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REVIEW

Advancements and Optimization Strategies for Hybrid Photovoltaic–Diesel–Battery Systems in Remote and Off-Grid Applications: A Narrative Review

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ABSTRACT: Hybrid photovoltaic (PV)–diesel–battery systems are an important option for remote and off-grid electrification, where diesel generation remains common despite high fuel costs, emissions, and logistical constraints. This structured narrative review synthesizes developments in system architecture, DC–DC converter topology, energy management, communication, and techno-economic optimization. The reviewed evidence indicates that integrating PV generation and battery storage can reduce diesel operation, improve autonomy, and lower lifecycle costs when components and dispatch strategies are matched to local conditions. In one representative study, total modeled pollutant emissions decreased from 15,922 kg/year for a diesel-only system to 606.9 kg/year for a PV–diesel–battery system, a reduction of approximately 96%. Remaining barriers include capital cost, battery degradation, application-layer interoperability, cybersecurity, and limited field validation of advanced artificial-intelligence-based control. The synthesis also shows that published cost of energy, net present cost, and renewable-fraction values should not be compared without accounting for location, load, fuel price, component cost, discount rate, and reliability assumptions.

KEYWORDS: DC–DC converter topology; energy management system (EMS); hybrid photovoltaic–diesel–battery system; off-grid microgrid; techno-economic optimization

1 Introduction

Reliable and sustainable electricity access remains a persistent challenge in remote and off-grid regions. Many developing communities lack adequate grid infrastructure and therefore depend on diesel generators. Although diesel generation is dispatchable, it is associated with high operating costs, inefficient part-load operation, greenhouse-gas emissions, and difficult fuel logistics [1–3]. Hybrid energy systems that combine solar photovoltaic (PV) generation, diesel backup, and battery energy storage systems (BESSs) offer a practical alternative [4,5].

A PV–diesel–battery system coordinates three complementary technologies. During periods of sufficient irradiance, PV modules supply the load and charge the battery bank. When PV production is insufficient, the battery supports the load until a specified state-of-charge limit is reached. The diesel generator is then dispatched to meet the remaining demand and, when required, recharge the battery [6]. Coordinated dispatch can reduce fuel use and operating cost while preserving supply reliability under resource and load variability [7].

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These systems are used in rural service centers, telecommunications sites, remote homes, healthcare facilities, and industrial microgrids [5,8–11]. Their principal advantages are lower lifecycle fuel use and emissions, greater operational flexibility, and improved resilience relative to diesel-only supply. Simulation and field studies across several regions report substantial reductions in diesel consumption and operating cost, although the magnitude depends strongly on the site, load profile, and component assumptions [12–15].

The optimal configuration is site-specific and depends on solar irradiation, load profile, fuel price, autonomy requirements, component availability, and reliability criteria. Tools such as HOMER, MATLAB/Simulink, and PVsyst are commonly used for sensitivity and techno-economic analyses [16,17]. Typical indicators include net present cost (NPC), levelized cost of energy (LCOE), renewable fraction (RF), loss-of-power-supply probability, and carbon-dioxide emissions. Dispatch methods ranging from deterministic scheduling to fuzzy logic, model-predictive control, and reinforcement learning can further improve energy allocation and battery utilization [18–20].

A major strength of hybrid systems is their adaptability to different climates and geographical settings. High-PV-penetration configurations are particularly attractive at solar-rich sites, whereas locations with greater seasonal or daily variability require more conservative storage and diesel-backup strategies [21–23].

Energy storage also supports demand-side management through peak shaving and load shifting, which can reduce generator cycling and avoid oversizing in systems with variable demand [24].

Despite these benefits, implementation and long-term sustainability remain challenging. PV modules, inverters, battery banks, controls, and installation increase initial capital cost relative to a diesel-only system, although lifecycle economics may be more favorable when avoided fuel and maintenance are considered [1,6,8,16,25]. Battery degradation and replacement are particularly important where high-quality storage technologies and maintenance services are difficult to obtain [26,27]. Dust, humidity, and elevated temperature can also reduce PV and battery performance, requiring appropriate sizing, ventilation, and protective enclosures [28,29].

Cybersecurity and control interoperability have become increasingly important as monitoring and control functions move to networked and cloud-connected platforms. Although the underlying communication protocols may be standardized, manufacturer-specific data models can create integration risks [30], while weak authentication and insecure remote access can introduce cybersecurity risks [31,32]. Digital twins and continuous monitoring can support fault detection, predictive maintenance, and performance optimization, but they may also expand the system's cyber-physical attack surface [31,32].

Public policy and development finance can accelerate deployment, particularly in low-income settings. Relevant measures include equipment subsidies, tax incentives, and concessional finance [33,34]. Capacity building is essential because long-term performance depends on competent operation, preventive maintenance, and timely component replacement [35,36].

