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From Renewable Energy Integration to Grid Resilience in Libya: A Critical Comparative Review of Grid-Forming Inverters, Energy Storage, and AI-Based Control

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Index Terms

Grid-Forming Inverters (GFM); Energy Storage Systems (ESS); Artificial Intelligence (AI); Renewable Energy Integration; Grid Resilience; Weak Grids; Low-Inertia Power Systems; Libyan Power System.

Abstract

The transition toward renewable-rich power systems is reshaping conventional approaches to grid stability, flexibility, and resilience, particularly as solar photovoltaic and wind generation increase the share of inverter-based resources. This study presents a systematic critical comparative review of three enabling technologies—Grid-Forming Inverters (GFM), Energy Storage Systems (ESS), and Artificial Intelligence (AI)-based control—and evaluates their potential contribution to renewable energy integration and grid resilience, with particular emphasis on the Libyan power system. The review integrates systematic evidence identification, thematic synthesis, critical evaluation, and comparative technological assessment to examine frequency stability, voltage support, virtual inertia, renewable smoothing, flexibility, black-start capability, weak-grid suitability, implementation complexity, data dependency, and cybersecurity. The comparative synthesis demonstrates that no single technology can independently address the multidimensional challenges of renewable-rich weak grids. GFM provides voltage- and frequency-forming capabilities and dynamic stability support; ESS supplies controllable energy, fast flexibility, reserves, and renewable smoothing; while AI enables forecasting, optimization, adaptive coordination, fault detection, and intelligent energy management. However, each technology also presents important limitations related to converter current constraints, storage degradation and cost, or AI explainability, data quality, and cybersecurity. The study therefore proposes a GFM–ESS–AI Integrated Resilience Framework for Libya, in which these technologies operate as complementary layers rather than competing alternatives. The review concludes that Libya's renewable transition should move beyond maximizing installed renewable capacity toward strengthening secure renewable hosting capability through staged integration of physical flexibility, grid-forming stability, and intelligent coordination. The proposed framework provides a foundation for future simulation, techno-economic assessment, experimental validation, and pilot-scale deployment.

من تكامل الطاقة المتجددة إلى مرونة الشبكة الكهربائية في ليبيا: مراجعة نقدية مقارنة للعاكسات المُشكِّلة للشبكة، وأنظمة تخزين الطاقة، والتحكم القائم على الذكاء الاصطناعي

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الكلمات المفتاحية

العاكسات المُشكِّلة للشبكة (GFM)؛ أنظمة تخزين الطاقة (ESS)؛ الذكاء الاصطناعي (AI)؛ تكامل الطاقة المتجددة؛ مرونة الشبكة الكهربائية؛

الملخص

تُعيد عملية التحول نحو أنظمة القدرة الكهربائية ذات الاعتماد المرتفع على مصادر الطاقة المتجددة تشكيل الأساليب التقليدية لتحقيق استقرار الشبكة ومرونتها وموثوقيتها، ولا سيما مع تزايد مساهمة الطاقة الشمسية الكهروضوئية وطاقة الرياح وارتفاع حصة الموارد القائمة على العاكسات. تقدم هذه الدراسة مراجعة منهجية نقدية مقارنة لثلاث تقنيات تمكينية رئيسة، هي: العاكسات المُشكِّلة للشبكة (**GFM**)، وأنظمة تخزين الطاقة

(**ESS**)، والتحكم القائم على الذكاء الاصطناعي (**AI**)، وتقيّم إسهامها المحتمل في تكامل الطاقة المتجددة وتعزيز مرونة الشبكة، مع التركيز بصورة خاصة على نظام القدرة الكهربائية الليبي. وتجمع المراجعة بين التحديد المنهجي للأدلة، والتركيب الموضوعي، والتقييم النقدي، والمقارنة التكنولوجية لتحليل استقرار التردد، ودعم الجهد، والقصور الذاتي الافتراضي، وتنعيم تقلبات الطاقة المتجددة، والمرونة التشغيلية، وقدرات البدء الأسود، والملاءمة للشبكات الضعيفة، وتعقيدات التنفيذ، والاعتماد على البيانات، والأمن السيبراني. وتُظهر نتائج التحليل المقارن أنه لا توجد تقنية واحدة قادرة بصورة مستقلة على معالجة التحديات متعددة الأبعاد التي تواجه الشبكات الضعيفة ذات الاختراق المرتفع للطاقة المتجددة. فالعاكسات المُشكِّلة للشبكة توفر إمكانات تشكيل الجهد والتردد ودعم الاستقرار الديناميكي، بينما توفر أنظمة تخزين الطاقة طاقة قابلة للتحكم ومرونة سريعة واحتياطيات تشغيلية وتنعيمًا لتقلبات الطاقة المتجددة، في حين يتيح الذكاء الاصطناعي التنبؤ والتحسين والتنسيق التكيفي واكتشاف الأعطال والإدارة الذكية للطاقة. ومع ذلك، تواجه كل تقنية قيودًا مهمة ترتبط بحدود تيار المحولات، وتدهور أنظمة التخزين وتكاليفها، وقابلية تفسير نماذج الذكاء الاصطناعي وجودة البيانات والأمن السيبراني. وبناءً على ذلك، تقترح الدراسة إطار **GFM–ESS–AI** المتكامل لتعزيز مرونة الشبكة في ليبيا، بحيث تعمل التقنيات الثلاث في صورة طبقات متكاملة ومتكاملة وظيفيًا بدلًا من كونها بدائل متنافسة. وتخلص الدراسة إلى أن تحول ليبيا نحو الطاقة المتجددة ينبغي أن يتجاوز مجرد تعظيم القدرة المتجددة المركبة إلى تعزيز قدرة الشبكة الآمنة على استيعاب الطاقة المتجددة، من خلال التكامل المرحلي بين المرونة المادية، والاستقرار القائم على تشكيل الشبكة، والتنسيق الذكي. ويوفر الإطار المقترح أساسًا للدراسات المستقبلية القائمة على المحاكاة، والتقييم التقني والاقتصادي، والتحقق التجريبي، والتنفيذ على نطاق المشروعات التجريبية.

الشبكات الضعيفة؛ أنظمة القدرة منخفضة القصور الذاتي؛ نظام القدرة الكهربائية الليبي.

1. INTRODUCTION

The global power sector is undergoing a fundamental transition from electricity systems dominated by large synchronous generators toward increasingly decentralized and converter-interfaced renewable energy resources. Rapid deployment of solar photovoltaic (PV) and wind generation has accelerated this transition, with power electronic converters becoming the primary interface between renewable generation and electrical networks. Unlike conventional synchronous machines, however, most inverter-based resources (IBRs) are electrically decoupled from grid frequency and therefore do not inherently contribute rotational inertia in the same manner as synchronous generation. As renewable penetration increases, this structural change alters the dynamic behavior of power systems and challenges several assumptions underlying conventional frequency regulation, protection, and stability control. Fernández-Guillamón et al. (2019) demonstrated that increasing penetration of converter-interfaced renewable generation reduces aggregate system inertia and fundamentally changes frequency-response requirements, while Ratnam et al. (2020) identified low inertia as one of the defining technical challenges of future renewable-dominated power systems.

The implications of declining synchronous inertia extend beyond frequency response alone. High levels of inverter-based generation can increase the rate of change of frequency (RoCoF), deepen frequency excursions after disturbances, introduce voltage-regulation challenges, and create new interactions among converter controls, protection systems, and weak-grid dynamics. The intermittency and forecast uncertainty associated with wind and solar generation further increase the need for fast and flexible balancing resources. These challenges become particularly significant in electrically weak networks, where reduced short-circuit strength and strong coupling between converter controllers can lead to synchronization instability, voltage oscillations, or disconnection during disturbances. The broader literature therefore increasingly treats renewable integration not simply as an energy-balancing problem, but as a system-dynamics and resilience problem requiring new control architectures and ancillary-service technologies (Alam et al., 2020; Ratnam et al., 2020).

One of the most prominent technological responses to this transition is the development of Grid-Forming (GFM) inverters. Conventional grid-following converters generally synchronize to an existing voltage waveform and therefore depend on a sufficiently strong external grid reference. Grid-forming converters, by contrast, can actively establish voltage magnitude and frequency and can emulate selected characteristics traditionally provided by synchronous machines. Their potential functions include voltage formation, frequency support, virtual inertia, black-start capability, islanded operation, and improved performance in weak-grid environments. Zhang et al. (2021) showed that GFM converters are becoming increasingly important as renewable penetration rises, while also emphasizing unresolved challenges related to transient stability, current limitation, fault behavior, and interactions among multiple grid-forming units. Similarly, Song et al. (2022) concluded that grid-forming technology offers substantial opportunities for supporting stable operation of converter-dominated systems, but its performance depends strongly on control architecture, system strength, operating conditions, and coordination with other network resources. Thus, GFM should not be interpreted as a universally superior replacement for conventional converter control, but rather as a key component of a broader resilience strategy.

A second essential component is Energy Storage Systems (ESSs), particularly battery energy storage systems (BESSs), which provide the fast active-power flexibility required to compensate for renewable variability and support frequency regulation. Storage technologies can contribute to renewable smoothing, peak shifting, operating reserves, voltage support, ramp-rate control, black-start services, and islanded operation. Importantly, energy storage also provides the controllable energy source required for many practical implementations of grid-forming functionality. Consequently, the combination of BESS and GFM control has attracted increasing attention because it integrates fast power availability with voltage- and

frequency-forming capabilities. Chaudhary et al. (2021) highlighted the central role of storage and coordinated energy-management strategies in improving microgrid flexibility and renewable integration. Nevertheless, ESS deployment involves important trade-offs related to capital cost, degradation, sizing, state-of-charge management, lifetime, safety, and technology-specific response characteristics. Therefore, the contribution of storage to resilience depends not only on installed capacity but also on appropriate control, sizing, and coordination with renewable generation and network requirements.

