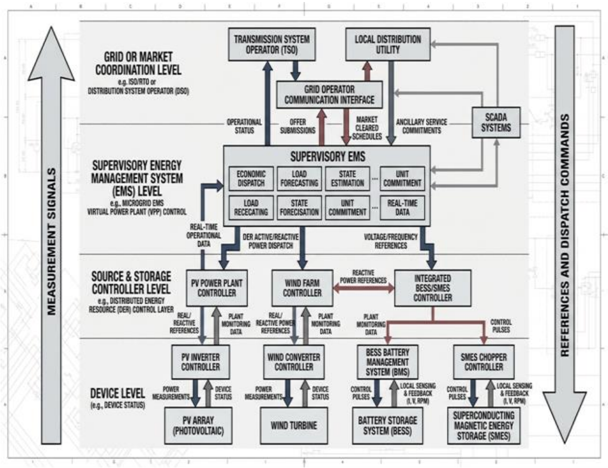

Figure 3. Hierarchical Control Architecture for Grid-Connected Renewable Energy, Storage, and Supervisory Energy Management Systems (Liu *et al.*, 2018; Marín *et al.*, 2019).

Hierarchical control structure showing transmission system operator (TSO), local distribution utility, supervisory energy management system (EMS), grid operator communication interface, supervisory control and data acquisition (SCADA) systems, distributed energy resource (DER) controllers, photovoltaic (PV) and wind power controllers, battery energy storage system (BESS), superconducting magnetic energy storage (SMES), and battery management system (BMS). Abbreviations: ISO = Independent System Operator; RTO = Regional Transmission Organization; DSO = Distribution System Operator; VPP = Virtual Power Plant; TSO = Transmission System Operator; EMS = Energy Management System; SCADA = Supervisory Control and Data Acquisition; DER = Distributed Energy Resource; PV = Photovoltaic; BESS = Battery Energy Storage System; BMS = Battery Management System; SMES = Superconducting Magnetic Energy Storage; RPM = Revolutions Per Minute.

3.7 Distributed, Decentralized and Multi Agent Control

Distributed control became more prominent as integrated renewable systems expanded from single microgrids to interconnected clusters of microgrids. Centralized energy management required complete system information and a powerful coordinator, creating communication, privacy and single point of failure concerns. Distributed methods attempted to divide the optimization problem among subsystems while maintaining sufficient coordination.

Chen *et al.* addressed this issue in a hybrid AC/DC microgrid with high penetration of distributed resources. The energy management problem was formulated as a mixed integer quadratic program and decomposed between AC and DC subgrids using a projection based ADMM approach. Each subgrid was allowed to determine its schedule while exchanging limited information with the other subgrid (Chen *et al.*, 2021). This architecture provided a direct example of how mathematical decomposition could support scalable energy management.

El Zerk *et al.* proposed a decentralized energy management strategy for collaborative microgrids using multi agent control. Each microgrid could be treated as an autonomous

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agent while collaborative exchanges allowed the wider system to coordinate energy management decisions (El Zerk *et al.*, 2022). This approach was particularly relevant where multiple microgrids had different owners, operational priorities or data privacy constraints.

A separate primary study developed a multi agent energy management and control system for wind PV battery microgrids and evaluated its response under renewable resource fluctuations and seasonal load variation (Azeroual *et al.*, 2022). The study found that the multi agent framework provided more resilient and higher performance control than the centralized approach used as the comparison.

Communication quality remained an important determinant of distributed control performance. A real microgrid communication study demonstrated a distributed data distribution framework that achieved message latency below 2 milliseconds while processing approximately 1,000 messages per second and was tested on a real microgrid where voltage violations were mitigated through distributed control execution (Saxena *et al.*, 2021). This result highlighted the fact that distributed control was not solely an algorithmic problem. Communication infrastructure, timing, synchronization and network reliability also became part of the energy control problem.

Table 8 presents distributed and decentralized control approaches together with their coordination mechanisms, applications, communication characteristics, and reported outcomes. It illustrates how ADMM, multi agent control, collaborative microgrid coordination, and distributed communication support scalable and resilient energy management.

Table 8. Distributed control approaches and communication structures

Approach	Coordination mechanism	Main application	Communication characteristic	Reported outcome	Citation(s)
ADMM distributed optimization	Iterative information exchange	Hybrid AC/DC	Subgrid coordination	Distributed optimal EMS	(Chen *et al.*, 2021)
Multi agent control	Autonomous agents	Wind/PV/battery	Agent cooperation	Improved resilience	(Azeroual *et al.*, 2022)
Collaborative multi microgrid	Decentralized agents	Multiple microgrids	Local decisions with cooperation	Scalable EMS	(El Zerk *et al.*, 2022)
Distributed communication framework	Data Distribution Service	Real microgrid	<2 ms latency; 1,000 messages/s	Voltage violation mitigation	(Saxena *et al.*, 2021)

Abbreviations: ADMM, alternating direction method of multipliers; EMS, energy management system; AC, alternating current; DC, direct current; PV, photovoltaic. AC/DC denotes coordinated alternating and direct current subgrids, while ms means milliseconds and s means seconds in the communication performance values reported.

3.8 Optimization Based Energy Management Strategies

Optimization was one of the most heavily represented approaches in the reviewed primary studies. It was applied to system sizing, unit dispatch, storage scheduling, demand response, energy trading, uncertainty management and multi objective operation. The choice of optimization method depended on the mathematical properties of the problem and the number of discrete or nonlinear decision variables.

Classical mathematical programming was particularly suitable where the system could be represented through linear or mixed integer relationships. Chen *et al.* formulated hybrid AC/DC microgrid management as a mixed integer quadratic programming problem and used ADMM decomposition to distribute the computation (Chen *et al.*, 2021). Thang *et al.* formulated stochastic multi energy hub operation as a mixed integer nonlinear problem and represented uncertainty through scenario generation and reduction. Their results indicated operation cost reductions of 2.0% to 14.5% under different analyzed conditions, while combined renewable integration and demand response produced substantial emissions reductions (Thang *et al.*, 2022).

Metaheuristic algorithms remained common where nonlinearities and complex search spaces made conventional mathematical optimization difficult. The Zanjan study used an improved crow search algorithm and explicitly compared it with the original crow search and particle swarm optimization approaches (Moghaddam *et al.*, 2019). Al Shamma'a *et al.* used the Harris hawk optimizer for PV wind microgrid sizing (Al-Shamma'a *et al.*, 2022). Zhang used robust multi objective optimization with NSGA II to balance energetic, economic, environmental and flexibility objectives in a renewable and natural gas microgrid (Zhang, 2022).

Multi objective approaches were especially relevant because integrated renewable systems rarely had one meaningful objective. Reducing cost could conflict with improving reliability; minimizing emissions could increase storage capacity requirements; and increasing renewable penetration could increase curtailment or investment requirements.

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Rule based strategies remained useful as benchmarks because they were transparent and simple to implement. However, optimization based control generally provided a more systematic method for dealing with multiple constraints such as battery SOC, converter limits, minimum generator outputs, demand satisfaction, grid import limits and ramping restrictions.

The evidence therefore showed that optimization had moved from equipment sizing toward real time and near real time energy management. The major unresolved issue was computational scalability, especially when stochastic scenarios, mixed integer decisions and high frequency control had to be considered simultaneously.

This table compares optimization techniques according to their main objectives, system constraints, and primary applications in integrated renewable energy systems. It includes mathematical programming, stochastic optimization, metaheuristic algorithms, multi objective methods, particle swarm optimization, and rule based dispatch.