Earlier reviews often treated PV design, diesel-generator operation, batteries, converter control, and communication as separate topics. An updated integrated synthesis is therefore useful for understanding developments from 2015 onward and for identifying remaining deployment gaps. Recent in-scope studies illustrate both progress and contextual variation: a Northern West Bank PV–diesel–battery case reported an LCOE of US$0.285/kWh and an RF of 88.6% [37], while a 2026 rural Ethiopian case reported an RF of 84% and an energy cost of 4.468 Birr/kWh [38]. These values are reported in their original study currencies and cannot be ranked without normalization. This review therefore emphasizes architecture, control, communication, techno-economic context, and evidence gaps rather than a single universal performance benchmark.

Table 1 compares annual pollutant emissions reported for three off-grid configurations: PV–diesel–battery, PV–wind–diesel–battery, and diesel-only. The modeled diesel-only system produced 15,922 kg/year of total pollutants, whereas the two hybrid configurations produced 606.9 and 597.7 kg/year, respectively [2]. These values are specific to the assumptions of the cited study and should not be generalized without considering load, resource, and dispatch conditions.

Table 1: Annual pollutant emissions for three off-grid system configurations [2].

Emissions (kg/year)	System Configuration		
	PV/Diesel/Battery	PV/Wind/Diesel/Battery	Diesel Only
Carbon dioxide	591	582	15,505
Carbon monoxide	1.46	1.44	38.3
Unburned hydrocarbons	0.162	0.159	4.24
Particulate matter	0.11	0.108	2.89
Sulfur dioxide	1.19	1.17	31.1
Nitrogen oxides	13	12.8	341
Total	606.9	597.7	15,922

2 Review Scope and Narrative Method

This article is a structured narrative review rather than a systematic review or meta-analysis. Its purpose is to integrate engineering evidence across system architecture, power conversion, energy management, communication, techno-economic assessment, and field deployment. Accordingly, the review does not claim exhaustive retrieval, duplicate screening, or a formal risk-of-bias assessment, and a PRISMA flow diagram is not applicable.

The existing reference set was screened for direct thematic relevance to stationary hybrid PV–diesel–battery systems, off-grid microgrids, energy-management control, converter design, battery integration, techno-economic assessment, or cybersecurity of inverter-based distributed energy resources. Publications on passenger-vehicle combustion, thermoelectric air conditioning, agricultural logistics, unrelated building-retrofit models, and unrelated motor or biomedical applications were excluded and replaced with directly relevant sources.

The synthesis emphasizes peer-reviewed studies published from 2015 onward, supplemented by recent applied studies through 2026 where they clarify current performance or research gaps. Study selection was interpretive: primary case studies were retained when they reported system configuration, control architecture, or techno-economic metrics, while review articles were used to frame control, storage, interoperability, and cybersecurity themes. Numerical values are reported in their original units and are treated as context-specific rather than pooled estimates.

3 Literature Synthesis

Hybrid-system performance depends on coordinated advances in power electronics, embedded control, and communication. This section synthesizes the principal developments in circuit architecture, converter topology, subsystem communication, and energy-management control. The discussion distinguishes component-level functions from system-level evidence and avoids treating reported case-study metrics as directly comparable.

Fig. 1 organizes the reviewed technologies into converter classes (buck, boost, buck–boost, bidirectional, and multiphase), control methods (PID, fuzzy logic, model predictive control, and AI-assisted methods), and communication protocols (Modbus, CAN, and MQTT). These elements support voltage regulation, state-of-charge monitoring, source coordination, and real-time diagnostics [4,14,16,24,39,40].

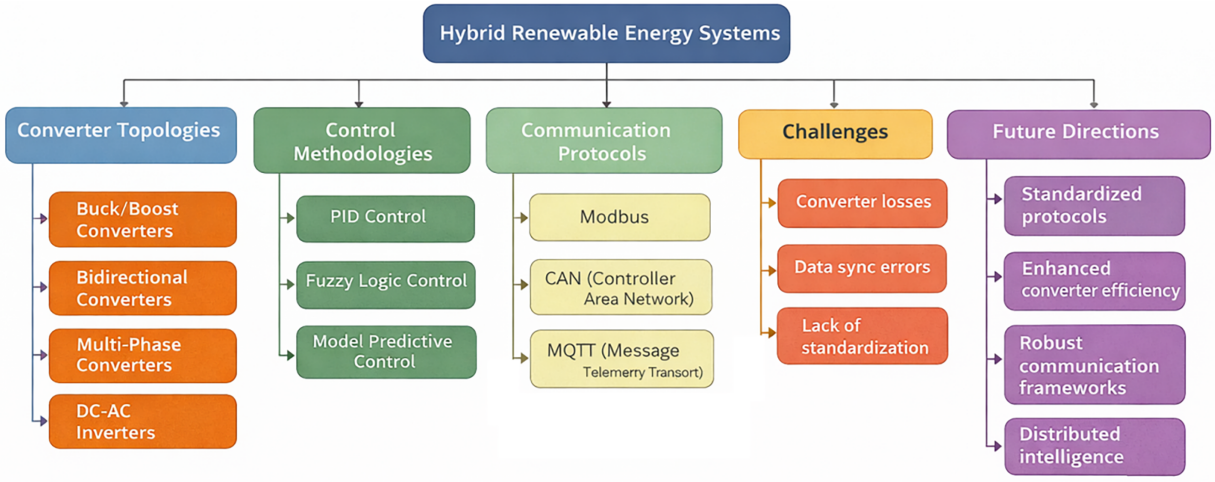


Figure 1: Taxonomy of converter topologies, communication protocols, and control strategies synthesized from representative studies [4,14,16,24,40,41].