A third emerging pathway is the use of Artificial Intelligence (AI)-based control and energy management to improve forecasting, optimization, monitoring, and adaptive decision-making in increasingly complex power systems. Machine learning, deep learning, reinforcement learning, and hybrid intelligent methods are being applied to renewable generation forecasting, load prediction, energy-storage scheduling, voltage and frequency control, fault diagnosis, predictive maintenance, demand response, and real-time energy management. AI is particularly attractive in high-renewable systems because it can process nonlinear and high-dimensional operational data and potentially coordinate multiple resources across different temporal and spatial scales. Zhou (2022) highlighted the expanding use of AI in renewable energy systems for prediction and intelligent energy management, while Machlev et al. (2022) emphasized that widespread adoption in energy and power systems is constrained by explainability, transparency, trust, and the need for technically interpretable decisions. These limitations are especially relevant in safety-critical grid applications, where black-box control, data dependency, cybersecurity vulnerabilities, and poor generalization under unseen operating conditions can restrict deployment. Hence, AI should be considered an enabling coordination layer rather than a substitute for physical grid-support resources.

These technological developments are highly relevant to Libya, which possesses substantial renewable-energy potential but continues to face important electricity-system challenges. Previous studies have identified solar PV, concentrated solar power, and onshore wind as particularly promising resources for diversifying Libya's energy mix. Belgasim et al. (2018) demonstrated the technical potential for concentrating solar power development in Libya, while Almaktar and Shaaban (2021) concluded that solar PV and onshore wind represent major renewable alternatives capable of contributing to the displacement of fossil-fuel-based electricity generation. More recent assessments have reinforced the geographical potential of both solar and wind resources across different Libyan regions (Lagili et al., 2023). However, resource availability alone does not guarantee secure renewable integration; the ability of the power network to absorb variable generation while maintaining voltage, frequency, protection coordination, and operational reliability is equally important.

Evidence from the Libyan power system already illustrates this distinction between renewable-resource potential and grid-integration capability. Alasali et al. (2023), in their assessment of a 10-MW grid-connected PV system in the Libyan network, showed that renewable integration must be evaluated not only in terms of energy production but also through voltage profiles, losses, short-circuit levels, fault-ride-through behavior, and protection-system performance. Their study highlighted the importance of technical grid assessment before large-scale renewable deployment and demonstrated that PV integration can modify power-system operating and protection conditions. Earlier work on Libya has similarly emphasized the gap between abundant renewable resources and the technical, economic, institutional, and infrastructural conditions required for their effective exploitation (Almaktar & Shaaban, 2021; Maka et al., 2021). These conditions make Libya an especially relevant case for investigating resilience-oriented technologies because a future increase in converter-based renewable generation may intensify existing operational vulnerabilities unless integration is accompanied by suitable stability, flexibility, and intelligent-control mechanisms.

Despite the rapid development of GFM converters, energy storage, and AI-based power-system control, the literature remains substantially technology-fragmented. Reviews of grid-forming converters primarily focus on control structures, synchronization, stability, and converter interactions (Zhang et al., 2021; Song et al., 2022), whereas energy-storage studies commonly emphasize flexibility, energy management, and storage technologies (Chaudhary et al., 2021). AI-oriented reviews, meanwhile, focus largely on forecasting, optimization, data-driven control, and explainability (Zhou, 2022; Machlev et al., 2022). Such specialization has advanced individual technologies, but it provides limited guidance on how these approaches compare, complement one another, or should be combined in weak and institutionally constrained power systems. The gap is particularly evident for Libya, where existing research has concentrated predominantly on renewable-resource assessment, techno-economic feasibility, individual PV or wind projects, and localized grid impacts rather than an integrated comparison of modern resilience technologies.

Accordingly, this study addresses the following central question: Which technology—or combination of technologies—is most appropriate for improving renewable-energy integration and grid resilience under the technical and institutional conditions of the Libyan power system? To answer this question, the paper develops a systematic critical comparative review of Grid-Forming Inverters, Energy Storage Systems, and AI-based control, evaluating their respective capabilities, limitations, complementarities, and applicability to weak renewable-rich networks. The contribution of the review is threefold. First, it moves beyond technology-specific reviews by comparatively assessing the three technological pathways against common resilience criteria, including frequency support, voltage regulation,

renewable smoothing, black-start capability, flexibility, scalability, implementation complexity, data dependency, and cybersecurity. Second, it examines their potential synergistic integration, rather than treating GFM, ESS, and AI as competing alternatives. Third, it translates the international evidence into a context-specific framework for Libya, providing a foundation for a proposed GFM–ESS–AI integrated grid-resilience architecture and a future implementation roadmap. The remainder of the paper presents the review methodology, conceptual foundations of renewable integration and grid resilience, individual analyses of the three technologies, a critical comparative synthesis, their potential integration, implications for the Libyan power system, the proposed framework and research agenda, and the main conclusions.

2. RESEARCH GAP AND NOVELTY

Although research on renewable energy integration and grid resilience has expanded rapidly, the existing literature still reveals important conceptual and analytical limitations. The first concerns the fragmentation of technological research. Grid-Forming Inverters (GFM), Energy Storage Systems (ESS), and Artificial Intelligence (AI)-based control are commonly investigated as separate technological streams rather than as interacting components of the same resilience architecture. GFM-oriented studies predominantly examine synchronization, virtual inertia, voltage and frequency regulation, fault-current limitation, and converter stability (Zhang et al., 2021; Mahmoud et al., 2022). In contrast, energy-storage research generally focuses on renewable-energy smoothing, reserve provision, flexibility, energy balancing, and grid support (Kebede et al., 2022; Deguenon et al., 2023), whereas AI-oriented research concentrates on forecasting, optimization, adaptive control, predictive maintenance, and decision support (Machlev et al., 2022). This specialization has advanced understanding within each technological domain, but it has also produced a fragmented knowledge base in which the potential interactions among GFM, ESS, and AI remain comparatively underdeveloped.

A second limitation is the comparative gap. Existing reviews frequently assess the performance of one technology or compare alternative control strategies within the same technological family, yet substantially fewer studies evaluate GFM, ESS, and AI-based control against a common set of resilience-oriented criteria. For example, GFM reviews compare converter-control structures in terms of grid-support capability, fault-current limitation, and stability, while storage reviews assess technologies according to capacity, response time, efficiency, cost, and renewable-integration potential (Zhang et al., 2021; Kebede et al., 2022). These approaches are valuable, but they do not fully answer a more strategic engineering question: which technology is best suited to provide frequency support, voltage regulation, renewable smoothing, black-start capability, real-time optimization, fault recovery, or resilience under weak-grid conditions? More importantly, they provide limited insight into whether these technologies should be regarded as substitutes or complementary resources. A common multi-criteria analytical framework is therefore required to distinguish the functions that each technology can independently provide from those that require coordinated operation.

A third gap is contextual. Much of the advanced literature on converter-dominated grids, intelligent energy management, and grid-scale storage is developed for systems with comparatively mature transmission infrastructure, extensive monitoring, advanced ancillary-service arrangements, and high levels of digitalization. However, technological effectiveness is strongly conditioned by system characteristics. Weak and low-inertia networks may experience reduced short-circuit strength, protection difficulties, converter-control interactions, voltage instability, and greater sensitivity to disturbances. Likewise, AI-based operation depends heavily on data availability, computational infrastructure, model transparency, and cybersecurity. Consequently, technologies demonstrated successfully in strong and highly digitalized networks cannot be assumed to produce equivalent outcomes in weaker or institutionally constrained systems. The growing literature on GFM fault behavior and current limitation reinforces this point, showing that converter performance remains highly dependent on network conditions and protection requirements (Baeckeland et al., 2024). Similarly, the energy and power-system AI literature identifies explainability, data quality, trust, and implementation reliability as important barriers to operational deployment (Machlev et al., 2022).

This contextual limitation becomes particularly important when considering Libya. Existing Libyan renewable-energy research has mainly examined resource availability, photovoltaic deployment, techno-economic opportunities, and the network impacts of individual renewable projects. For example, Alasali et al. (2023) demonstrated through a 10-MW grid-connected PV case that renewable integration into the Libyan network can affect voltage profiles, power losses, fault behavior, and protection-system performance. Such findings show that Libya's renewable-energy challenge cannot be reduced to the availability of solar and wind resources; the ability of the power system to safely accommodate converter-based generation is equally critical. Yet, there remains limited research that systematically evaluates how modern resilience technologies—particularly GFM, ESS, and AI-based control—could respond collectively to the technical requirements of the Libyan grid.

The Libyan gap is therefore both technological and systemic. Research has not yet sufficiently addressed how grid-forming capability could improve operation in weak network areas, how storage could provide the active-power flexibility and reserve needed to support renewable variability, or how AI could coordinate forecasting, storage scheduling, fault detection, and real-time energy management under Libyan operational conditions. More importantly, these technologies have rarely been evaluated together within a common resilience

framework. This omission limits the ability of planners to determine whether investment should prioritize converter modernization, storage infrastructure, intelligent control, or an integrated portfolio combining all three. It also leaves unresolved the question of how technology deployment should be sequenced under financial, institutional, technical, and digital constraints.

The novelty of the present review lies in addressing these gaps through an integrated critical comparative perspective. Rather than treating Grid-Forming Inverters, Energy Storage Systems, and AI-based control as isolated technological alternatives, the study evaluates them against shared grid-resilience criteria, including frequency stability, voltage regulation, virtual inertia, renewable smoothing, fault recovery, black-start capability, scalability, implementation complexity, data dependence, cybersecurity, and suitability for weak-grid operation. The review therefore moves beyond technology-specific synthesis toward a systems-level assessment of the functional role of each technology.