Table 9. Optimization methods, objective functions and constraints

Optimization type	Typical objective	Main constraints	Primary evidence	Citation(s)
Mixed integer quadratic	Operating cost and scheduling	DER, converter and storage	Hybrid AC/DC microgrid	(Chen *et al.*, 2021)
Stochastic MINLP	Cost and emissions	Renewable, demand and price uncertainty	Multi energy hub	(Thang *et al.*, 2022)
Harris hawk optimizer	System sizing	Component capacities	PV/wind microgrid	(Al-Shamma'a *et al.*, 2022)
Improved crow search	NPC and reliability	DPHIP and capacities	Zanjan system	(Moghaddam *et al.*, 2019)
NSGA II	Energy, cost, emissions, flexibility	Operational/resource	Renewable/gas microgrid	(Zhang, 2022)
Particle swarm	Cost and renewable penetration	Source/load limits	Hybrid renewable resources	(Elgammal, 2018)
Rule based dispatch	Operational balance	SOC and power balance	Hybrid microgrids	(Al Sumarmad *et al.*, 2022)

Abbreviations: MINLP, mixed integer nonlinear programming; NPC, net present cost; DPHIP, deficit power hourly interruption probability; NSGA II, nondominated sorting genetic algorithm II; DER, distributed energy resource; SOC, state of charge. AC/DC denotes alternating and direct current microgrid structures, while PV refers to photovoltaic generation and AI to artificial intelligence where applicable in the optimization framework.

3.9 Intelligent and AI Based Energy Management

Artificial intelligence had become one of the most rapidly developing areas in integrated renewable energy system research. The reviewed studies showed an evolution from fuzzy logic and heuristic algorithms toward machine learning, deep reinforcement learning and digitally integrated management systems.

Fuzzy logic remained useful where system behavior was nonlinear but precise mathematical models were difficult to maintain. The fuzzy logic EMS study integrated PV, wind and battery storage and used MATLAB and Simulink together with a cloud monitoring platform. Its hardware and software arrangement demonstrated that intelligent control could be linked to monitoring infrastructure rather than existing only as an offline optimization model (Al Sumarmad *et al.*, 2022).

Deep reinforcement learning represented a stronger movement toward adaptive dispatch. Liu *et al.* developed a deep deterministic policy gradient based EMS for microgrid operation under uncertainty. The framework explicitly treated the energy management problem as a sequential control problem and evaluated computational requirements and cumulative operating cost against alternative approaches (Liu *et al.*, 2023). Darshi *et al.* investigated decentralized reinforcement learning for stochastic microgrid energy management, allowing agents to develop policies under uncertain renewable generation and demand conditions (Darshi *et al.*, 2023).

A model free data driven reinforcement learning study considered uncertainty from both PV generation and EV demand and combined probabilistic load flow with battery energy storage and an EMS (Kaewdornhan & Chatthaworn, 2023). This was important because it extended AI based EMS beyond conventional renewable uncertainty to the additional variability introduced by transportation electrification.

Digital twin based research also emerged as a new direction. Wu and Mei developed a realistic digital twin simulator for a smart islanded hybrid microgrid integrating PV, biogas and vanadium redox flow battery storage, with internet of things communication and energy management (Wu & Mei, 2024).

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The study demonstrated how digital representations could support testing of EMS decisions under realistic system conditions without requiring every control experiment to be performed directly on physical infrastructure.

More recent 2025 research extended intelligent EMS toward cognitive fuzzy control, multi objective optimization and autonomous reinforcement learning. These studies showed that AI was increasingly being used not only to determine dispatch schedules but also to improve adaptation to changing loads, resource availability and operating constraints (Hamadneh *et al.,* 2025; Julin *et al.,* 2025; Moosavi *et al.,* 2025).

The main limitation was that intelligent control had often been evaluated in simulation rather than under long duration field operation. The evidence therefore supported the technical promise of AI while also showing that robustness, explainability, data quality, computational requirements and safe integration with established protection systems remained important conditions for deployment.

Table 10 summarizes artificial intelligence based energy management approaches according to system context, data inputs, outputs, and reported contributions. It covers fuzzy logic, deep reinforcement learning, decentralized learning, digital twins, cognitive fuzzy control, multi objective AI, and artificial bee colony approaches.

Table 10. Intelligent energy management models and performance gains

AI approach	System context	Main data/input	Main output	Reported contribution	Citation(s)
Fuzzy logic	PV/wind/battery	Generation, load, SOC	Power sharing	Adaptive balancing	(Al Sumarmad *et al.*, 2022)
DDPG	Uncertain microgrid	State and uncertainty	Real time dispatch	Reduced operating cost	(Liu *et al.*, 2023)
Decentralized RL	Stochastic microgrid	Local states	Distributed policies	Decentralized EMS	(Darshi *et al.*, 2023)
Data driven DRL	PV, battery, EV demand	Time series data	EMS actions	Adaptation to uncertainty	(Kaewdornhan & Chatthaworn, 2023)
Digital twin EMS	PV, biogas, VRFB	IoT and simulated states	EMS decisions	Virtual experimentation	(Wu & Mei, 2024)
Cognitive fuzzy EMS	Self sustaining hybrid	Operating states	Adaptive EMS	Peak demand coordination	(Julin *et al.*, 2025)
Multi objective AI EMS	Hybrid sources/DR	Generation and load	Multi objective dispatch	Technical/economic optimization	(Moosavi *et al.*, 2025)
Artificial bee colony EMS	Distributed generation	Load/solar irradiance	Optimal dispatch	Improved search	(Hamadneh *et al.*, 2025)
Artificial bee colony EMS	Distributed generation	Load/solar irradiance	Optimal dispatch	Improved search	(Hamadneh *et al.*, 2025)

Abbreviations: AI, artificial intelligence; EMS, energy management system; SOC, state of charge; DDPG, deep deterministic policy gradient; RL, reinforcement learning; DRL, deep reinforcement learning; EV, electric vehicle; VRFB, vanadium redox flow battery; IoT, Internet of Things; DR, demand response. PV denotes photovoltaic generation, while V2G denotes vehicle to grid operation where EVs provide bidirectional energy exchange.

Figure 4 illustrates an integrated AI-driven energy management workflow linking measurement and data acquisition, renewable generation and load forecasting, integrated state estimation, digital twin simulation, optimization, and automated dispatch. It further depicts the closed-loop interaction between AI decision-making, system actuation, real-time feedback, performance monitoring, and continuous model learning for adaptive energy system control.

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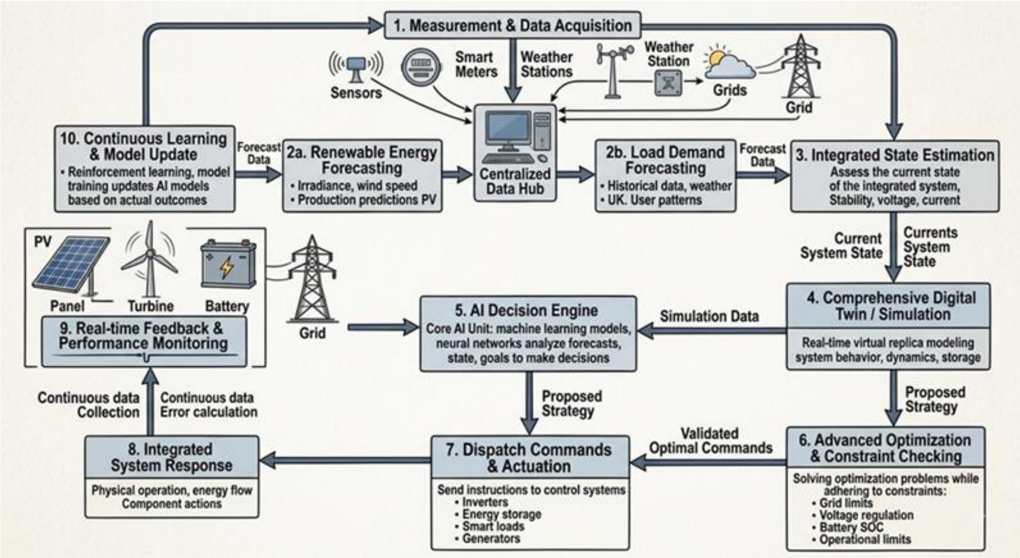

Figure 4. AI-Enabled Digital Twin Framework for Real-Time Renewable Energy System Monitoring, Optimization, and Control (Darshi *et al.*, 2023; Kaewdornhan & Chatthaworn, 2023; Liu *et al.*, 2023; Wu & Mei, 2024; Hamadneh *et al.*, 2025; Julin *et al.*, 2025; Moosavi *et al.*, 2025).