Control may be centralized, distributed, or hierarchical and may be implemented on embedded controllers, programmable logic controllers, or supervisory platforms. As system scale and renewable penetration increase, low-latency communication, fault tolerance, and well-defined data models become more important.

The taxonomy also highlights recurring limitations, including converter losses, thermal stress, data-synchronization errors, vendor-specific payload definitions, and limited field validation. The literature is therefore grouped into converter and circuit design, communication and interoperability, energy-management control, battery integration, and environmental robustness.

Table 2 summarizes representative techno-economic case studies that include PV–diesel–battery configurations, together with one closely related PV/battery case benchmarked against diesel-only supply. Values are reproduced in the units and currencies reported by the original sources.

A graphical comparison of the reported LCOE values is presented in Fig. 2.

3.1 Electrical Circuit Design and DC–DC Converter Topologies

Electrical architecture determines the stability, efficiency, and scalability of a hybrid PV–diesel–battery system. Contemporary designs emphasize modular power-conversion stages, coordinated protection, and control structures capable of responding to changes in irradiance, load, and battery state of charge.

Embedded control platforms: Microcontrollers and single-board computers can acquire sensor data, execute maximum-power-point-tracking (MPPT) and dispatch logic, drive relays or gate signals, and communicate with supervisory systems. Platform selection should be based on sampling requirements, electromagnetic compatibility, computational demand, environmental rating, and maintainability rather than cost alone [30].

Table 2: Reported techno-economic performance of representative PV–diesel–battery case studies and one PV/battery benchmark. "n/r" indicates not reported.

Case Study (Location)	System Configuration	Reported Energy Cost	Reported NPC	Renewable Fraction	Source
Northern West Bank, Palestine	PV/diesel/battery	US$0.285/kWh	n/r	88.6%	[37]
Jawi, Ethiopia (rural village)	PV/diesel/battery	4.468 Birr/kWh	7,284,233 Birr	84%	[38]
Nigeria (residential building)	Standalone PV/diesel/battery	US$0.412/kWh	US$24,197.46	74.4%	[42]
West Arsi, Oromia, Ethiopia (telecom site)	PV/battery (optimal; diesel-only benchmark)	US$0.355/kWh	US$57,508	n/r	[12]

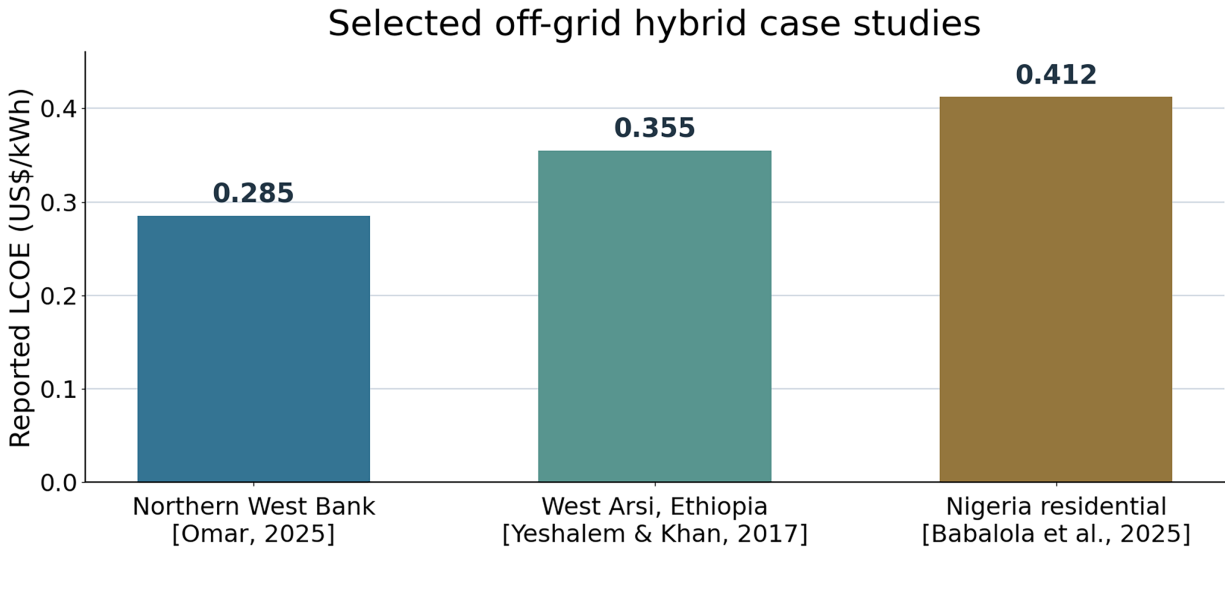


Figure 2: Reported LCOE for selected off-grid hybrid cases expressed in US dollars per kilowatt-hour [12,37,42]. Values are source-specific and are not normalized for location, load, fuel price, discount rate, component cost, or reliability assumptions.