More specifically, the paper advances the proposition that these technologies should primarily be understood as complementary layers of a resilience architecture rather than direct competitors. GFM provides the electrical interface required to establish and stabilize voltage and frequency; ESS supplies controllable energy and fast flexibility; and AI provides an intelligent supervisory layer for forecasting, optimization, coordination, and adaptive decision-making. Existing studies already demonstrate the individual importance of GFM for converter-dominated grids, storage for renewable integration, and AI for power-system intelligence, but the novelty here lies in critically synthesizing these strands into a unified framework suitable for weak and renewable-rich systems.

Accordingly, this review contributes to the literature in two related ways. At the theoretical and engineering level, it reframes renewable-energy integration as a multilayer grid-resilience problem involving physical stability, energy flexibility, and intelligent coordination. At the contextual level, it translates international evidence into the technical realities of the Libyan electricity system and uses this synthesis to develop the conceptual basis for a GFM–ESS–AI integrated resilience framework for Libya. This approach is intended to provide a more rigorous foundation for technology prioritization, future pilot projects, grid modernization, and subsequent techno-economic and simulation-based research.

3. RESEARCH QUESTIONS

Building on the identified fragmentation, comparative, contextual, and Libyan research gaps, this review is guided by four interrelated research questions. These questions are designed to move the analysis beyond a conventional technology-by-technology review toward a critical assessment of how Grid-Forming Inverters (GFM), Energy Storage Systems (ESS), and Artificial Intelligence (AI)-based control can individually and collectively contribute to renewable energy integration and grid resilience. Particular attention is given to weak and low-inertia power systems, where increasing penetration of inverter-based renewable resources creates challenges related to frequency stability, voltage regulation, system flexibility, disturbance recovery, and operational reliability. Accordingly, the study addresses the following research questions:

1. **What are the principal technical challenges associated with large-scale renewable energy integration in weak and low-inertia power systems?** This question establishes the technical foundation of the review by identifying the major challenges arising from increasing penetration of inverter-based renewable resources, including reduced system inertia, frequency deviations, voltage instability, renewable intermittency, limited short-circuit strength, converter interactions, protection coordination, and post-disturbance recovery. Identifying these challenges is essential because technology selection should be driven by specific system requirements rather than by technological availability alone.
2. **RQ2: How do Grid-Forming Inverters (GFM), Energy Storage Systems (ESS), and AI-based control differ in their ability to enhance frequency stability, voltage regulation, system flexibility, reliability, and grid resilience?** This question provides the basis for the critical comparative dimension of the study. Rather than evaluating each technology in isolation, the review compares their capabilities against a common set of performance criteria. This enables the identification of areas in which one technology offers a distinct advantage, areas where technological functions overlap, and, more importantly, areas where complementary deployment may generate greater system-level benefits than the application of any single technology.
3. **RQ3: What technical, economic, computational, cybersecurity, and implementation limitations constrain the deployment and effectiveness of GFM, ESS, and AI-based control in renewable-rich power systems?** This question introduces a critical perspective by moving beyond the technological benefits emphasized in much of the existing literature. The review evaluates unresolved issues such as GFM current limitation and fault behavior, ESS investment costs and degradation, AI dependence on data quality and computational infrastructure, cybersecurity exposure, interoperability, control complexity, technology maturity, and implementation requirements. Such an assessment is particularly important for avoiding the assumption that technologies demonstrated successfully under controlled or advanced-grid conditions can be transferred directly to weaker power systems.

4. **RQ4: How can Grid-Forming Inverters, Energy Storage Systems, and AI-based control be integrated into a technically feasible framework for strengthening renewable energy integration and grid resilience in Libya?** The fourth research question represents the central contribution of the study. It shifts the analysis from technological comparison toward technological integration by examining whether GFM, ESS, and AI should be considered complementary layers of a unified resilience architecture. Within this perspective, GFM provides voltage- and frequency-forming capabilities and fast stability support; ESS provides controllable energy, reserve capacity, and operational flexibility; while AI serves as an intelligent supervisory layer for forecasting, optimization, adaptive coordination, fault detection, and energy management. The question therefore seeks to translate international evidence into the specific requirements and constraints of the Libyan power system and to establish the conceptual basis for a proposed GFM–ESS–AI Integrated Grid-Resilience Framework for Libya.

Collectively, these research questions establish a logical progression from problem identification (RQ1) to technology comparison (RQ2), followed by critical evaluation of implementation constraints (RQ3) and ultimately context-specific technological integration (RQ4). This sequence ensures that the review does not merely summarize previous studies but critically synthesizes the available evidence to determine what the grid requires, what each technology can provide, what limits its application, and how the three technologies can be strategically combined within the Libyan context. In this sense, RQ4 serves as the integrative question through which the findings of the first three research questions are synthesized into the study's proposed resilience framework.

4. REVIEW METHODOLOGY

4.1 Review Design

This study adopts a Systematic Critical Comparative Review (SCCR) design to investigate the contribution of Grid-Forming Inverters (GFM), Energy Storage Systems (ESS), and Artificial Intelligence (AI)-based control to renewable energy integration and grid resilience, with particular emphasis on their applicability to the Libyan power system. The methodology was selected because the objective of the study extends beyond summarizing the available literature; it seeks to systematically identify relevant evidence, critically evaluate technological capabilities and limitations, compare alternative solutions using common engineering criteria, and synthesize the findings into an integrated resilience framework. This approach is consistent with the broader methodological principle that rigorous literature reviews should follow transparent procedures for searching, selecting, evaluating, and synthesizing evidence rather than relying on unsystematic narrative selection (Snyder, 2019).

The review therefore combines four complementary analytical processes: systematic evidence identification, thematic synthesis, critical evaluation, and comparative technological assessment. Systematic evidence identification is used to establish a transparent and reproducible evidence base; thematic synthesis organizes the selected studies according to the major technological and resilience themes; critical evaluation examines not only reported advantages but also assumptions, methodological limitations, implementation barriers, and conflicting findings; and comparative technological assessment evaluates GFM, ESS, and AI-based control against a common set of grid-resilience criteria. This structure is particularly appropriate for the present research because critical reviews should move beyond descriptive aggregation toward analysis, synthesis, and conceptual development (Grant & Booth, 2009).

The identification, screening, eligibility assessment, and final inclusion of studies are structured in accordance with the principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020). PRISMA is used primarily to improve transparency in documenting how records were identified, screened, excluded, and retained rather than as a substitute for the engineering analysis itself (Page et al., 2021). Accordingly, the final paper should include a PRISMA flow diagram reporting the number of records identified from each database, duplicates removed, studies screened by title and abstract, full-text articles assessed, exclusions with reasons, and the final number of studies included in the critical comparative synthesis.

4.2 Information Sources and Databases

The literature search is conducted across four major scientific databases: Scopus, Web of Science (WoS), IEEE Xplore, and ScienceDirect. These databases were selected to provide complementary coverage of electrical engineering, power electronics, renewable energy, energy storage, artificial intelligence, and power-system resilience. IEEE Xplore is particularly relevant for converter control, grid-forming technologies, smart grids, protection, and power-system engineering, while ScienceDirect provides extensive coverage of energy storage, renewable-energy integration, energy systems, and AI applications. Scopus and Web of Science provide broader multidisciplinary coverage and facilitate the identification of peer-reviewed studies across the interconnected technological domains considered in this review.

Google Scholar is used only as a supplementary search and verification source rather than as the primary database. Its role is to identify potentially relevant studies not captured in the main database search, verify bibliographic information, locate accessible full-text versions, and conduct backward and forward citation checks where appropriate. Such supplementary searching is useful because relying exclusively on a single database may fail to capture all relevant evidence, particularly in interdisciplinary research areas (Snyder, 2019).

4.3 Search Period

The principal search window covers studies published between January 2018 and December 2025. This period was selected to capture the rapid development of converter-dominated power systems, grid-forming control, large-scale battery storage, and data-driven power-system management during the recent acceleration of renewable energy integration. Particular analytical emphasis is placed on literature published between 2020 and 2025, reflecting the most recent technological developments and operational experience.

However, the temporal criterion is not applied rigidly to foundational literature. Seminal studies published before 2018 may be retained when they establish essential concepts, control principles, or analytical foundations that remain necessary for interpreting contemporary research. This exception is particularly relevant to early work on droop control, Virtual Synchronous Machines (VSM), Virtual Synchronous Generators (VSG), converter synchronization, energy-storage control, and fundamental definitions of power-system stability. The purpose of this approach is to maintain contemporary relevance without excluding foundational knowledge required for technically accurate synthesis.

4.4 Search Strategy and Keywords

A structured search strategy is developed by organizing keywords into five conceptual groups corresponding to the main components of the research questions. Boolean operators (AND, OR) are used to combine related terms and progressively narrow the search toward studies addressing renewable-rich, weak, and low-inertia power systems.

- Group A – Renewable Energy Integration: “renewable energy integration” OR “inverter-based resources” OR “IBR” OR “low-inertia power systems” OR “low inertia grid” OR “weak grids” OR “converter-dominated power systems”.
- Group B – Grid-Forming Technology: “grid-forming inverter” OR “grid-forming converter” OR “GFM inverter” OR “virtual synchronous machine” OR “virtual synchronous generator” OR “droop control” OR “synchronverter”.
- Group C – Energy Storage: “battery energy storage system” OR “BESS” OR “energy storage system” OR “grid-scale energy storage” OR “frequency regulation” OR “storage-based grid support”.
- Group D – Artificial Intelligence and Intelligent Control: “artificial intelligence” OR “machine learning” OR “deep learning” OR “reinforcement learning” OR “AI-based control” OR “intelligent energy management” OR “predictive control”.
- Group E – Grid Resilience and Stability: “grid resilience” OR “power system resilience” OR “frequency stability” OR “voltage stability” OR “frequency regulation” OR “power system reliability” OR “system flexibility” OR “black start”.