AI-enabled digital twin framework for intelligent energy system management. The framework integrates sensors, smart meters, weather stations, photovoltaic (PV) panels, wind turbines, batteries, and the electrical grid through a centralized data hub for forecasting, state estimation, simulation, optimization, AI-based decision-making, dispatch, and feedback control. Abbreviations: AI, artificial intelligence; PV, photovoltaic; SOC, state of charge.

3.10 Technical Performance Outcomes

Technical performance was assessed through reliability, voltage and frequency stability, power quality, renewable utilization, battery behavior and energy adequacy. The evidence demonstrated that integrated architectures generally improved technical performance when the renewable sources and storage devices were appropriately coordinated.

Reliability was a primary design objective in stand alone systems. Moghaddam *et al.* evaluated a PV wind battery system using deficit power hourly interruption probability and net present cost, directly linking economic design to supply reliability (Moghaddam *et al.*, 2019). This was important because higher reliability generally required more renewable generation or storage capacity, increasing investment requirements.

At grid connected scale, Fendzi Mbasso *et al.* applied hybrid Monte Carlo and Newton Raphson methods to a grid connected hybrid renewable energy system and evaluated reliability through probabilistic generation and power flow analysis (Fendzi Mbasso *et al.*, 2024). The study emphasized that renewable integration changed not only generation adequacy but also the probabilistic behavior of the grid connected system.

Voltage and power quality were also significant. Chang *et al.* examined voltage stability in an AC/DC hybrid microgrid using grid forming and grid following converters and evaluated the effect of faults and power mismatches on the voltage nadir (Chang *et al.*, 2023). Venkatesan *et al.* assessed a grid connected PV wind battery system supported by a unified power quality conditioner and optimized fractional order PID controller. Under sag conditions, reported THD values were 5.9038% for PI, 4.9592% for FOPID and 3.7027% using the optimized method (Venkatesan *et al.*, 2024). This represented a substantial improvement in power quality relative to the less optimized controllers.

Economic predictive control also demonstrated the importance of operational coordination. Al Quraan and Al Mhairat reported total system costs of approximately US$114,224, including fixed operation and maintenance, investment and operating components, while approximately 90% of generated power was imported from the grid (Al-Quraan & Al-Mhairat, 2024). This result showed that the presence of renewable technologies did not automatically produce high renewable utilization and that operational control could determine the extent to which installed renewable capacity actually displaced grid electricity.

The technical evidence therefore supported the conclusion that system integration itself did not guarantee superior performance. The outcome depended on architecture, control coordination, reserve allocation, converter behavior and the ability of storage and flexible demand to compensate for variability.

Table summarizes the principal technical indicators used to evaluate integrated renewable systems and the main outcomes reported for reliability, voltage stability, power quality, renewable utilization, battery health, and frequency response. It provides a concise comparison of how different system configurations and control strategies influenced measurable technical performance.

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Table 11. Technical performance indicators and reported outcomes

Indicator	Primary measurement/application	Reported outcome or observation	Citation(s)
Supply reliability	DPHIP in stand alone PV/wind/battery	Reliability used as sizing constraint	(Moghaddam *et al.*, 2019)
Voltage stability	AC/DC hybrid microgrid	Voltage nadir under faults/mismatch	(Chang *et al.*, 2023)
Power quality	PV/wind/battery with UPQC	THD 3.7027% with optimized controller	(Venkatesan *et al.*, 2024)
Grid reliability	Grid connected HRES	Monte Carlo and Newton Raphson	(Fendzi Mbasso *et al.*, 2024)
Renewable utilization	Grid connected HRES	Control determined renewable self use	(Al-Quraan & Al-Mhairat, 2024)
Battery health	PV microgrid	MPC considered degradation	(Nair *et al.*, 2021)
Frequency response	Hybrid storage/V2G	Coordinated storage supported regulation	(Ge *et al.*, 2021; Mahela *et al.*, 2022)

Abbreviations: DPHIP, deficit power hourly interruption probability; PV, photovoltaic; AC, alternating current; DC, direct current; UPQC, unified power quality conditioner; THD, total harmonic distortion; HRES, hybrid renewable energy system; MPC, model predictive control; V2G, vehicle to grid; PI, proportional integral; FOPID, fractional order proportional integral derivative. AC/DC refers to alternating and direct current systems, while THD expresses harmonic distortion in the power quality assessment.

3.11 Economic Performance

Economic performance was evaluated using levelized cost of energy, net present cost, payback period, capital cost, operating cost, replacement cost, dispatch cost and sensitivity analysis. The evidence showed that integrated renewable systems frequently achieved better economic outcomes when renewable resource complementarity reduced storage requirements or diesel utilization.

The Zanjan study incorporated capital, replacement, operation and maintenance costs into net present cost while imposing a reliability constraint (Moghaddam *et al.*, 2019). This provided a more realistic representation of system economics than considering capital cost alone. The Tumbatu Island study provided another direct example. The optimized grid connected system had a lowest NPC of approximately US$4,003,851 and a payback period of about 3.79 years, with wind speed identified as a major sensitivity factor (Said *et al.*, 2024).

An integrated off grid system incorporating PV, wind, micro hydropower, biogas and battery storage was optimized against economic, environmental and social objectives. The study considered an average demand ranging from approximately 39.6 to 63.6 kW and obtained an energy cost of approximately US$0.126/kWh for the selected optimum, while the model also evaluated employment creation and life cycle emissions (Hassan *et al.*, 2022).

Economic predictive control produced a different result because it focused on operation and control as well as sizing. The reported total system cost was about US$114,224, with approximately US$15,090 attributed to annual fixed operation and maintenance, US$28,351 to investment and US$70,783 to operating cost (Al-Quraan & Al-Mhairat, 2024). The relatively large operating component and high grid import share demonstrated the importance of assessing actual energy flows rather than assuming that installed renewable capacity translated directly into economic savings.

The evidence also showed that economic performance depended strongly on the assumptions used for battery degradation, fuel prices, electricity tariffs, discount rates, equipment replacement and system lifetime. The economic ranking of a PV wind battery system could therefore change substantially when storage replacement or resilience value was incorporated.

Table 12 compares the main economic indicators reported across the reviewed studies, including net present cost, payback period, energy cost, capital and operating expenditures, battery lifecycle effects, and dispatch cost. It shows how investment, operating conditions, degradation, and renewable coordination influenced the economic performance of integrated renewable systems.

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Table 12. Economic indicators and comparative cost outcomes

Economic indicator	Primary study finding	Interpretation	Citation(s)
NPC	Zanjan optimization	Investment, replacement and O&M	(Moghaddam *et al.*, 2019)
NPC	Tumbatu ≈ US$4.004 million	Economic feasibility in the case study	(Said *et al.*, 2024)
Payback	Tumbatu ≈3.79 years	Capital recovery	(Said *et al.*, 2024)
Energy cost	Off grid hybrid ≈US$0.126/kWh	Multi objective optimum	(Hassan *et al.*, 2022)
CAPEX/OPEX	Investment ≈US$28,351; fixed O&M ≈US$15,090; operating ≈US$70,783	Operation influenced total cost	(Al-Quraan & Al-Mhairat, 2024)
Battery lifecycle	PV/wind/battery sizing	Degradation influenced optimum	(Zhang *et al.*, 2021)
Dispatch cost	Stochastic multi energy hub	Renewables and DR reduced operating cost	(Thang *et al.*, 2022)

Abbreviations: NPC, net present cost; CAPEX, capital expenditure; OPEX, operating expenditure; O&M, operation and maintenance; DR, demand response. US$ denotes United States dollars, while kWh denotes kilowatt hour and the reported cost values represent the economic quantities presented in the reviewed studies.

3.12 Environmental and Sustainability Performance

Environmental performance was assessed through life cycle emissions, fossil fuel displacement, renewable penetration, emissions reduction, resource efficiency and wider sustainability indicators. The evidence showed that integrated renewable systems generally improved environmental performance, but the degree of improvement depended on system configuration, storage technology and backup generation.

The integrated off grid system optimized by a multi objective approach included economic, environmental and social indicators simultaneously (Hassan *et al.*, 2022). This was significant because environmental benefits were not treated as a secondary result but as an explicit optimization objective.