Converter architecture: Buck, boost, buck–boost, and bidirectional converters provide the voltage adaptation required between the PV array, battery bank, DC bus, and inverter. Bidirectional conversion is particularly important for controlled battery charging and discharging, while coordinated DC–DC and DC–AC stages maintain bus voltage and AC-side power quality [4,19,24,40,43].

Sensing and protection: Hall-effect current sensors, voltage dividers, temperature sensors, fuses, contactors, and isolated interfaces support measurement and fault protection. Protection design should address overcurrent, overvoltage, reverse polarity, thermal stress, ground faults, and safe isolation between power and control circuits [30,43].

Component sizing and layout: Inductor and capacitor values, switching frequency, thermal management, semiconductor ratings, and printed-circuit-board layout affect ripple, efficiency, electromagnetic interference, and service life. Simulation is useful for initial sizing, but hardware-in-the-loop and field testing are needed to capture parasitic and thermal effects [44].

The principal design approaches can be summarized as follows:

- Microcontroller-based control is configurable and comparatively inexpensive, but it requires appropriate programming, calibration, protection, and validation.
- DC–DC converters provide voltage adaptation and battery-power control, but their switching devices, magnetics, and thermal design must be selected for the full operating envelope.
- Pulse-width-modulated inverter stages provide regulated AC output, but poor modulation or filter design can increase harmonic distortion and device stress.
- Additional sensing and protection improve reliability but increase component count, cost, and commissioning complexity.

DC–DC converters regulate energy transfer among PV arrays, batteries, and DC loads while maintaining a stable DC bus. Their importance increases when multiple sources with different voltage ranges and dynamic characteristics must operate on a common bus.

The main converter functions in hybrid systems are step-down conversion, step-up conversion, bidirectional battery interfacing, and regulated DC-bus support:

- Buck converters reduce a higher source voltage to the level required by a battery or DC load [4,24].
- Boost converters raise a lower PV voltage to the DC-bus or load voltage [4,24,40].
- Buck–boost converters provide step-up and step-down operation when source and bus voltages overlap across the operating range [24].
- Bidirectional DC–DC converters allow controlled power flow to and from the battery, supporting charging, discharge, peak support, and DC-bus regulation [4,40].

Converter performance depends on the modulation and control method, including pulse-width modulation, MPPT, current or voltage loops, and supervisory energy-management commands:

- Perturb-and-observe MPPT is widely used because of its simple implementation, although its tracking performance can degrade during rapid irradiance changes [17].
- Fuzzy and hybrid fuzzy–PID controllers can improve voltage regulation and source coordination under nonlinear or uncertain operating conditions [20].
- Digital controllers based on DSP, ARM, or industrial platforms enable higher sampling rates, real-time monitoring, and adaptive compensation, but require verified timing and fail-safe behavior [30,45].

At the system level, converters support efficient energy transfer, voltage stability, and power quality. In stand-alone systems, they match PV and battery operating voltages to the DC bus; in AC-coupled or grid-connected systems, the inverter stage also regulates synchronization and AC output.

Multistage and interleaved converter structures can reduce ripple and distribute thermal stress, while soft-switching methods can reduce switching loss and electromagnetic interference [30,40]. Table 3 summarizes the principal converter roles and trade-offs.

Representative findings from hybrid-system studies include the following:

- MPPT-controlled conversion improves utilization of available PV power and coordinates battery charging in residential and remote hybrid systems [8,25].
- Bidirectional conversion supports controlled charge and discharge and can reduce generator cycling when integrated with an appropriate dispatch strategy [4,40,46].

- Interleaved and optimized converter structures can reduce input-current ripple and switching stress, but their added components and control complexity must be justified by the application [30,40].

Overall, converter development is moving toward compact, efficient, digitally controlled, and fault-aware interfaces. Field validation remains essential because simulated efficiency and stability may not capture thermal, parasitic, and environmental effects.

Table 3: Functional comparison of common DC–DC converter types.