These groups are combined using Boolean search strings. A representative core search expression is formulated as follows:

("renewable energy integration" OR "inverter-based resources" OR "weak grid" OR "low-inertia power system") AND ("grid-forming inverter*" OR "grid-forming converter*" OR "energy storage" OR BESS OR "artificial intelligence" OR "machine learning") AND ("grid resilience" OR "frequency stability" OR "voltage stability" OR reliability OR flexibility).

Because one of the principal contributions of this study is the contextual application of international evidence to Libya, a second search layer combines the technological terms with “Libya” OR “Libyan power system” OR “North Africa” OR “developing power systems” OR “weak power systems.” This two-stage strategy is important because restricting all searches to “Libya” would risk excluding internationally significant engineering studies that provide the technological evidence required to evaluate GFM, ESS, and AI. The global technological evidence is therefore identified first, followed by a context-specific search examining its relevance to Libya and comparable power-system environments.

4.5 Study Selection and Eligibility Criteria

Studies are included when they satisfy the following criteria: (i) peer-reviewed journal articles, review articles, or high-quality conference papers relevant to power-system engineering; (ii) published primarily between 2018 and 2025; (iii) written in English; (iv) directly addressing at least one of the three technological domains—GFM, ESS, or AI-based control—in relation to renewable-energy integration; and (v) reporting evidence relevant to at least one resilience outcome, including frequency stability, voltage support, flexibility, renewable smoothing, fault response, black-start capability, reliability, or recovery following disturbances.

Studies are excluded when they focus exclusively on renewable-resource assessment without grid implications, device-level power electronics without system-level relevance, battery chemistry without grid-support applications, generic AI algorithms without application to power or energy systems, or publications lacking sufficient methodological or technical information for comparative assessment. Duplicate records, editorials, non-technical commentary, and publications for which adequate full text cannot be obtained are also excluded from the principal analytical dataset.

The selection process is performed sequentially through duplicate removal → title screening → abstract screening → full-text eligibility assessment → final inclusion. This sequential procedure follows the transparency principles recommended by PRISMA 2020 (Page et al., 2021).

4.6 Data Extraction and Thematic Classification

For each eligible study, a structured extraction matrix is used to record bibliographic and technical information. The extracted fields include author and year, geographical context, power-system configuration, renewable-energy technology, grid strength, GFM control

strategy, ESS technology, AI technique, study method, simulation or experimental platform, performance indicators, principal findings, reported advantages, limitations, and relevance to weak-grid conditions.

The selected literature is then organized into four principal analytical themes: (1) renewable integration challenges in weak and low-inertia systems; (2) grid-forming technologies and stability support; (3) energy storage and system flexibility; and (4) AI-based forecasting, optimization, and intelligent control. A fifth integrative theme examines the interaction among GFM–ESS–AI and their potential applicability to the Libyan power system. Thematic synthesis is particularly useful where a literature base is interdisciplinary and fragmented because it enables evidence to be organized around concepts and relationships rather than merely presented chronologically (Snyder, 2019).

4.7 Critical Comparative Assessment

The final analytical stage moves beyond descriptive synthesis by comparing the three technological pathways against a common set of engineering and implementation criteria. These criteria include frequency support, voltage regulation, virtual inertia, renewable smoothing, system flexibility, black-start capability, fault recovery, weak-grid suitability, scalability, response speed, technological maturity, capital requirements, computational requirements, data dependency, cybersecurity exposure, and implementation complexity.

The comparison does not assume that one technology is universally superior. Instead, the evidence is critically evaluated to determine where each technology provides a distinctive function, where functional overlap occurs, what limitations constrain its effectiveness, and under what system conditions technologies become complementary. Contradictory results among previous studies are retained and examined rather than eliminated, particularly when differences may arise from grid strength, converter topology, control strategy, ESS sizing, AI training data, simulation assumptions, or experimental conditions.

This critical comparative approach is central to the novelty of the review. As emphasized in methodological literature, a strong critical review should not merely reproduce previous findings but should evaluate the existing evidence and generate higher-order conceptual understanding (Grant & Booth, 2009). In the present study, this synthesis is ultimately used to determine how GFM, ESS, and AI-based control may function as complementary technological layers and to develop the conceptual basis for a GFM–ESS–AI Integrated Grid-Resilience Framework for Libya.

4.8 Methodological Workflow

Overall, the review follows the sequence:

Research Questions → Database Search → Duplicate Removal → Title/Abstract Screening → Full-Text Eligibility → Quality and Relevance Assessment → Data Extraction → Thematic Synthesis → Critical Comparative Assessment → Libyan Contextualization → Integrated GFM–ESS–AI Framework.

This methodological structure strengthens both the reproducibility and the analytical depth of the review. Systematic procedures reduce arbitrary study selection, while the critical comparative component prevents the paper from becoming a descriptive catalogue of technologies. The resulting methodology is therefore aligned with the central objective of the study: not merely to identify what has been published on GFM, ESS, and AI, but to determine what the accumulated evidence implies for designing a more resilient, renewable-rich Libyan power system.

5. CONCEPTUAL FOUNDATIONS: FROM RENEWABLE ENERGY INTEGRATION TO GRID RESILIENCE

5.1 Renewable Energy Integration and the Changing Structure of Power Systems

The increasing penetration of renewable energy resources is fundamentally changing the physical and operational characteristics of modern electrical power systems. Conventional electricity networks have historically relied on large synchronous generators whose rotating masses inherently contribute inertia, fault current, voltage support, and frequency-response capability. In contrast, solar photovoltaic (PV) systems, modern variable-speed wind turbines, battery storage, and several other emerging resources are increasingly connected to the network through power-electronic converters and are collectively referred to as Inverter-Based Resources (IBRs). As the share of IBRs increases, the dynamic behavior of the power system becomes progressively determined by converter control algorithms rather than solely by the electromechanical characteristics of synchronous machines (Hatziargyriou et al., 2021; Kong et al., 2022).

Solar PV and wind power also introduce an additional operational challenge because their primary energy inputs are weather-dependent. Solar output varies with irradiance, cloud movement, temperature, and the diurnal cycle, while wind generation depends strongly on temporal and spatial variations in wind speed. Consequently, large-scale renewable integration introduces both variability and uncertainty into generation portfolios. These characteristics increase the need for flexible reserves, faster balancing, forecasting, storage, and advanced grid-control capabilities. Importantly, renewable variability and low inertia are related but conceptually different problems: variability concerns changes in available generation over time, whereas declining inertia concerns the dynamic ability of the power system to resist rapid frequency changes following an imbalance.

The transition toward IBR-dominated generation therefore represents more than a substitution of one energy source for another. It constitutes a transformation in the underlying dynamics of the electricity system. As Hatziargyriou et al. (2021) emphasized in their revised classification of power-system stability, the increasing presence of converter-interfaced technologies has introduced dynamic phenomena that are not adequately

captured by the traditional stability framework alone. Similarly, Kong et al. (2022) demonstrated that converter controls, operating points, grid strength, and interactions among multiple converters can create new small-signal stability phenomena.

This distinction has important implications for renewable-energy planning. A power system may possess abundant solar and wind resources yet remain technically unable to accommodate high renewable penetration without corresponding investments in stability, flexibility, protection, and control. Renewable-energy potential should therefore be distinguished from renewable-energy hosting capability. This conceptual distinction is particularly relevant to weak networks and provides the basis for examining why technologies such as grid-forming inverters, energy storage, and intelligent control are becoming increasingly important.

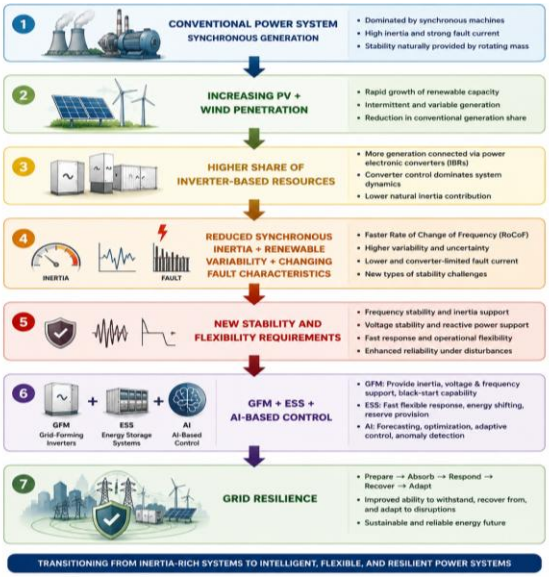
Figure 1. conceptual Transition

5.2 Weak and Low-Inertia Power Systems

Two concepts are particularly important for understanding the challenges created by high IBR penetration: low inertia and weak system strength. Although these conditions can occur simultaneously, they should not be treated as synonymous.

A low-inertia power system is one in which the aggregate kinetic energy stored in synchronously rotating generation has declined relative to system demand. When a sudden generation–load imbalance occurs, lower inertia can result in a faster Rate of Change of Frequency (RoCoF) and potentially larger frequency deviations before primary and fast-frequency control mechanisms respond. Consequently, replacing synchronous generation with conventionally controlled converter-interfaced renewable generation can fundamentally alter the frequency dynamics of the system.

System strength, by contrast, refers broadly to the ability of the electrical network at a particular connection point to maintain a stable voltage waveform when subjected to disturbances or changes in converter current



injection. This issue becomes particularly important for IBRs because conventional grid-following converters typically rely on the surrounding network for synchronization. When system strength declines, synchronization and converter-control interactions may become more difficult, potentially causing oscillations, voltage instability, or converter disconnection. Recent research confirms that system strength assessment has become a central concern for IBR integration and that traditional indicators can become less informative as multiple converters interact within the same network.