Zhang *et al.* developed a robust optimization framework for a microgrid containing wind, solar and natural gas and assessed primary energy savings, annual total cost savings and carbon dioxide reduction together with flexibility indicators. When flexibility was explicitly included in the optimization objectives, primary energy saving, cost saving and CO_2 reduction changed by 1.7%, 19.8% and 1.2%, respectively, relative to optimization without the flexibility dimension (Zhang, 2022). This result demonstrated an important systems level trade off: optimizing only for environmental benefit could produce a different operating configuration from one that also valued flexibility.

Hydrogen added another dimension to sustainability. Hydrogen storage could reduce dependence on fossil backup generation and permit excess renewable electricity to be retained for later use. However, the hydrogen pathway introduced electrolyzer and fuel cell conversion losses and additional equipment. A feasibility study of hydrogen storage in microgrids found that under contemporary market conditions hydrogen investment was environmentally attractive but not economically viable in the modeled scenarios (Shao *et al.*, 2023). This demonstrated that environmental superiority did not automatically translate to economic superiority.

The green hydrogen energy storage service study further showed how power to gas could be used to absorb otherwise curtailed renewable power and improve renewable utilization (Qiu *et al.*, 2023). The environmental value of such systems was greatest when they captured renewable electricity that otherwise would have been curtailed.

The evidence consequently supported a more nuanced sustainability interpretation. Integrated systems were most environmentally effective when they maximized renewable utilization, reduced curtailment, limited fossil backup and minimized excessive conversion losses.

Table 13 summarizes the principal environmental and sustainability metrics used to assess carbon reduction, renewable utilization, fossil fuel displacement, lifecycle emissions, renewable absorption, and social sustainability. It shows how integrated renewable configurations contributed to environmental performance and broader sustainability objectives across different applications.

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Table 13. Environmental and sustainability metrics

Metric	Application	Primary observation	Citation(s)
CO2 reduction	Renewable/natural gas microgrid	Reduction changed when flexibility included	(Zhang, 2022)
Renewable utilization	Multi energy hub	Renewables reduced emissions/cost	(Thang *et al.*, 2022)
Fossil displacement	Hybrid PV/wind/biomass/battery	Reduced backup dependence	(Sawle, 2025)
Life cycle emissions	Integrated off grid HRES	Environmental objective jointly optimized	(Hassan *et al.*, 2022)
Renewable absorption	Green hydrogen P2G	Surplus renewable converted to hydrogen	(Qiu *et al.*, 2023)
Social sustainability	Rural hybrid	Employment considered	(Hassan *et al.*, 2022)

Abbreviations: CO_2, carbon dioxide; PV, photovoltaic; HRES, hybrid renewable energy system; P2G, power to gas. PV/wind/biomass/battery denotes the combined use of photovoltaic, wind, biomass, and battery technologies, while P2G refers to conversion of surplus renewable electricity into hydrogen or another gaseous energy carrier.

3.13 Operational Resilience, Reliability and Flexibility Services

Operational resilience emerged as a major theme because renewable dominated systems were required to continue operating during disturbances, communication failures, grid outages and renewable fluctuations. Integrated renewable systems achieved resilience through combinations of storage, islanding capability, flexible demand, distributed control and multiple energy carriers.

The hybrid renewable microgrid studies demonstrated that batteries were central to resilience because they could respond rapidly to generation deficits. In stand alone systems, storage was used to sustain supply when PV and wind generation fell below demand (Moghaddam *et al.*, 2019; Canziani *et al.*, 2021). In grid connected systems, resilience also depended on whether the microgrid could transition to island operation.

Peer to peer energy trading further expanded resilience. Spiliopoulos *et al.* developed a peer to peer energy exchange framework for microgrids and tested it under different geographical and tariff conditions and fault scenarios. The study reported resilience improvements of up to 80% and battery lifetime extensions of approximately 32% to 37% (Spiliopoulos *et al.*, 2022). These findings showed that market coordination could potentially provide a physical resilience function by changing the allocation of distributed energy resources during disturbances.

V2G also provided a flexibility pathway. The V2G study integrating a 1,000 household equivalent microgrid used EV batteries to regulate microgrid parameters over a 24 hour operating period (Mahela *et al.*, 2022). EVs therefore acted not only as transportation loads but also as distributed reserve resources.

Hydrogen provided long duration resilience. Hydrogen based rural microgrid planning incorporated multiscale storage and examined resilience under uncertainty (Shao *et al.*, 2023). The value of hydrogen was particularly relevant where outages exceeded the economical duration of conventional battery storage.

Black start capability also became increasingly important as inverter based renewable generation replaced conventional generators. Grid forming converters and batteries provided a possible mechanism through which renewable plants could participate in restoration rather than simply waiting for a stable grid waveform.

Table 14 identifies the main resilience and flexibility services supported by integrated renewable systems and the resources used to provide them. It also summarizes the evidence and quantitative or operational characteristics associated with islanding, fault resilience, battery flexibility, frequency support, long duration storage, power quality, and voltage support.

Table 14. Operational resilience and flexibility services provided by the systems

Service	Enabling resource	Primary evidence	Quantitative finding or characteristic	Citation(s)
Islanded operation	Battery and inverter	PV/wind/battery	Local supply during deficits	(Moghaddam *et al.*, 2019; Canziani *et al.*, 2021)
Fault resilience	Distributed control/P2P	Community microgrids	Resilience improved up to 80%	(Spiliopoulos *et al.*, 2022)

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Service	Enabling resource	Primary evidence	Quantitative finding or characteristic	Citation(s)
Battery life flexibility	P2P exchange	Community microgrids	Lifetime increased about 32% to 37%	(Spiliopoulos *et al.*, 2022)
Frequency support	V2G	1,000 household equivalent	24 hour regulation assessment	(Mahela *et al.*, 2022)
Long duration reserve	Hydrogen	Rural hydrogen microgrid	Multiscale storage	(Shao *et al.*, 2023)
Power quality	UPQC/controller	Grid connected HRES	THD 3.7027% in sag case	(Venkatesan *et al.*, 2024)
Voltage support	Hybrid converter control	AC/DC microgrid	Stability under faults	(Chang *et al.*, 2023)

Abbreviations: P2P, peer to peer; V2G, vehicle to grid; UPQC, unified power quality conditioner; HRES, hybrid renewable energy system; THD, total harmonic distortion; AC, alternating current; DC, direct current. AC/DC represents hybrid alternating and direct current systems, while THD expresses harmonic distortion and V2G represents bidirectional energy exchange between electric vehicles and the grid.

3.14 Implementation Challenges and Barriers

Despite the technical progress, several barriers continued to limit large scale implementation. The most important technical challenge remained the coordination of multiple heterogeneous devices with different dynamic responses, operating limits and communication requirements.

Hybrid AC/DC systems had introduced converter interactions, protection complexity and voltage stability concerns. Chang *et al.* showed that hybrid microgrid voltage behavior depended on grid forming and grid following converter behavior, power mismatch and fault conditions (Chang *et al.*, 2023). This suggested that converter dominated systems required stability analysis beyond conventional synchronous machine based methods.

Control complexity also increased with the number of devices. Distributed optimization reduced centralized computational burden but introduced communication dependence. Chen *et al.* used ADMM to distribute the optimization process between AC and DC subsystems (Chen *et al.*, 2021). However, distributed solutions depended on reliable information exchange and appropriate convergence behavior.

Cybersecurity emerged as an important barrier because increasing reliance on digital control increased exposure to communication attacks and corrupted measurements. The distributed communication study demonstrated that microgrid control could depend on real time data exchange, making communication latency and integrity important operational parameters (Saxena *et al.*, 2021). Interoperability created another challenge because microgrids contained devices from different manufacturers with different control interfaces, communication protocols and data structures.

Economic barriers remained equally significant. The hydrogen feasibility study found that hydrogen storage could be environmentally attractive but economically unattractive under contemporary market assumptions (Shao *et al.*, 2023). Similarly, economic predictive control showed that the existence of renewable generation did not guarantee low grid dependence, because the system still imported approximately 90% of its power in the investigated case (Al-Quraan & Al-Mhairat, 2024).

Battery degradation, equipment replacement, supply chain dependence and uncertain electricity prices also affected system economics. The increasing number of critical materials in batteries and power electronic equipment introduced additional lifecycle considerations. Policy and market rules also affected whether EVs could deliver grid services, whether distributed systems could sell surplus energy and whether flexibility could be adequately compensated.