Converter Type	Primary Role	Advantages	Limitations
Buck	Step-down conversion	Simple; low cost; high efficiency	Cannot provide step-up conversion
Boost	Step-up conversion	Raises low PV voltage to DC-bus level	Higher switch and diode voltage stress
Buck–boost	Step-up or step-down conversion	Useful across overlapping voltage ranges	More complex control; possible polarity inversion
Bidirectional	Two-way battery power flow	Supports controlled charging and discharging	Requires coordinated current, voltage, and protection control

3.2 Communication between Subsystems

Reliable communication enables coordinated operation among PV arrays, batteries, diesel generators, converters, sensors, and load controllers. Even a well-designed converter cannot provide adaptive dispatch, remote monitoring, or coordinated fault response without timely and trustworthy data exchange.

A typical communication architecture contains four functional layers:

- Device layer: Sensors and actuators acquire electrical, thermal, and equipment-status data.
- Controller layer: Local controllers process measurements and execute protection and control logic.
- Network layer: Serial, CAN, Ethernet, or wireless links connect local devices to supervisory controllers or gateways.
- Application layer: Supervisory control, data acquisition, battery-management, and energy-management interfaces provide visualization, alarms, analytics, and remote commands.

Common protocols and interfaces include the following:

- Modbus RTU and Modbus TCP/IP are widely used to connect meters, inverters, programmable controllers, and supervisory software over serial and Ethernet networks [30,32].
- MQTT is a lightweight publish/subscribe protocol suited to bandwidth-constrained telemetry and cloud-connected monitoring, provided that authentication and encryption are configured appropriately [31,32].
- Zigbee and other low-power wireless sensor networks can support short-range sensing, but coverage, interference, latency, and security must be evaluated for the deployment [30,31].
- CAN, I2C, and SPI are commonly used within tightly integrated controller and battery-management hardware; CAN is preferable when robust multi-node communication and error detection are required.

Interoperability is constrained less by the availability of standardized protocols and interfaces than by differences in vendor-specific registers, data types, naming conventions, units, update rates, and application-layer payloads. Gateways therefore require explicit data mapping, time synchronization, error handling, and version control [30,32].

- Long links and electrically noisy environments may introduce signal degradation, ground potential differences, packet loss, and timing errors. Shielded cabling, isolation, proper termination, and monitored communication quality reduce these risks.
- Wireless links add variability and should be designed with adequate signal margin, retry logic, local fallback control, and fail-safe behavior.

Networked monitoring and remote control also create cybersecurity risks. Systems should apply defense-in-depth measures appropriate to their criticality [31,32].

- Access control should use unique credentials, least privilege, secure remote access, and audit logs.
- Data integrity and availability should be protected through authenticated encryption, backups, validation, and resilient local control.
- Device trust should be supported by signed firmware, controlled updates, asset inventory, and monitoring for unauthorized devices.

Practical communication design should therefore prioritize:

- local autonomous control for safety-critical functions, with remote platforms used for supervision and optimization rather than as a single point of failure;
- documented data models, synchronized time stamps, communication-health monitoring, and cybersecurity controls matched to the operational risk. Table 4 compares common protocol families.

Table 4: Comparison of communication protocols and interfaces used in hybrid microgrids.

Protocol/Interface	Type	Strengths	Limitations
Modbus RTU/TCP	Serial/Ethernet application protocol	Widely supported; simple integration	Limited semantics and native security
MQTT	Publish/subscribe messaging	Lightweight; suitable for telemetry	Requires a broker and secure configuration
Zigbee	Low-power wireless mesh	Low energy use; mesh capability	Range, interference, and security constraints
CAN bus	Robust serial field bus	Error detection; deterministic arbitration	Limited payload and network length
Wi-Fi/Ethernet gateway	IP network access	High throughput; easy supervisory integration	Power use, coverage, and cyber exposure

3.3 Optimization and Control Strategies

Energy-management and control strategies balance generation, storage, and demand while maintaining technical constraints. Their objectives commonly include minimizing fuel and operating costs, preserving battery state of charge, limiting emissions, and maintaining voltage and frequency.

The reviewed strategies range from deterministic rules to predictive and learning-based control:

- Rule-based control uses state-of-charge thresholds, hysteresis, and ON/OFF logic. It is transparent and inexpensive but may be suboptimal when forecasts, fuel costs, or component degradation vary [4].
- Proportional–integral–derivative (PID) control is widely used for converter current and voltage loops. Adaptive or gain-scheduled tuning can improve performance across changing operating points [30].
- Fuzzy-logic control is useful for nonlinear systems and uncertain PV output or load demand; published studies report improved source coordination and smoother battery operation [16,20].
- Model-predictive control uses a system model and forecasts to optimize future control moves subject to constraints. Its performance depends on model quality, forecast accuracy, and available computation [47].
- Machine-learning models can support load and generation forecasting, fault detection, and dispatch. Their use in field-deployed, low-power controllers remains less mature than simulation-based demonstrations. Reference [48], by contrast, presents an FPGA-accelerated, AI-integrated multi-time-domain simulation framework for power systems with high penetration of power converters; it addresses simulation acceleration and fidelity rather than forecasting or seasonal scheduling. Optimization algorithms are often combined with these control structures to size components or schedule energy flow.
- Genetic algorithms are used for component sizing and multi-objective dispatch in nonconvex design spaces [49].
- Particle-swarm optimization is widely applied to cost, reliability, and emission objectives, although convergence and repeatability should be reported [49].
- Artificial-bee-colony, grey-wolf, salp-swarm, and related metaheuristics have been used for multi-objective sizing and dispatch; comparative studies should report parameter settings, multiple runs, and benchmark methods [41,49–51].