A conventional indicator is the Short-Circuit Ratio (SCR), which conceptually compares the short-circuit strength available at the Point of Connection (POC) with the rated capacity of the converter-based resource. Lower SCR values generally indicate weaker grid conditions. However, SCR should not be interpreted as a complete description of system strength. In networks containing multiple interacting IBRs, conventional SCR may fail to capture converter–converter interactions, network topology, control bandwidth, and operating-point effects. This limitation has motivated extensions such as interaction-adjusted and multiple-renewable short-circuit-ratio indices (Kim et al., 2020; Yu et al., 2024).

The critical point is therefore that weak grid $\neq$ low inertia, even though renewable-rich systems may experience both. A network may have low inertia while maintaining reasonable voltage strength, or it may exhibit weak-grid characteristics despite adequate synchronous inertia. This distinction matters because the appropriate technological response depends on the underlying problem. Energy storage may supply rapid active-power support, whereas grid-forming control can directly modify converter voltage-frequency behavior, and intelligent control can optimize system-level coordination.

5.3 Grid Stability in Converter-Dominated Power Systems

Power-system stability refers broadly to the ability of an electrical power system to regain an acceptable operating equilibrium following a physical disturbance. The modern stability framework recognizes that increasing penetration of converter-interfaced technologies requires traditional stability categories to be supplemented by new categories associated with power-electronic dynamics (Hatziargyriou et al., 2021).

Frequency stability concerns the ability of the system to maintain or restore frequency following a severe imbalance between generation and demand. Traditionally, synchronous inertia slows the initial frequency excursion, giving governors and reserves time to respond. As synchronous generation is displaced by IBRs, frequency dynamics increasingly depend on fast converter controls, energy-storage availability, synthetic inertia, and fast-frequency response.

Voltage stability concerns the ability of the system to maintain acceptable voltages following disturbances or changes in operating conditions. High IBR penetration can affect voltage stability because converters have current limits and their reactive-power response is control-dependent. These effects become more

pronounced in weak networks where changes in active and reactive current can produce stronger voltage variations.

Rotor-angle stability, traditionally associated with maintaining synchronism among synchronous machines, remains relevant in hybrid power systems containing both synchronous generation and converter-based resources. However, as converter penetration increases, the concept of synchronization itself changes because converters do not possess physical rotor angles. Their synchronization behavior is determined by control systems, making interactions between synchronous-machine dynamics and converter-control dynamics an increasingly important research problem.

Most importantly, modern power systems increasingly exhibit converter-driven stability phenomena. Kong et al. (2022) demonstrated that these phenomena can arise from interactions among converter controllers, grid impedance, system strength, operating conditions, and other network devices. This means that a system may satisfy conventional rotor-angle or voltage-stability requirements while still experiencing oscillatory instability associated with converter control.

The stability problem in renewable-rich networks should therefore be viewed as multidimensional:

Frequency Stability + Voltage Stability + Electromechanical Stability + Converter-Driven Stability → Overall Dynamic Security

This broader interpretation is important for the present review because GFM, ESS, and AI-based control address different parts of this stability problem rather than performing identical functions.

5.4 From Grid Stability and Reliability to Grid Resilience

A further conceptual distinction must be established among stability, reliability, and resilience. Although these terms are sometimes used interchangeably, they describe different dimensions of power-system performance.

Stability primarily concerns the dynamic response of the system following a disturbance and whether critical electrical variables return to acceptable operating conditions.

Reliability has a broader operational meaning and concerns the ability of the electricity system to continuously and adequately supply customers under expected operating conditions and credible contingencies.

Resilience, however, extends beyond conventional stability and reliability by emphasizing the ability of a system to anticipate disruptive events, withstand their immediate consequences, maintain critical functions, recover rapidly, and adapt its configuration or operating strategy to reduce vulnerability to future events.

The conceptual relationship can therefore be expressed as:

Reliability ≠ Stability ≠ Resilience

but the three are strongly interconnected.

For the purposes of this review, grid resilience can be conceptualized through five sequential capabilities:

Prepare → Absorb → Respond → Recover → Adapt

- Prepare concerns forecasting, risk identification, planning, reserve allocation, preventive control, and situational awareness.
- Absorb represents the system's ability to withstand the initial disturbance without catastrophic loss of functionality.
- Respond refers to rapid corrective actions such as frequency support, voltage control, storage dispatch, protection, islanding, and adaptive control.
- Recover represents restoration of electricity supply and return toward acceptable system conditions.
- Adapt involves learning from disturbances and modifying infrastructure, control strategies, operational procedures, or investment decisions to improve future performance.

This broader resilience perspective changes the technological question. Instead of asking which individual technology provides the "best" grid support, the relevant question becomes which combination of technologies supports different stages of the resilience cycle. GFM can strengthen the ability to absorb and respond to disturbances through voltage and frequency formation; ESS can provide fast flexibility and reserve during response and recovery; and AI-based systems can improve preparation, forecasting, adaptive coordination, anomaly detection, and post-event learning. This conceptual transition provides the theoretical bridge to the three technological pillars examined in the following sections.

6. GRID-FORMING INVERTERS

6.1 *From Grid-Following to Grid-Forming Operation*

The distinction between Grid-Following (GFL) and Grid-Forming (GFM) control is fundamental to understanding the future operation of inverter-dominated power systems. Conventional renewable-energy converters generally operate in grid-following mode. They synchronize with an externally established voltage waveform—commonly through a Phase-Locked Loop (PLL)—and regulate injected current to achieve active- and reactive-power objectives. Consequently, their operation assumes that a sufficiently strong electrical grid already exists.

Grid-forming converters adopt a fundamentally different control philosophy. Rather than merely following an externally imposed voltage angle and frequency, a GFM converter controls its terminal voltage waveform and can contribute to establishing the local voltage and frequency reference. Rosso et al. (2021) describe GFM technology as increasingly relevant not only to isolated microgrids but also to interconnected transmission systems experiencing increasing converter penetration. Anttila et al. (2022) similarly highlight the importance of GFM operation for microgrids characterized by high renewable shares and reduced synchronous inertia.

TABLE I. CONCEPTUAL COMPARISON OF GFL AND GFM OPERATION

Feature	Grid-Following (GFL)	Grid-Forming (GFM)
Grid voltage/frequency reference	Externally required	Can establish/support
Typical synchronization	PLL-based	Control-generated reference
Frequency support	Limited/control-dependent	Strong potential
Voltage-forming capability	Limited	Core capability
Weak-grid operation	More challenging	Greater potential
Islanded operation	Generally unsuitable alone	Suitable with appropriate control
Black-start capability	Limited	Potentially achievable
Virtual inertia	Not inherent	Can be emulated
Fault behavior	Current controlled	More complex due to voltage-forming objective
Main strength	Mature and simple grid-connected operation	Stability support in low-inertia/weak systems

The comparison should nevertheless be interpreted cautiously. GFM is not inherently superior under every operating condition. Grid-following technology remains mature, efficient, and appropriate for many strong-grid applications. The benefit of GFM becomes particularly significant where system strength, inertia, islanding capability, or restoration requirements make voltage-forming behavior valuable.

6.2 Grid-Forming Control Strategies

There is no single universal GFM control strategy. Rather, several control families have been proposed, each attempting to establish stable voltage-frequency behavior through different physical or mathematical principles (Rosso et al., 2021; Anttila et al., 2022).

- Droop Control represents one of the most established approaches. It emulates the steady-state power-frequency and reactive-power-voltage relationships traditionally observed among parallel synchronous generators. Its main advantages are simplicity, decentralized implementation, and effective power sharing. However, conventional droop control involves trade-offs between power-sharing accuracy, frequency/voltage deviation, and transient performance.
- Virtual Synchronous Machine (VSM) control attempts to reproduce selected dynamic characteristics of synchronous machines through software, including inertia and damping. The approach is attractive for low-inertia systems because it can provide an interpretable electromechanical analogy. Nevertheless, parameter tuning, transient response, current saturation, and DC-side energy availability remain important implementation issues.
- Virtual Synchronous Generator (VSG) is closely related to VSM and similarly reproduces synchronous-generator behavior through converter control. Depending on implementation, VSG strategies can emulate swing dynamics, damping, and governor-like characteristics. However, emulating a synchronous generator does not eliminate the physical current limits of semiconductor converters, which becomes particularly important during severe faults.
- Synchronverter control also seeks to reproduce synchronous-machine equations directly within inverter control. Its conceptual simplicity and machine-like behavior make it attractive for distributed-generation applications, although practical performance remains sensitive to parameter selection, measurement quality, current constraints, and network conditions.
- Virtual Oscillator Control (VOC) takes a different approach by exploiting nonlinear oscillator dynamics to achieve synchronization and power sharing. Aghdam and Agamy (2022) show that oscillator-based methods have become an important alternative to conventional droop and synchronous-machine-emulation strategies. VOC can provide fast synchronization and decentralized behavior, but practical issues including fault management, parameter design, and integration with conventional grid requirements remain areas of continuing investigation.
- Matching Control establishes a relationship between DC-side dynamics and AC-side frequency, thereby linking converter behavior more directly to the energy dynamics of the DC source. Research comparing matching control with droop, VSM, and oscillator-based methods suggests that DC-side constraints can fundamentally influence GFM stability, particularly when converters encounter current or energy limitations (Samanta & Chaudhuri, 2021).

The existence of these different strategies demonstrates an important point: GFM is a functional category rather than a single controller. Consequently, conclusions concerning the performance of "GFM" should identify the specific control implementation, network strength, converter limits, and operating scenario being evaluated.