Table 15 summarizes the principal technical, economic, communication, cybersecurity, interoperability, and policy barriers affecting integrated renewable energy systems. It links each barrier to the affected subsystem, supporting evidence, and a practical mitigation approach relevant to system deployment.

Table 15. Major barriers, affected subsystems and mitigation options

Barrier	Affected subsystem	Primary evidence	Practical mitigation	Citation(s)
Converter interaction	AC/DC microgrid	Voltage stability study	Grid forming and coordination	(Chang *et al.*, 2023)
Communication dependence	Distributed EMS	Distributed communication	Low latency, redundancy	(Saxena *et al.*, 2021)
Computational	Multi energy optimization	Stochastic hub studies	Scenario	(Thang *et al.*, 2022)

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Barrier	Affected subsystem	Primary evidence	Practical mitigation	Citation(s)
burden			reduction/distribution	
Battery degradation	Storage/economics	Lifecycle study	Degradation aware dispatch	(Zhang *et al.*, 2021)
Hydrogen cost	Long duration storage	Hydrogen feasibility	Efficiency and market design	(Shao *et al.*, 2023)
Interoperability	Multi vendor devices	Multi agent/communication	Standardized interfaces	(Saxena *et al.*, 2021; El Zerk *et al.*, 2022)
Cybersecurity	EMS/communications	Digital control	Secure communications/anomaly detection	(Saxena *et al.*, 2021)
Capital cost	Generation/storage	HRES economic studies	Optimal sizing/staged investment	(Said *et al.*, 2024; Sawle, 2025)
Forecast uncertainty	EMS	RL and stochastic studies	Robust uncertainty aware control	(Thang *et al.*, 2022; Darshi *et al.*, 2023; Liu *et al.*, 2023)
Policy/market restrictions	EV/grid services	V2G studies	Remuneration and market rules	(Mahela *et al.*, 2022)

Abbreviations: AC, alternating current; DC, direct current; EMS, energy management system; HRES, hybrid renewable energy system; RL, reinforcement learning; V2G, vehicle to grid; EV, electric vehicle. AC/DC refers to hybrid alternating and direct current microgrids, while EMS refers to the digital system responsible for coordinating generation, storage, demand, and grid interaction.

3.15 Emerging Trends, Research Gaps and Future Directions

The final evidence synthesis showed that the field was moving toward increasingly integrated architectures in which electricity generation, storage, transport, hydrogen, flexible demand and digital control were treated as parts of one energy system. Several research directions stood out.

First, sector coupling had become a major pathway for increasing renewable utilization. Instead of curtailing surplus PV or wind generation, energy could be redirected toward hydrogen production, EV charging, heating or other flexible loads. Multi energy hub optimization had already demonstrated economic and emissions benefits from coordinating different energy carriers (Thang *et al.*, 2022).

Second, hydrogen storage had emerged as a complement rather than an unconditional replacement for batteries. Batteries remained technically attractive for short duration and fast response applications, while hydrogen offered greater potential for long duration energy storage. The principal gap involved determining where the economic break even point between batteries and hydrogen occurred under different renewable penetration levels, storage durations and electricity market conditions (Qiu *et al.*, 2023; Shao *et al.*, 2023).

Third, EV grid integration represented a growing opportunity. V2G demonstrated that EV batteries could participate in frequency regulation and flexibility services (Mahela *et al.*, 2022). However, future research needed to incorporate actual travel behavior, user preferences, battery degradation, charging availability, network constraints and market remuneration rather than assuming that the full EV battery capacity was continuously available.

Fourth, AI based energy management was likely to become more important. Reinforcement learning could make dispatch decisions without solving a complete optimization problem at every time step, while digital twins could provide a safe environment for controller testing (Darshi *et al.*, 2023; Liu *et al.*, 2023; Wu & Mei, 2024). Nevertheless, explainability, generalization, cyber resilience and verification under abnormal conditions remained insufficiently addressed.

Fifth, research increasingly needed to move toward hardware in the loop and field validation. Much of the reviewed literature was simulation based, although the evidence included real resource data, field systems and real communication environments. Longer duration experiments were needed to determine whether control improvements observed in simulation were retained under component aging, communication failures, changing tariffs and seasonal weather.

Sixth, future integrated systems needed scalable architectures. Centralized control remained effective for small systems, but distributed and multi agent architectures offered advantages as system size increased (Azeroual *et al.*, 2022; El Zerk *et al.*, 2022). The major research opportunity therefore lay in combining hierarchical supervisory control with distributed local optimization and device level intelligent control.

Seventh, future planning studies needed to include uncertainty more rigorously. Renewable variability, load uncertainty, price uncertainty, equipment failure and grid outage probabilities should be treated together rather than independently. Robust and stochastic optimization already

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represented progress in this direction (Thang *et al.*, 2022; Zhang, 2022).

Finally, the evidence suggested that next generation integrated renewable systems would be increasingly defined by flexibility rather than generation capacity alone. A system containing PV, wind and batteries became more valuable when it could also provide voltage support, frequency regulation, demand response, EV charging, hydrogen production and islanding capability.

The overall synthesis showed that integrated renewable energy systems had progressed from simple hybrid generation arrangements to complex cyber physical energy platforms. The strongest future direction was therefore not the replacement of one technology with another, but the coordinated integration of complementary technologies. Batteries were expected to remain central to rapid balancing; hydrogen was positioned for longer duration storage and sector coupling; EVs could provide distributed flexibility; smart grids could provide the communication and market infrastructure; and AI based energy management could coordinate these resources under uncertainty.

The most important research gap was the lack of common, reproducible, experimentally validated benchmarks that evaluated architectures, controllers and optimization strategies using the same load profiles, renewable data, outage scenarios, economic assumptions and performance metrics. Without such benchmarking, reported improvements remained difficult to compare across studies. A next generation research framework should therefore combine field measurements, digital twins, hardware in the loop testing, uncertainty aware optimization, distributed control and lifecycle assessment.

The evidence also demonstrated that performance should no longer be evaluated through a single metric. A high renewable fraction was not sufficient if reliability was poor; a low operating cost was not sufficient if battery degradation was excessive; and high technical reliability was not sufficient if the system depended on economically unrealistic storage or market assumptions. Integrated renewable energy systems were therefore most appropriately assessed through multidimensional technical, economic, environmental and resilience indicators.

In conclusion, the evidence showed a consistent movement toward flexible, multi carrier and digitally coordinated energy systems. The transition from conventional power systems toward renewable dominated infrastructure was not achieved simply by adding more solar panels and wind turbines. It depended on how effectively generation, storage, conversion, demand and intelligent control were integrated into a coherent operating architecture. The strongest future pathway therefore involved scalable hybrid architectures supported by distributed and hierarchical control, AI enabled forecasting and dispatch, long duration hydrogen storage, battery energy storage, EV grid integration, smart grid modernization and market mechanisms that appropriately valued flexibility and resilience.

Table 16 summarizes the principal research gaps identified in the review and links them with corresponding opportunities and proposed technical solutions. It highlights future priorities involving long duration storage, sector coupling, AI validation, scalability, battery degradation, EV integration, converter stability, cybersecurity, market design, and benchmarking.