A real-time energy-management system (EMS) integrates measurement, forecasting, dispatch, and local control. Core functions include:

- load prioritization and controlled shedding;
- diesel-generator scheduling and minimum-runtime management;
- battery charge/discharge control with state-of-charge and degradation constraints; and
- grid-exchange control where a grid connection is available.

Representative studies demonstrate several control directions:

- fuzzy and hybrid controllers can coordinate PV, battery, and diesel resources while maintaining voltage and state-of-charge limits [20];
- predictive scheduling can reduce unnecessary generator operation when adequate load and irradiance forecasts are available [16,47]; and
- forecast-informed and predictive scheduling may reduce unnecessary generator operation, but the reported benefits depend on data quality and require independent field validation [16,47].

Important implementation considerations are:

- Computational burden: Advanced MPC and AI methods may exceed the resources of inexpensive controllers or violate real-time deadlines.
- Data quality: Missing, delayed, biased, or poorly synchronized measurements can degrade forecasting and optimization.
- Hardware–software co-design: Firmware, sensing, actuation, protection, and communication must be validated together rather than as independent modules.

- Scalability and fallback: Control should accommodate added PV or storage capacity and retain safe local operation during communication or supervisory-computing failures.

4 Challenges and Limitations

Hybrid PV–diesel–battery systems offer technical and environmental benefits, but their feasibility depends on resolving economic, maintenance, interoperability, environmental, and institutional constraints.

1. Initial capital cost: PV modules, batteries, inverters, controls, engineering, installation, and training increase upfront cost relative to diesel-only supply [1,6,8,16,25]. Remote logistics can add materially to project cost [33]. A PV–diesel–battery study for Yanbu, Saudi Arabia, used local insolation and climate data to optimize a site-specific configuration, underscoring the site dependence of reported results [29]. Lifecycle rather than capital cost alone should therefore guide comparison.
2. Design and maintenance complexity: Multiple sources require coordinated dispatch, protection, battery management, and synchronization [3–5,9,19–21,23,24,52]. In areas with limited technical capacity, spare parts, diagnostic tools, and trained personnel may be as important as the nominal component specification.
3. Interoperability and data exchange: Controllers, inverters, meters, battery-management systems, and supervisory platforms may use different registers and application-layer data models [30,32]. Poorly specified mappings can cause unit errors, stale data, and unreliable dispatch even when the communication protocol is standardized.
4. Environmental variability: Solar and wind resources vary over time and by location [53–55]. Diesel backup improves adequacy but can undermine emission and fuel-saving targets if dispatch thresholds, minimum loading, and maintenance are poorly managed [12,56,57].
5. Emissions and sustainability: Hybrid configurations retain direct emissions whenever the diesel generator operates. In the study summarized in Table 1, total modeled pollutant emissions were 15,922 kg/year for diesel-only supply and 606.9 and 597.7 kg/year for two hybrid alternatives [2]. These figures demonstrate potential rather than a universal emission factor.
6. Battery performance and end of life: Storage is essential to reducing diesel cycling, but battery chemistry, depth of discharge, temperature, charge rate, and maintenance affect efficiency and service life. Comparative studies also show that battery choice changes NPC, reliability, and environmental performance [26,27]. Procurement and design should include replacement, recycling, and safe disposal.
7. Policy and regulation: Unclear regulatory frameworks, inconsistent incentives, market-access constraints, and limited access to finance can delay projects, particularly in developing regions [33,34].
8. User acceptance and local capacity: Operators and users need clear operating procedures, realistic expectations, and maintenance support. Capacity building, spare-parts planning, and meaningful community participation should be incorporated into deployment rather than added after commissioning [34–36].

Table 5 condenses the evidence to a selective set of analytically significant studies on system modeling, converter control, energy management, and techno-economic performance. The shorter table avoids repeating background studies that do not materially strengthen the cross-study synthesis.

Across the selected studies, the principal integration challenge is coordination among subsystems that operate at different voltage levels and use different control and communication interfaces. Hierarchical control, explicit data models, and monitored communication quality are recurring requirements.

Table 5: Selective summary of representative studies on hybrid-system modeling, converter control, and techno-economic performance.