6.3 *Advantages and Grid-Support Capabilities of GFM*

The principal advantage of grid-forming technology is its ability to contribute actively to the establishment and stabilization of the AC voltage waveform. This capability makes GFM particularly relevant as synchronous generation declines and conventional grid-following converters become a larger proportion of installed generation.

First, GFM can provide rapid frequency support by adjusting active-power response according to frequency or power imbalance. Depending on the control strategy and available DC-side energy, this response can emulate inertial and damping characteristics.

Second, GFM provides voltage regulation and reactive-power support, potentially improving operation in weak networks where conventional grid-following synchronization may become difficult.

Third, GFM can support islanded operation, making it particularly relevant to microgrids and networks requiring autonomous operation following separation from the

main system. Anttila et al. (2022) identify this voltage- and frequency-forming function as central to high-renewable microgrid operation.

Fourth, appropriately designed GFM resources may contribute to black-start and system restoration, because they do not necessarily require an already energized AC voltage reference before beginning operation. This characteristic becomes particularly valuable from a resilience perspective.

Finally, GFM offers substantial potential in low-inertia and weak-grid conditions, where maintaining a stable externally imposed voltage reference becomes increasingly difficult. This makes GFM an important candidate technology for future renewable-rich systems, although the degree of benefit remains dependent on control design and system conditions.

6.4 Critical Limitations and Unresolved Engineering Challenges

Despite these advantages, the current literature does not justify treating GFM as an unconditional solution to converter-dominated grid stability. Several engineering limitations remain unresolved.

A fundamental issue is current limiting. Synchronous machines can naturally produce several multiples of rated current for short periods during faults, whereas semiconductor-based converters possess relatively strict overcurrent limits. A GFM controller may therefore attempt to maintain a voltage-forming objective that is physically incompatible with the converter's maximum current during severe disturbances. Current saturation can alter the converter's effective dynamics and potentially threaten post-fault synchronization and transient stability (Samanta & Chaudhuri, 2021).

Closely related is Fault Ride-Through (FRT). Rosso et al. (2021) identify fault behavior, angle stability, and transitions between operating conditions as important unresolved issues for GFM deployment. Current-limiting mechanisms must protect power-electronic devices without destroying the grid-forming behavior required to support the network.

A third issue concerns protection coordination. Conventional protection schemes were largely developed around predictable high fault currents from synchronous generation. Large-scale replacement with converter-interfaced generation changes fault-current magnitude, waveform, sequence components, and duration. Consequently, widespread GFM deployment may require coordinated evolution of converter controls and network protection philosophies.

Fourth, control interactions remain a significant concern. Multiple GFM units may interact with each other, with GFL converters, synchronous generators, HVDC systems, FACTS devices, and network impedances. Converter-driven instability research demonstrates that control parameters, grid strength, operating points, and network configuration can materially affect stability (Kong et al., 2022).

Fifth, GFM performance under extreme disturbances cannot be inferred from small-signal or normal-operation studies alone. Controllers that perform well under moderate disturbances may behave differently when current saturation, DC-side limitations, severe voltage depression, or topology changes occur. Comparative research has even shown that some GFM implementations with particular inner-loop structures may exhibit reduced stability margins under weak-grid conditions, reinforcing the need to distinguish between the GFM concept and specific control realizations.

Finally, challenges remain regarding standardization, interoperability, validation, and large-scale deployment evidence. Much of the academic literature is based on simulation, laboratory prototypes, microgrids, or limited demonstrations. Moving from these environments toward power-system-wide penetration requires validated grid codes, interoperable performance specifications, protection standards, testing procedures, and greater operational experience.

The evidence therefore supports a more nuanced conclusion:

- **The superiority of GFM is operating-condition dependent rather than universal**. GFM has particularly strong potential where voltage-forming capability, low-inertia support, islanding, weak-grid operation, or restoration are required. However, its actual contribution depends on controller architecture, converter current capability, DC-side energy availability, grid strength, protection design, operating point, and interactions with other grid resources. This critical interpretation is particularly important for the Libyan context, because technology selection should follow a detailed assessment of network conditions rather than assume that replacing GFL with GFM alone will resolve renewable-integration challenges.

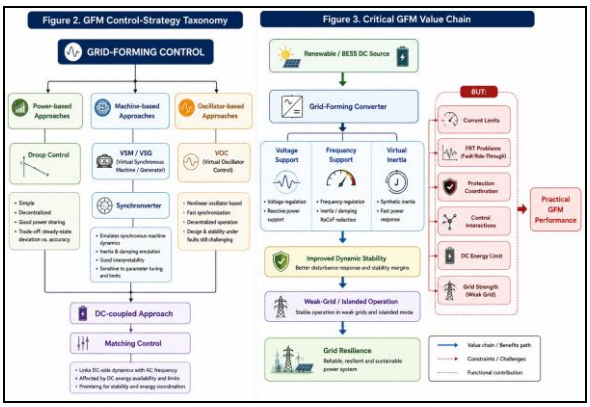


Figure 2. Proposed GFM control-strategy taxonomy

7. GRID-FORMING INVERTERS

Grid-Forming Inverters (GFM) have emerged as one of the most important technological responses to the increasing penetration of inverter-based renewable resources in low-inertia power systems. Unlike conventional Grid-Following (GFL) inverters, which typically synchronize with an externally established grid

voltage and frequency, GFM inverters are designed to actively establish or regulate the local voltage waveform and frequency reference. This distinction becomes increasingly important as synchronous generation declines, because future power systems require converter-interfaced resources not only to inject active and reactive power but also to provide some of the stabilizing functions historically supplied by synchronous machines. Research roadmaps on GFM technology identify frequency control, voltage control, protection, fault ride-through, and modeling as central technical areas that must be resolved before widespread deployment can occur (Lin et al., 2020).

7.1 *Grid-Following versus Grid-Forming Inverters*

The fundamental difference between GFL and GFM lies in their relationship with the grid reference. GFL inverters are generally designed to follow an existing voltage waveform and inject controlled currents relative to that reference. Their successful operation therefore depends strongly on the availability of an adequately strong external grid. By contrast, GFM inverters behave more like controlled voltage sources and can contribute directly to establishing voltage magnitude, phase angle, and frequency. This feature gives them greater potential for supporting low-inertia systems, weak grids, islanded operation, and black-start processes. Nevertheless, the distinction should not be interpreted as implying that GFL is technologically obsolete. GFL remains mature, efficient, and appropriate in sufficiently strong networks; the added value of GFM becomes more evident as grid strength decreases and system stability increasingly depends on converter-based resources (Lin et al., 2020; Mohammed et al., 2025).

TABLE II. COMPARATIVE ASSESSMENT OF GRID-FOLLOWING (GFL) AND GRID-FORMING (GFM) INVERTERS FOR GRID STABILITY AND RESILIENCEFEATURE

Feature	Grid-Following (GFL)	Grid-Forming (GFM)
Grid reference	Requires an external voltage/frequency reference	Can establish or actively regulate the reference
Typical behavior	Controlled current source	Controlled voltage-source behavior
Frequency support	Generally limited and control-dependent	Stronger potential for fast frequency support
Voltage support	Reactive-current based	Direct voltage-forming capability
Weak-grid operation	More vulnerable to synchronization problems	Greater potential, depending on controller design
Islanded operation	Generally requires an external forming source	Can support autonomous operation
Black start	Limited	Potentially feasible
Inertia emulation	Possible only through additional control	Commonly incorporated in several GFM strategies
Fault response	Mature current-controlled behavior	More challenging because forming action and current limits must be reconciled
Technology maturity	High	Rapidly developing

This comparison demonstrates that the technological advantage of GFM is primarily functional. Its value arises when the network requires resources capable of contributing actively to the establishment of voltage and frequency rather than merely tracking them. However, comparative studies also show that GFM performance varies considerably across control strategies and network conditions, especially between strong, weak, and very weak grids (Mohammed et al., 2025).

7.2 Grid-Forming Control Strategies

GFM should not be treated as a single control algorithm. It represents a broader family of converter-control approaches that share the objective of forming or regulating the AC voltage waveform while differing substantially in their dynamic equations, inertia emulation, damping behavior, nonlinear response, and dependence on DC-side energy. Recent comparative work has evaluated droop, Virtual Synchronous Machine (VSM), matching control, and dispatchable Virtual Oscillator Control (dVOC) under different frequency-domain and time-domain conditions, demonstrating that no single strategy dominates across all performance indicators (Mohammed et al., 2025).

- **Droop Control** is among the most established GFM strategies. It reproduces relationships analogous to the active-power/frequency and reactive-power/voltage droop characteristics historically used for parallel synchronous generators. Its major strengths are relatively simple implementation, decentralized power sharing, and limited reliance on communication infrastructure. However, conventional droop control typically involves a trade-off between accurate power sharing and frequency or voltage deviation. Its transient performance may also be less satisfactory under large disturbances unless supplemented by additional damping, virtual impedance, or secondary-control mechanisms.
- **Virtual Synchronous Machine (VSM)** control introduces virtual swing dynamics so that the converter reproduces selected dynamic properties of a synchronous machine. This allows virtual inertia and damping to be incorporated directly into converter behavior. The main attraction of VSM is its intuitive physical interpretation and its ability to provide frequency-support functions that resemble conventional generator behavior. Nevertheless, its effectiveness depends strongly on parameter tuning, DC-side energy availability, and the interaction between inertia emulation and converter current limits.
- **Virtual Synchronous Generator (VSG)** follows a closely related concept. VSG implementations emulate synchronous-generator dynamics, including inertia, damping, and in some cases governor-like behavior. Although this can improve frequency response and provide grid-forming functionality, the concept must not be confused with actual synchronous-machine physics: the

semiconductor converter cannot sustain the high fault currents naturally produced by a synchronous generator. This difference becomes critical during severe voltage disturbances.