Table 16. Research gaps, future opportunities and next generation solutions

Research gap	Opportunity	Recommended solution	Supporting evidence
Limited long duration storage	Seasonal balancing	Battery plus hydrogen	(Qiu *et al.*, 2023; Shao *et al.*, 2023)
Fragmented sector integration	Excess renewable utilization	Electricity, hydrogen, EV and thermal coupling	(Mahela *et al.*, 2022; Thang *et al.*, 2022; Qiu *et al.*, 2023)
Limited field validation of AI	Safe intelligent EMS	HIL and digital twin validation	(Liu *et al.*, 2023; Wu & Mei, 2024)
Centralized scalability	Large microgrid clusters	Hierarchical distributed multi agent EMS	(Chen *et al.*, 2021; Azeroual *et al.*, 2022; El Zerk *et al.*, 2022)
Battery degradation	Lifecycle cost reduction	Degradation aware optimization	(Zhang *et al.*, 2021)
EV user uncertainty	Reliable V2G	Behavior aware scheduling	(Mahela *et al.*, 2022)
Converter dominated stability	High inverter penetration	Grid forming coordinated converters	(Datta *et al.*, 2021; Chang *et al.*, 2023)
Cybersecurity	Secure digital EMS	Anomaly detection/resilient communications	(Saxena *et al.*, 2021)
Market barriers	Flexibility monetization	Ancillary/local energy markets	(Mahela *et al.*, 2022; Spiliopoulos *et al.*, 2022)

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Research gap	Opportunity	Recommended solution	Supporting evidence
Lack of standard benchmarks	Reproducible AI comparison	Common datasets/test microgrids	(Darshi *et al.*, 2023; Liu *et al.*, 2023; Wu & Mei, 2024)

Abbreviations: AI, artificial intelligence; EMS, energy management system; HIL, hardware in the loop; EV, electric vehicle; V2G, vehicle to grid. PV denotes photovoltaic generation, while AC/DC denotes alternating and direct current systems and P2P denotes peer to peer energy exchange where relevant to the proposed research directions.

Figure 5 presents a systems-level framework linking major renewable-energy challenges to storage, control, communication, artificial intelligence, and demand-flexibility solutions. It illustrates how these innovations and deployment pathways contribute to improved grid stability, renewable-energy penetration, economic efficiency, power-system resilience, and resource utilization.

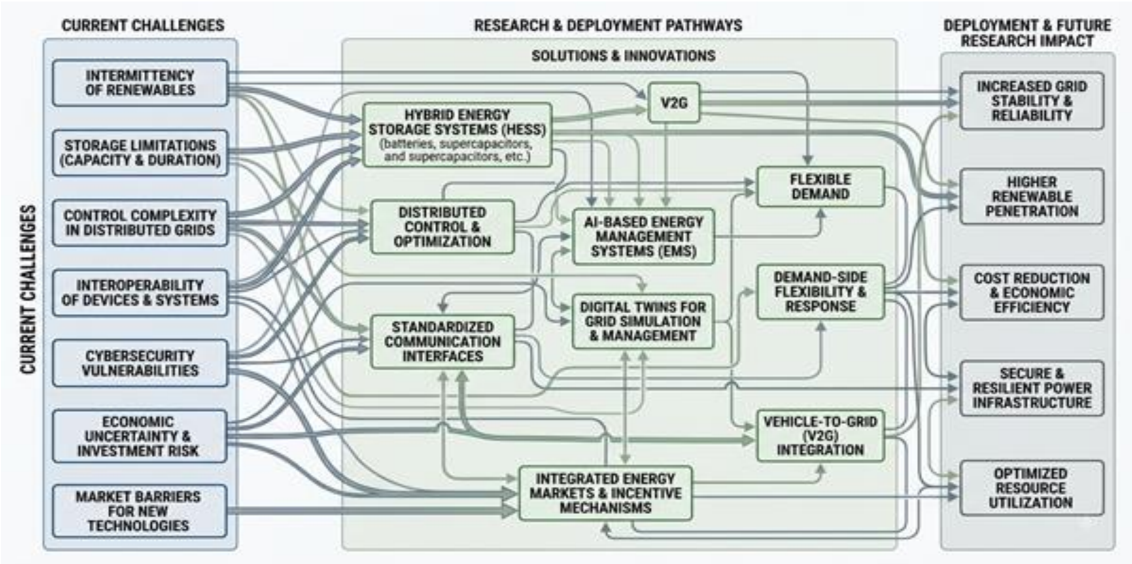

Figure 5. Integrated Energy Storage, Grid Management, and Deployment Pathways for Renewable Energy Systems (Mahela *et al.*, 2022; Darshi *et al.*, 2023; Liu *et al.*, 2023; Qiu *et al.*, 2023; Wu & Mei, 2024).

Conceptual framework showing the relationships among current energy-system challenges, technological solutions, and deployment outcomes, including hybrid energy storage systems, distributed control, standardized communication, digital twins, flexible demand, and vehicle-to-grid integration. Abbreviations: HESS, hybrid energy storage systems; EMS, energy management systems; V2G, vehicle-to-grid; AI, artificial intelligence.

CONCLUSION

Integrated renewable energy systems have evolved from simple hybrid configurations into flexible, intelligent, and interconnected energy platforms. Their effectiveness depends not on renewable capacity alone, but on coordinated integration of generation, storage, conversion, demand, and control. Battery storage remains essential for short term balancing, while hydrogen offers promising opportunities for long duration storage and sector coupling. Artificial intelligence, predictive control, distributed coordination, and digital technologies are increasingly important for adaptive and efficient energy management. The evidence indicates that technical, economic, environmental, reliability, and resilience outcomes should be assessed together rather than through a single performance measure. Future studies should give greater attention to battery degradation, uncertainty, converter stability, cybersecurity, communication reliability, and the operational variability of electric vehicles. Field validation of intelligent energy management systems should be strengthened through digital twins, hardware in the loop experiments, and long duration real world testing. Research should also develop scalable hierarchical and distributed control architectures capable of coordinating increasingly interconnected microgrids and multi energy systems. Common datasets, standardized test systems, and reproducible benchmarks are needed to enable meaningful comparison of competing architectures, control strategies, and optimisation methods.

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COMPETING INTEREST

The authors declare that they have no competing financial, professional, or personal interests that could have influenced the conduct, analysis, or interpretation of this systematic review.