Ref.	Method	System/Components	Setting	Principal Contribution	Main Limitation or Transferability Issue
[1]	Dynamic simulation and techno-economic assessment	PV, diesel generator, battery	Karagöl area, Kahramanmaraş, Türkiye	Quantifies coordinated source operation and diesel reduction	Results depend on load and solar-resource assumptions; battery replacement remains material
[2]	HOMER optimization using COE, NPC, and emissions	PV, wind, diesel generator, batteries, converter	Doka-Sharia, Kaduna State, Nigeria	Provides the pollutant comparison reproduced in Table 1	Site-specific resource, fuel-price, and component-cost assumptions limit direct transfer
[4]	Simulation and experimental validation of a control strategy	PV, diesel generator, battery, bidirectional converters	Stand-alone microgrid	Coordinates converter operating modes and DC-bus control	Validation scale is limited; broader field operation was not demonstrated
[8]	Techno-economic optimization	PV, diesel generator, inverter, battery bank	Ndiagu-Akpugo, Enugu State, Nigeria	Evaluates cost and emission benefits of hybridization	Performance is sensitive to solar availability, battery cost, and replacement assumptions
[12]	HOMER techno-economic simulation	PV/battery and PV/wind/battery; diesel-only benchmark	Remote telecom site in West Arsi, Oromia, Ethiopia	Reports NPC and COE for the optimal PV/battery configuration	Resource and load-data uncertainty affects sizing and transferability
[14]	Two-level energy-management simulation	PV, diesel generator, battery	Islanded microgrid	Demonstrates coordinated power management and voltage/frequency support	Field-scale aging, communication failures, and maintenance were not evaluated
[15]	Comparative configuration and cost assessment	PV/diesel, PV/battery, and PV/diesel/battery alternatives	Gwakwani, Limpopo, South Africa	Compares off-grid alternatives for rural electrification	Conclusions are sensitive to local load growth and component assumptions
[16]	Predictive scheduling using Kalman filtering and ARMA forecasting	PV, diesel generator, battery	Stand-alone microgrid	Uses forecasts to schedule diesel and battery operation	Forecast error and model calibration can reduce real-time performance

The literature also shows a shift from isolated simulation prototypes toward integrated, communication-aware systems. Nevertheless, field evidence remains limited for fault-tolerant converter control, embedded AI, cybersecurity, and long-duration operation under harsh environmental conditions.

5 Research Gaps

The principal research gaps concern the transition from simulation to dependable field operation. Converter and control studies often simplify nonlinear loads, thermal behavior, parasitic losses, communication failures, and component aging. Application-layer interoperability remains inconsistent despite the availability of standardized protocols such as Modbus TCP/IP and MQTT. AI and machine learning are promising for forecasting and fault detection, while FPGA-accelerated simulation can improve the tractability of multi-time-domain power-system models [48]. Evidence from low-power embedded implementations and extended field trials is limited. Greater connectivity also creates a need for secure-by-design architectures,

including authenticated communication, intrusion monitoring, secure updates, and resilient local fallback control [31,32,58].

Fig. 3 presents these gaps as a data-flow problem extending from sensing and communication to decision making and actuation. The most important gaps identified in the reviewed literature are:

1. Circuit design under realistic conditions: More studies are needed on nonlinear loads, thermal limits, parasitic effects, aging, and adaptive protection during long-duration field operation.
2. Communication semantics and compatibility: Vendor-specific registers, units, update rates, and payload structures impede integration even when standard protocols are used.
3. Converter-control validation: FPGA acceleration can make detailed multi-time-domain simulation more tractable [48], but simulation-based results should still be complemented with controller- and power-hardware-in-the-loop testing under site-specific load and DER operating profiles to expose implementation limits before field deployment [44].
4. Embedded AI and machine learning: Forecasting and fault-detection models require validation on resource-constrained hardware, with attention to latency, generalization, explainability, and safe fall-back behavior.
5. Cybersecurity and data integrity: End-to-end security architectures, realistic attack testing, secure update processes, and resilience metrics remain insufficiently represented in hybrid off-grid demonstrations [31,32].