- **Synchronverter control** reproduces synchronous-machine mathematical equations within inverter control and is intended to make power-electronic resources behave in a machine-like manner from the network perspective. Its conceptual transparency and compatibility with conventional electromechanical interpretations are attractive, yet practical performance remains sensitive to current limits, control tuning, and system impedance.
- **Virtual Oscillator Control (VOC)** represents a different conceptual family. Instead of explicitly emulating synchronous-machine equations, VOC uses nonlinear oscillator dynamics to achieve synchronization and power sharing. Oscillator-based control can offer rapid decentralized synchronization and attractive large-signal behavior, but the associated nonlinear dynamics make tuning, fault operation, and interoperability with conventional grid controls important areas of ongoing research.
- **Matching Contro**l links converter frequency behavior more directly to DC-side energy dynamics. This creates an explicit relationship between the energy stored or supplied on the DC side and the AC frequency response. Its principal conceptual advantage is that it does not treat virtual inertia as entirely detached from physical energy availability. Nevertheless, matching control remains sensitive to the characteristics of the DC source and may be constrained when stored energy or power capacity is limited. Comparative analysis shows that droop, VSM, matching, and dVOC may exhibit similar local behavior under some assumptions while differing materially under nonlinear, weak-grid, and fault conditions (Mohammed et al., 2025).

This diversity of strategies leads to an important methodological conclusion: comparisons should not simply categorize a resource as “GFM” and assume uniform behavior. The actual response of a GFM resource depends on the specific control law, inner-loop architecture, current-limiting mechanism, DC-side energy source, network impedance, and operating point.

7.3 *Advantages and Grid-Support Capabilities*

The primary technical advantage of GFM is its ability to participate directly in the formation and stabilization of grid voltage and frequency. This capability can become increasingly important as conventional synchronous machines are displaced by converter-interfaced renewable generation.

- First, GFM can provide fast frequency support. By adjusting active-power output in response to frequency or power imbalance, appropriately controlled GFM resources can emulate inertia-like and damping behavior. This does not create physical rotating inertia, but it can improve frequency dynamics if sufficient energy is available on the DC side.
- Second, GFM can provide stronger voltage regulation because the converter directly controls its terminal voltage rather than merely injecting reactive current relative to an externally imposed voltage reference. This characteristic can improve performance under weak-grid conditions.
- Third, GFM enables islanded operation more naturally than conventional GFL architectures because the converter can establish the voltage and frequency reference required by the islanded network. The same forming capability also gives appropriately designed GFM resources black-start potential, making them relevant to system restoration after major outages. NREL's research roadmap specifically identifies frequency control, voltage control, system protection, and fault recovery as major areas where GFM can contribute to future converter-dominated systems (Lin et al., 2020).
- Fourth, GFM has significant potential for low-inertia and weak-grid operation. Since it does not rely on exactly the same synchronization mechanism as conventional PLL-based GFL control, it can remain effective in circumstances where external voltage references are less stiff. However, this advantage is not unconditional; very weak-grid conditions can still produce unfavorable interactions depending on control design and parameterization, and comparative analysis demonstrates that control performance changes materially as network impedance changes (Mohammed et al., 2025).
- From a resilience perspective, therefore, GFM contributes primarily to the absorb, respond, and recover stages of disturbance management. It can help maintain voltage and frequency during disturbances, facilitate islanded operation, and potentially support restoration. Nevertheless, these benefits depend strongly on appropriate energy-storage coordination and protection design.

7.4 Critical Limitations and Unresolved Challenges

The rapid growth of interest in GFM should not lead to the conclusion that it provides a universally superior solution. The most important limitation is converter current capability. Power-electronic devices cannot tolerate the same magnitude and duration of overcurrent that synchronous generators can sustain. Consequently, current-limiting mechanisms are indispensable. However, the method used to impose a current limit fundamentally changes converter behavior during and immediately after a disturbance. Baeckeland et al. (2024) demonstrate that current limiting can affect inverter-level dynamics, transient system stability, fault recovery, and protection performance, making it one of the central unresolved challenges in GFM engineering.

Closely related is Fault Ride-Through (FRT). During severe voltage sags, a GFM controller may attempt to maintain its voltage-forming objective while the semiconductor hardware simultaneously requires strict current limitation. These objectives can become contradictory. Ordoño et al. (2024) distinguish between methods designed primarily to restrict current and those intended to preserve transient stability, emphasizing that successful low-voltage ride-through requires simultaneous treatment of both problems rather than viewing current limitation alone as sufficient.

Protection coordination represents a further challenge. Existing protection systems were largely developed around the relatively predictable and high fault-current contribution of synchronous generators. GFM resources may provide limited and controller-dependent fault currents, and their effective output impedance can change dynamically when current-limiters activate. This can alter the quantities observed by conventional relays and complicate fault detection and selectivity. The GFM research roadmap therefore treats system protection as one of the principal research requirements for large-scale inverter-dominated systems (Lin et al., 2020), while recent studies continue to propose control concepts explicitly designed to maintain compatibility between FRT behavior and protection systems.

Another limitation concerns control interactions. A future power system may simultaneously contain droop-controlled GFM resources, VSM units, GFL solar and wind converters, synchronous generators, HVDC links, storage devices, and FACTS equipment. Their control loops can interact across different time scales. Therefore, stability cannot be determined by studying each inverter independently. Comparative studies under different grid impedances demonstrate that the relative performance of GFM control strategies varies between strong and weak network conditions, further challenging the assumption of universal controller superiority (Mohammed et al., 2025).

Stability during extreme disturbances remains particularly important. Small-signal stability and satisfactory steady-state power sharing do not guarantee successful operation during faults, converter saturation, abrupt islanding, or large changes in power angle. Current-limiting controls can modify post-fault dynamics and, depending on their design, either improve or degrade transient recovery. The extensive review by Baeckeland et al. (2024) therefore emphasizes that current-limiting strategy must be considered part of the overall GFM stability design rather than merely a semiconductor-protection function.

A further issue is standardization and interoperability. Research roadmaps have repeatedly identified the need for consistent performance definitions, standardized models, verification procedures, and grid-code requirements for GFM resources. Although laboratory demonstrations and commercial battery-based implementations are increasing, widespread transmission-level deployment still requires greater operational evidence concerning heterogeneous fleets, protection interactions, multi-vendor interoperability, and system-wide control coordination (Lin et al., 2020).

Finally, the available evidence remains uneven across deployment scales. Many control strategies have been validated using simulation, controller-hardware-in-the-loop testing, laboratory microgrids, or limited demonstrations. Such evidence is valuable, but performance observed in controlled test systems cannot automatically be extrapolated to geographically large networks containing thousands of heterogeneous inverter-based resources. This gap between control-level performance and system-level validation remains an important research priority.

The resulting conclusion should therefore be deliberately nuanced:

- The superiority of GFM is operating-condition dependent rather than universal. The technical value of GFM is greatest when a system requires voltage-forming capability, low-inertia support, weak-grid stabilization, islanded operation, or restoration services.
- However, its practical superiority depends on the control strategy, grid strength, converter current rating, DC-side energy availability, protection architecture, fault conditions, and interaction with other grid resources.
- This is especially important for Libya: deployment should not begin from the assumption that GFM is inherently better than GFL, but from an engineering assessment of where the Libyan grid actually requires grid-forming functionality and which GFM–ESS configuration can satisfy those requirements most effectively.

8. Energy Storage Systems for Grid Resilience

Energy Storage Systems (ESS) have become a central component of renewable-rich power systems because they provide the temporal and operational flexibility needed to compensate for the variability of solar and wind generation, support frequency and voltage regulation, and assist grid recovery following major disturbances. Unlike Grid-Forming Inverters (GFM), which primarily define converter behavior at the grid interface, energy storage provides the physical energy reserve required to sustain active-power support over time. For this reason, ESS should be viewed not merely as an energy-shifting asset but as an enabling infrastructure for grid flexibility and resilience. Utility-scale storage can provide multiple services across transmission, distribution, microgrid, and restoration applications, although its suitability depends strongly on discharge duration, power rating, efficiency, response speed, siting, and lifecycle characteristics (Augustine et al., 2021).

8.1 *Storage Technologies*

The principal storage technologies relevant to grid resilience differ substantially in their power density, energy duration, response speed, geographic requirements, and operational maturity. Consequently, no single storage technology can be considered optimal across all resilience functions.

Lithium-ion Battery Energy Storage Systems (Li-ion BESS) are currently among the most practical options for short- to medium-duration grid support because they combine rapid response, high round-trip efficiency, modular deployment, and mature power-electronic interfaces. Their response characteristics make them particularly appropriate for frequency regulation, renewable smoothing, reserve provision, and grid-forming applications. However, Li-ion systems are fundamentally constrained by degradation, thermal management requirements, state-of-charge limits, and finite cycle life. These characteristics mean that their value for resilience depends not only on installed megawatts but also on how frequently and aggressively they are dispatched.

Flow batteries offer a different operational profile. Their most important system-level characteristic is that energy capacity and power capacity can be scaled more independently than in conventional electrochemical batteries because stored energy resides in external electrolyte tanks. This makes flow batteries potentially attractive for applications requiring longer-duration storage and frequent cycling. NREL's storage technology assessment identifies flow batteries as a grid-scale option with characteristics that differ significantly from Li-ion in terms of cost structure, duration, and scaling behavior (Augustine et al., 2021). Their disadvantage is that they typically involve larger footprints, pumping systems, lower energy density, and less commercial maturity than Li-ion.

Supercapacitors occupy the opposite end of the power–energy spectrum. They can deliver extremely fast bursts of power and withstand large numbers of cycles, making them attractive for power-quality support, frequency containment, transient smoothing, and protection of batteries from high-frequency power fluctuations. However, their low energy capacity limits their suitability for sustained balancing or long-duration recovery. Their greatest value may therefore arise when they are combined with batteries rather than deployed alone.