REFERENCES

1. Al Afif, R., Ayed, Y., & Maaitah, O. N. (2023). Feasibility and optimal sizing analysis of hybrid renewable energy systems: A case study of Al-Karak, Jordan. *Renewable Energy, 204*, 229-249. https://doi.org/10.1016/j.renene.2022.12.109
2. Al Hamzawi, H. A. H., & Abed Al Sailawi, A. S. (2026). AI-assisted optimization of a hybrid renewable energy system for semi-arid regions using multi-source engineering data. *Energy, 360*, 100070. https://doi.org/10.1016/j.energ.2026.100070
3. Al Sumarmad, K. A. A., Sulaiman, N., Wahab, N. I. A., & Hizam, H. (2022). Microgrid energy management system based on fuzzy logic and monitoring platform for data analysis. *Energies, 15*, 4125. https://doi.org/10.3390/en15114125
4. Al-Quraan, A., & Al-Mhairat, B. (2024). Economic predictive control-based sizing and energy management for grid-connected hybrid renewable energy systems. *Energy, 302*, 131795. https://doi.org/10.1016/j.energy.2024.131795
5. Al-Shamma'a, A. A., Hussein Farh, H. M., Noman, A. M., Al-Shaalan, A. M., & Alkuhayli, A. (2022). Optimal sizing of a hybrid renewable photovoltaic-wind system-based microgrid using Harris Hawk optimizer. *International Journal of Photoenergy, 2022*, 4825411. https://doi.org/10.1155/2022/4825411
6. Azeroual, M., Boujoudar, Y., El Iysaouy, L. E., Aljarbouh, A., Fayaz, M., Qureshi, M. S., et al. (2022). Energy management and control system for microgrid based wind PV battery using multi-agent systems. *Wind Engineering, 46*, 1247-1263. https://doi.org/10.1177/0309524X221075583
7. Azizi, A., Karimi, H., & Jadid, S. (2022). Daily operation of multi-energy systems based on stochastic optimization considering prediction of renewable energy generation. *IET Renewable Power Generation, 16*, 245-260. https://doi.org/10.1049/rpg2.12292
8. Basnet, S., Deschinkel, K., Le Moyne, L., & Péra, M. C. (2024). Optimal integration of hybrid renewable energy systems for decarbonized urban electrification and hydrogen mobility. *International Journal of Hydrogen Energy, 83*, 1448-1462. https://doi.org/10.1016/j.ijhydene.2024.08.054
9. Canziani, F., Vargas, R., & Gastelo Roque, J. A. (2021). Hybrid photovoltaic wind microgrid with battery storage for rural electrification: A case study in Peru. *Frontiers in Energy Research, 8*, 528571. https://doi.org/10.3389/fenrg.2020.528571
10. Chang, F., O'Donnell, J., & Su, W. (2023). Voltage stability assessment of AC/DC hybrid microgrid. *Energies, 16*, 399. https://doi.org/10.3390/en16010399
11. Chen, Y., Hao, L., & Yin, G. (2021). Distributed energy management of the hybrid AC/DC microgrid with high penetration of distributed energy resources based on ADMM. *Complexity, 2021*, 1863855. https://doi.org/10.1155/2021/1863855
12. Darshi, R., Shamaghdari, S., Jalali, A., & Arasteh, H. (2023). Decentralized reinforcement learning approach for microgrid energy management in stochastic environment. *International Transactions on Electrical Energy Systems, 2023*, 1190103. https://doi.org/10.1155/2022/1190103
13. Datta, A., Atoche, A. C., Koley, I., Sarker, R., Castillo, J. V., et al. (2021). Coordinated AC frequency vs DC voltage control in a photovoltaic wind battery-based hybrid AC/DC microgrid. *International Transactions on Electrical Energy Systems, 31*, e13041. https://doi.org/10.1002/2050-7038.13041
14. Du, P., Liu, Z., Huang, B., Jing, G., Feng, L., & Yang, C. (2022). Blockchain-based peer-to-peer energy trading between wind power producer and prosumers in short-term market. *Frontiers in Energy Research, 10*, 923292. https://doi.org/10.3389/fenrg.2022.923292
15. El Zerk, A., Ouassaid, M., & Zidani, Y. (2022). Decentralised strategy for energy management of collaborative microgrids using multi-agent system. *IET Smart Grid, 5*, 440-462. https://doi.org/10.1049/stg2.12077
16. Elgammal, A. (2018). Energy management in smart grids for the integration of hybrid wind PV FC battery renewable energy resources using multi-objective particle swarm optimisation. *Journal of Engineering*. https://doi.org/10.1049/joe.2018.5036
17. Fendzi Mbasso, W., Molu, R. J. J., Ambe, H., Dzonde Naoussi, S. R., Alruwaili, M., Mobarak, W., et al. (2024). Reliability analysis of a grid-connected hybrid renewable energy system using hybrid Monte Carlo and Newton Raphson methods. *Frontiers in Energy Research, 12*, 1435221. https://doi.org/10.3389/fenrg.2024.1435221
18. Ge, S., He, X., Liu, H., Mi, Y., & Wang, C. (2021). Frequency coordinated control strategy based on sliding mode method for a microgrid with hybrid energy storage system. *IET Generation, Transmission & Distribution, 15*, 1962-1971. https://doi.org/10.1049/gtd2.12148
19. Hai, T., Singh, N. S. S., & Jamal, F. (2025). Energy management of a microgrid with integration of renewable energy sources considering energy storage systems with electricity price. *Journal of Energy Storage, 110*, 115191. https://doi.org/10.1016/j.est.2024.115191

*Corresponding Author: David Chinonso Anih

20. Hamadneh, T., Alsayyed, O., Batiha, B., Barhoumi, E. M., Ahmadi Kamarposhti, M., Haghighi, H., et al. (2025). Optimal energy management of distributed generation resources in a microgrid under various load and solar irradiance conditions using the artificial bee colony algorithm. *Scientific Reports, 15*, 31097. https://doi.org/10.1038/s41598-025-16813-9
21. Hassan, Q., Algburi, S., Sameen, A. Z., Salman, H. M., & Jaszczur, M. (2023). A review of hybrid renewable energy systems: Solar and wind-powered solutions: Challenges, opportunities, and policy implications. *Results in Engineering, 20*, 101621. https://doi.org/10.1016/j.rineng.2023.101621
22. Hassan, R., Das, B. K., & Hasan, M. (2022). Integrated off-grid hybrid renewable energy system optimization based on economic, environmental, and social indicators for sustainable development. *Energy, 250*, 123823. https://doi.org/10.1016/j.energy.2022.123823
23. Ibrahim, M. M. (2024). Energy management strategies of hybrid renewable energy systems: A review. *Wind Engineering, 48*, 133-161. https://doi.org/10.1177/0309524X231200010
24. Julin, E. M. Q., Subramanian, V., Bereznychenko, V., & Narayanamoorthi, R. (2025). Cognitive fuzzy logic integrated energy management for self-sustaining hybrid renewable microgrids. *Scientific Reports, 15*, 9915. https://doi.org/10.1038/s41598-025-94077-z
25. Kaewdornhan, N., & Chatthaworn, R. (2023). Model-free data-driven approach assisted deep reinforcement learning for optimal energy management in microgrid. *Energy Reports, 9*, 850-858. https://doi.org/10.1016/j.egyr.2023.05.130
26. Khalid, M. (2024). Smart grids and renewable energy systems: Perspectives and grid integration challenges. *Energy Strategy Reviews, 51*, 101299. https://doi.org/10.1016/j.esr.2024.101299
27. Khan, A. A., Minai, A. F., Pachauri, R. K., & Malik, H. (2022). Optimal sizing, control, and management strategies for hybrid renewable energy systems: A comprehensive review. *Energies, 15*, 6249. https://doi.org/10.3390/en15176249
28. Kouihi, M., Bikndaren, S., Moutchou, M., Ait ElMahjoub, A., & Majdoul, R. (2025). Comprehensive review of classical and AI-driven energy management strategies for hybrid renewable energy systems. *e-Prime - Advances in Electrical Engineering, Electronics and Energy, 13*, 101085. https://doi.org/10.1016/j.prime.2025.101085
29. Koulali, M., Mankour, M., Negadi, K., & Mezouar, A. (2019). Energy management of hybrid power system PV wind and battery based three level converter. *Tecnica Italiana, 63*, 297-304. https://doi.org/10.18280/ti-ijes.632-426
30. Kwon, K., Lee, H. B., Kim, N., Park, S., & Joshua, S. R. (2024). Integrated battery and hydrogen energy storage for enhanced grid power savings and green hydrogen utilization. *Applied Sciences, 14*, 7631. https://doi.org/10.3390/app14177631
31. Lee, J. O., & Kim, Y. S. (2020). Frequency and state of charge restoration method in a secondary control of an islanded microgrid without communication. *Applied Sciences, 10*, 1558. https://doi.org/10.3390/app10051558
32. León Gómez, J. C., De León Aldaco, S. E., & Aguayo Alquicira, J. (2023). A review of hybrid renewable energy systems: Architectures, battery systems, and optimization techniques. *Engineering, 4*, 1446-1467. https://doi.org/10.3390/eng4020084
33. Liu, W., Li, N., Jiang, Z., Chen, Z., Wang, S., Han, J., et al. (2018). Smart micro-grid system with wind/PV/battery. *Energy Procedia, 152*, 1212-1217. https://doi.org/10.1016/j.egypro.2018.09.171
34. Liu, D., Zang, C., Zeng, P., Li, W., Wang, X., Liu, Y., et al. (2023). Deep reinforcement learning for real-time economic energy management of microgrid system considering uncertainties. *Frontiers in Energy Research, 11*, 1163053. https://doi.org/10.3389/fenrg.2023.1163053
35. Mahela, O. P., Khan, B., & Pachauri, R. K. (2022). Development of vehicle-to-grid system to regulate the system parameters of microgrid. *Energy Engineering, 119*, 1261-1298. https://doi.org/10.32604/ee.2022.018913
36. Marín, L. G., Sumner, M., Muñoz Carpintero, D., Köbrich, D., Pholboon, S., Sáez, D., et al. (2019). Hierarchical energy management system for microgrid operation based on robust model predictive control. *Energies, 12*, 4453. https://doi.org/10.3390/en12234453
37. Moghaddam, S., Bigdeli, M., Moradlou, M., & Siano, P. (2019). Designing of stand-alone hybrid PV/wind/battery system using improved crow search algorithm considering reliability index. *International Journal of Energy and Environmental Engineering, 10*, 429-449. https://doi.org/10.1007/s40095-019-00319-y
38. Mohan, H. M., & Dash, S. K. (2023). Renewable energy based DC microgrid with hybrid energy management system supporting electric vehicle charging system. *Systems, 11*, 273. https://doi.org/10.3390/systems11060273
39. Monie, S. W., Gustafsson, M., Önnered, S., & Guruvita, K. (2025). Renewable and integrated energy system resilience: A review and generic resilience index. *Renewable and Sustainable Energy Reviews, 215*, 115554. https://doi.org/10.1016/j.rser.2025.115554
40. Moosavi, M., Olamaei, J., & Mohmmadnezhad Shourkaei, H. (2025). Optimizing microgrid performance: A multi-objective strategy for integrated energy management with hybrid sources and demand response. *Scientific Reports, 15*, 17827. https://doi.org/10.1038/s41598-025-00118-y