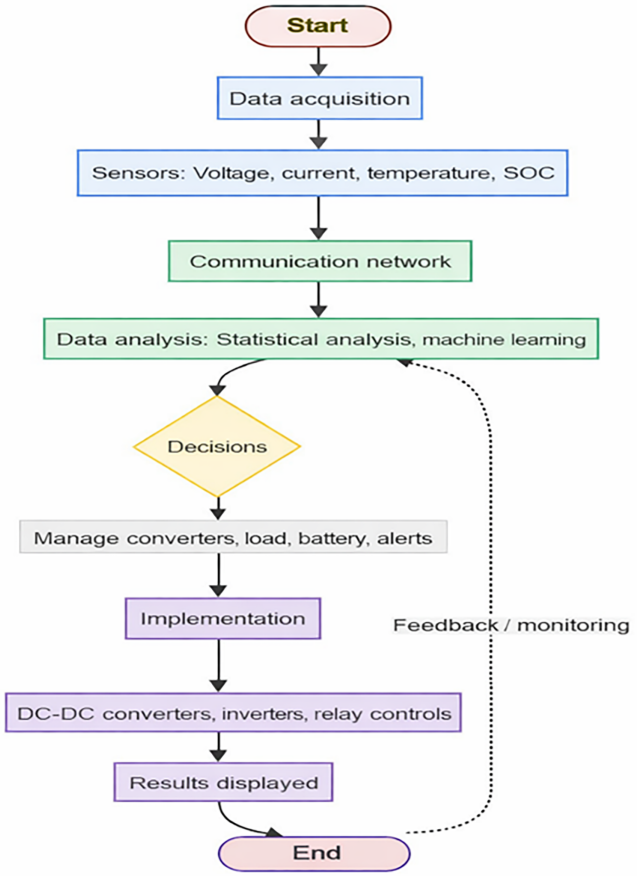


Figure 3: Author-developed conceptual gap map linking sensing, communication, decision making, and actuation in intelligent hybrid systems [31,32,48].

6 Synthesis and Discussion

The literature indicates that hybrid-system performance is determined by interactions among component sizing, converter design, dispatch control, communication, and local operating conditions. Advances in DC–DC conversion and embedded control improve voltage regulation and source coordination, while EMS platforms can reduce diesel operation by using forecasts and battery flexibility. These benefits are conditional: nonlinear loads, battery aging, vendor-specific data models, harsh environments, capital constraints, and cybersecurity can limit real-world performance.

Three qualitative themes recur across the reviewed evidence; percentages are not reported because the article does not use a systematic classification protocol.

Key synthesis findings:

- Control and optimization: Rule-based, fuzzy, predictive, and metaheuristic approaches can improve dispatch and component sizing, but comparative results depend on forecasts, objective functions, constraints, and assumed component models [16,18,20,41,47,49,51,59].
- Monitoring and communication: Modbus, CAN, MQTT, and wireless sensor networks enable remote monitoring and coordinated control. Their practical value depends on data-model consistency, time synchronization, communication health, and secure configuration [30–32].
- Simulation and AI-assisted control: HOMER, MATLAB/Simulink, PVsyst, and related tools support design and sensitivity analysis. AI-assisted forecasting and control are promising, but field validation, reproducibility, and embedded implementation remain limited [47,48]. Reference [48] instead contributes an FPGA-accelerated simulation framework for power-electronics-rich systems.

Cross-cutting limitations:

- Nonlinear and time-varying loads are not consistently represented in design and control studies.
- Converter efficiency, thermal stress, and switching loss are often modeled more simply than they occur in the field.
- Vendor-specific data definitions can delay integration and introduce silent control errors.
- Advanced controls, communication hardware, and maintenance capacity can be difficult to finance in low-resource settings.
- Remote connectivity increases exposure to credential theft, data manipulation, and denial-of-service events.

Research and design priorities:

- develop reconfigurable converter and protection designs validated under thermal and fault conditions;
- adopt documented, version-controlled data models and interoperable application-layer mappings;
- evaluate lightweight AI models on embedded hardware with defined latency and fallback requirements;
- conduct long-duration field trials across different climates, loads, and maintenance contexts; and
- embed security controls—including encryption, authenticated access, intrusion monitoring, and secure updates—within the system architecture from the design stage.

Overall interpretation:

Progress in hybrid PV–diesel–battery systems depends on interdisciplinary integration of power electronics, control, communications, cybersecurity, and lifecycle economics. Future systems should be efficient, resilient, maintainable, affordable, and secure for remote and off-grid deployment.

7 Conclusions

This structured narrative review shows that hybrid PV–diesel–battery systems can improve off-grid reliability and reduce diesel use and emissions when component sizes and dispatch strategies are matched to local resources and demand. Power-electronic interfaces and EMS algorithms are central to these benefits, but simulated gains do not automatically translate to field performance.

Communication protocols enable monitoring and coordinated control, yet interoperability problems frequently arise from vendor-specific application-layer data definitions rather than from protocol standards themselves. Secure configuration, resilient local control, and communication-health monitoring should therefore be treated as engineering requirements.

AI-assisted forecasting, fault detection, and optimization offer useful research directions, but the evidence base is dominated by simulation. More embedded implementations, hardware-in-the-loop testing, and long-duration field trials are needed before broad claims of superiority can be made.

Simpler rule-based and microcontroller-based controls remain appropriate where transparency, cost, and maintainability are priorities. Advanced methods should be selected only when their incremental benefit justifies added calibration, computational, maintenance, and cybersecurity requirements.

Priority directions for future research are:

- resource-efficient adaptive control for embedded platforms;
- interoperable and version-controlled application-layer data models;
- field validation under diverse environmental, load, and maintenance conditions; and
- cybersecurity-by-design at both hardware and network levels.

An integrated design approach that combines lifecycle economics, validated power electronics, resilient control, secure communication, and local maintenance capacity is most likely to support scalable and sustainable off-grid electrification.

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