*Corresponding Author: David Chinonso Anih

41. Mou, M., Zhou, Y., Zheng, W., & Xie, Y. (2022). Integration and modeling of multi-energy network based on energy hub. *Complexity, 2022*, 2698226. https://doi.org/10.1155/2022/2698226
42. Mukelabai, M. D., Barbour, E. R., & Blanchard, R. E. (2024). Modeling and optimization of renewable hydrogen systems: A systematic methodological review and machine learning integration. *Energy AI, 18*, 100455. https://doi.org/10.1016/j.egyai.2024.100455
43. Nair, R., Sandelic, M., Sangwongwanich, A., Dragicevic, T., Costa Castelló, R., & Blaabjerg, F. (2021). Grid congestion mitigation and battery degradation minimisation using model predictive control in PV-based microgrid. *IEEE Transactions on Energy Conversion, 36*, 1500-1509. https://doi.org/10.1109/TEC.2020.3032534
44. Nkambule, M. S., Hasan, A. N., & Shongwe, T. (2025). A review of intelligent control strategies for energy management systems in microgrids. *Energy Conversion and Management: X, 28*, 101323. https://doi.org/10.1016/j.ecmx.2025.101323
45. Odou, O. D. T., Bhandari, R., & Adamou, R. (2020). Hybrid off-grid renewable power system for sustainable rural electrification in Benin. *Renewable Energy, 145*, 1266-1279. https://doi.org/10.1016/j.renene.2019.06.032
46. Ojo, K. E., Saha, A. K., & Srivastava, V. M. (2025). Review of advances in renewable energy based microgrid systems: Control strategies, emerging trends, and future possibilities. *Energies, 18*, 3704. https://doi.org/10.3390/en18143704
47. Olatomiwa, L., Mekhilef, S., Ismail, M. S., & Moghavvemi, M. (2016). Energy management strategies in hybrid renewable energy systems: A review. *Renewable and Sustainable Energy Reviews, 62*, 821-835. https://doi.org/10.1016/j.rser.2016.05.040
48. Qiu, R., Zhang, H., Wang, G., Liang, Y., & Yan, J. (2023). Green hydrogen-based energy storage service via power-to-gas technologies integrated with multi-energy microgrid. *Applied Energy, 350*, 121716. https://doi.org/10.1016/j.apenergy.2023.121716
49. Said, T. R., Kichonge, B., & Kivevele, T. (2024). Optimal design and analysis of a grid connected hybrid renewable energy system using HOMER Pro: A case study of Tumbatu Island, Zanzibar. *Energy Science & Engineering, 12*, 2137-2163. https://doi.org/10.1002/ese3.1735
50. Saleh, A. M., Vokony, I., Waseem, M., Khan, M. A., & Al Areqi, A. (2025). Power system stability with high integration of RESs and EVs: Benefits, challenges, tools, and solutions. *Energy Reports, 13*, 2637-2663. https://doi.org/10.1016/j.egyr.2025.02.001
51. Sawle, Y. (2025). Assessing the economic and technical feasibility of off-grid renewable hybrid energy systems through optimization. *Frontiers in Energy Research, 13*, 1504972. https://doi.org/10.3389/fenrg.2025.1504972
52. Saxena, S., Farag, H. E. Z., & El Taweel, N. (2021). A distributed communication framework for smart grid control applications based on data distribution service. *Electric Power Systems Research, 201*, 107547. https://doi.org/10.1016/j.epsr.2021.107547
53. Shahzad, E., Khan, A. U., Iqbal, M., Saeed, A., Hafeez, G., Waseem, A., et al. (2022). Sensor fault tolerant control of microgrid using robust sliding mode observer. *Sensors, 22*, 2524. https://doi.org/10.3390/s22072524
54. Shao, Z., Cao, X., Zhai, Q., & Guan, X. (2023). Risk-constrained planning of rural area hydrogen-based microgrid considering multiscale and multi-energy storage systems. *Applied Energy, 334*, 120682. https://doi.org/10.1016/j.apenergy.2023.120682
55. Spiliopoulos, N., Sarantakos, I., Nikkhah, S., Gkizas, G., Giaouris, D., Taylor, P., et al. (2022). Peer-to-peer energy trading for improving economic and resilient operation of microgrids. *Renewable Energy, 199*, 517-535. https://doi.org/10.1016/j.renene.2022.08.061
56. Thang, V. V., Ha, T., Li, Q., & Zhang, Y. (2022). Stochastic optimization in multi-energy hub system operation considering solar energy resource and demand response. *International Journal of Electrical Power & Energy Systems, 141*, 108132. https://doi.org/10.1016/j.ijepes.2022.108132
57. Thirunavukkarasu, M., Sawle, Y., & Lala, H. (2023). A comprehensive review on optimization of hybrid renewable energy systems using various optimization techniques. *Renewable and Sustainable Energy Reviews, 176*, 113192. https://doi.org/10.1016/j.rser.2023.113192
58. Ukoba, K., Olatunji, K. O., Adeoye, E., Jen, T. C., & Madyira, D. M. (2024). Optimizing renewable energy systems through artificial intelligence: Review and future prospects. *Energy & Environment, 35*, 3833-3879. https://doi.org/10.1177/0958305X241256293
59. Venkatesan, R., Kumar, C., Balamurugan, C. R., & Senjyu, T. (2024). Enhancing power quality in grid-connected hybrid renewable energy systems using UPQC and optimized O-FOPID. *Frontiers in Energy Research, 12*, 1425412. https://doi.org/10.3389/fenrg.2024.1425412
60. Vivas Fernández, F. J., de las Heras, A., Segura, F., & Andújar, J. M. (2018). A review of energy management strategies for renewable hybrid energy systems with hydrogen backup. *Renewable and Sustainable Energy Reviews, 82*, 126-155. https://doi.org/10.1016/j.rser.2017.09.014
61. Wu, P., & Mei, X. (2024). Micrograds energy management considering net zero energy concept: The role of renewable energy landscaping design

*Corresponding Author: David Chinonso Anih

and IoT modeling in digital twin realistic simulator. *Sustainable Energy Technologies and Assessments, 63*, 103621. https://doi.org/10.1016/j.seta.2024.103621

62. Zebra, E. I. C., van der Windt, H. J., Nhumaio, G., & Faaij, A. P. C. (2021). A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. *Renewable and Sustainable Energy Reviews, 144*, 111036. https://doi.org/10.1016/j.rser.2021.111036
63. Zhang, J., & Wei, H. (2022). A review on configuration optimization of hybrid energy system based on renewable energy. *Frontiers in Energy Research, 10*, 977925. https://doi.org/10.3389/fenrg.2022.977925
64. Zhang, T. (2022). Robust optimization of micro-grid of natural gas and renewable energies considering operational performances and flexibility. *Frontiers in Energy Research, 9*, 814356. https://doi.org/10.3389/fenrg.2021.814356
65. Zhang, N., Yang, N. C., & Liu, J. H. (2021). Optimal sizing of PV/wind/battery hybrid microgrids considering lifetime of battery banks. *Energies, 14*, 6655. https://doi.org/10.3390/en14206655
66. Zhao, A. P., Li, S., Xie, D., Wang, Y., Li, Z., Hu, P. J. H., et al. (2025). Hydrogen as the nexus of future sustainable transport and energy systems. *Nature Reviews Electrical Engineering, 2*, 447-466. https://doi.org/10.1038/s44287-025-00178-2
67. Zhu, H., Ouahada, K., & Abu Mahfouz, A. M. (2022). Peer-to-peer energy trading in smart energy communities: A Lyapunov-based energy control and trading system. *IEEE Access, 10*, 42916-42932. https://doi.org/10.1109/ACCESS.2022.3167828

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