Pumped Hydro Energy Storage (PHES) remains highly suitable for bulk, long-duration storage where geographic and hydrological conditions permit. Its principal strengths are large energy capacity, long lifetime, and mature operation, making it suitable for energy shifting, reserve, and large-system balancing. However, PHES requires suitable terrain, significant civil infrastructure, long development periods, and substantial capital investment. These constraints make it less suitable for rapid distributed deployment than BESS.

Hydrogen energy storage provides a pathway for very long-duration and potentially seasonal storage by converting electricity to hydrogen, storing the hydrogen, and later reconverting it to electricity or using it in other sectors. Its strategic advantage lies in energy duration rather than round-trip efficiency. Recent techno-economic comparisons show that hydrogen storage may become increasingly relevant when the required storage horizon extends beyond the range in which conventional batteries are economical, although conversion losses and infrastructure requirements remain significant (Youssef et al., 2024).

Hybrid Energy Storage Systems (HESS) combine technologies with complementary characteristics. For example, a battery can provide sustained energy while a supercapacitor absorbs short-duration power fluctuations; similarly, a BESS can be combined with pumped hydro or hydrogen to separate short-term flexibility from long-duration energy balancing. The underlying rationale is that resilience is multi-timescale: milliseconds and seconds matter for stability, minutes and hours for balancing, and days or longer for restoration and renewable-energy adequacy. Hybrid architectures therefore offer an attractive way to allocate different dynamic functions to technologies best suited to them.

A useful comparative interpretation is shown below.

TABLE III. COMPARATIVE ASSESSMENT OF ENERGY STORAGE TECHNOLOGIES FOR POWER-SYSTEM RESILIENCE

Technology	Response Speed	Typical Strength	Main Resilience Role	Principal Limitation
Li-ion BESS	Very fast	High efficiency and modularity	Frequency, reserve, smoothing, GFM support	Degradation and thermal risk
Flow Battery	Fast	Decoupled power/energy scaling	Longer-duration cycling	Lower maturity/footprint
Supercapacitor	Extremely fast	High power and cycle life	Transients and fast frequency support	Low energy duration
Pumped Hydro	Moderate	Bulk long-duration storage	System balancing and recovery	Geographic constraints
Hydrogen	Slow–moderate	Very long-duration energy storage	Seasonal adequacy and restoration	Low round-trip efficiency
Hybrid ESS	Multi-timescale	Complementary performance	Integrated resilience	Control and design complexity

The appropriate conclusion is therefore not that one technology dominates, but that storage selection is timescale- and service-dependent.

8.2 Grid Services Provided by ESS

ESS can support grid resilience through a broad range of operational services. At the fastest timescale, storage can provide frequency regulation by rapidly injecting or absorbing active power following generation–load imbalance. Battery-based resources are particularly valuable in low-inertia systems because converter response is much faster than conventional governor action. NREL assessments of distributed and mobile storage show that battery resources can support frequency control, voltage regulation, and restoration services when their control and power-electronic interfaces are appropriately configured (Narang et al., 2021).

ESS can also provide voltage support by coordinating active- and reactive-power exchange through its inverter. While stored energy is primarily relevant to active-power

support, the converter interface can independently or jointly regulate reactive power within its current limits. This capability becomes increasingly valuable in weak-grid and high-PV environments.

At longer timescales, storage enables peak shaving and load shifting, reducing system stress during peak demand and redistributing renewable energy from periods of surplus generation to periods of higher demand. It can also provide ramp-rate control, smoothing rapid changes in PV and wind output and thereby reducing the balancing burden imposed on conventional generation.

A further function is renewable-energy smoothing. Rather than allowing every fluctuation in solar irradiance or wind speed to propagate directly into the grid, storage can buffer short-term variability and deliver a more controlled power profile. This improves operational predictability and may reduce voltage and frequency excursions.

Storage can additionally provide operating reserve, including contingency and fast-response reserve, provided sufficient state of charge is maintained. This emphasizes an important point: an installed BESS does not automatically provide resilience. Its ability to respond depends on available headroom, state of charge, converter rating, reserve scheduling, and energy duration.

Finally, ESS can provide black-start and restoration support. NREL demonstrations have shown that inverter-based battery systems can energize islanded networks and support restoration when operated with grid-forming control (Jain et al., 2020; Fix et al., 2023). Thus, storage becomes particularly important not only during normal renewable balancing but also after severe disruptions.

8.3 BESS + GFM: From Stored Energy to Grid-Forming Resilience

The relationship between BESS and GFM is central to the logic of this review. A grid-forming inverter is fundamentally a power-electronic control interface, not an independent energy source. Its ability to inject active power, emulate inertia, support frequency, or sustain islanded operation ultimately depends on an available DC-side resource. For this reason, the combination of BESS and GFM represents one of the most technically coherent architectures for renewable-rich weak grids.

The functional chain can be expressed as:

BESS → Stored Energy and Flexibility → GFM Converter → Voltage/Frequency-Forming Interface → Grid Support → Resilience

In this architecture, the battery provides the energy and power reserve, while the GFM converter determines how that reserve interacts dynamically with the AC grid. This distinction is fundamental. Without adequate DC-side energy, a GFM inverter may be able to establish a waveform but cannot sustain significant active-power support. Conversely, a large BESS connected through conventional control may possess substantial stored energy but may not provide the voltage-forming and autonomous synchronization functions required in weak or islanded conditions.

Experimental evidence supports the value of combining these functions. Koralewicz et al. (2022) demonstrated multi-megawatt operation of a renewable power system in which grid-forming BESS supported islanded operation and black start, including coordination with distributed PV and local loads. Similarly, Poudel et al. (2021) investigated the integration of storage on the DC link of full-converter wind generation, showing how battery storage can support converter-based renewable operation through direct DC-side coupling.

From a resilience perspective, BESS–GFM coupling is particularly attractive because it connects energy flexibility with dynamic stability. The BESS supplies controllable active power, while the GFM controller can translate that capability into fast frequency response, voltage support, virtual inertia, island formation, and restoration. However, the performance of the combined system depends critically on BESS sizing, state of charge, converter overload capability, control tuning, and the duration of the expected disturbance.

This means that the design question should not simply be:

How much battery capacity is required?

but rather:

What combination of energy capacity, power rating, GFM control, reserve margin, and operating strategy is required for a specific resilience function?

That distinction is particularly important for Libya, where storage investment is likely to be constrained and therefore should be targeted toward locations and services where it produces maximum stability and resilience benefit.

8.4 Critical Limitations of Energy Storage

Despite its strategic value, energy storage introduces significant technical and economic constraints. The first is capital cost. Although battery costs have declined substantially, utility-scale storage still requires significant upfront investment in cells, converters, balance-of-system equipment, cooling, protection, civil works, and control infrastructure. Cost also scales differently with power and energy duration, meaning that short-duration frequency support and multi-hour energy shifting cannot be evaluated using the same economic assumptions.

A second limitation is degradation. Battery capacity and power capability decline with calendar aging, cycling, temperature, depth of discharge, state-of-charge window, and charge/discharge rate. Consequently, intensive use for multiple grid services can increase revenue or resilience value while simultaneously accelerating aging. This creates a fundamental operational trade-off between short-term grid support and long-term asset life.

Closely related is State of Health (SoH). Reliable SoH estimation is essential because storage operators must know the remaining usable capacity and power capability of the system. Second-life and aged batteries require particularly careful assessment before deployment in stationary applications. NREL work on second-life battery suitability emphasizes the importance of characterizing remaining energy, power, degradation state, and application-specific requirements before reuse (Montes Torre et al., 2022).

Thermal management is another critical issue. High charge/discharge rates generate heat, and uneven temperatures can accelerate degradation and increase cell

imbalance. Thermal design is therefore not an auxiliary engineering feature but a core determinant of performance, safety, and lifetime.

Sizing represents a further challenge. Undersized storage may exhaust its energy reserve before a disturbance is resolved, whereas oversized storage may impose unnecessary capital cost. Appropriate sizing must therefore consider the required service duration, probability and severity of contingencies, renewable variability, reserve needs, network location, and expected control strategy.

End-of-life management and recycling are also increasingly important as BESS deployment grows. Large-scale storage raises questions concerning material recovery, waste management, second-life applications, supply-chain sustainability, and environmental impacts.

Lifetime remains technology- and duty-cycle dependent. A BESS designed for low-frequency energy shifting may experience a very different lifecycle from one providing continuous frequency regulation or repeated grid-forming response. Consequently, resilience planning must account for the operational profile rather than relying on nominal cycle-life values alone.

Finally, fire and safety risks require explicit attention. Lithium-ion systems can experience thermal runaway under certain failure conditions, including internal faults, overheating, mechanical damage, and failures in battery-management or protection systems. Official energy-storage safety studies continue to emphasize thermal runaway propagation, system-level protection, ventilation, monitoring, and emergency response as essential design considerations.

The critical conclusion is therefore that ESS does not automatically create resilience. Its contribution is service-, duration-, location-, and control-dependent. A BESS that is excellent for fast frequency regulation may not be economically optimal for multi-day energy adequacy, while hydrogen or pumped hydro may offer longer duration but slower response. Likewise, a storage system without appropriate GFM capability may provide energy flexibility without delivering the full dynamic support required by a weak grid.

For the Libyan power system, this suggests that storage planning should follow a multi-timescale resilience strategy rather than a single-technology deployment strategy: fast BESS/GFM resources for stability and restoration, potentially complemented by longer-duration storage technologies for energy adequacy and renewable balancing.

The limitations of storage also explain why physical flexibility alone is insufficient. As the number of renewable generators, storage devices, grid-forming converters, controllable loads, and network constraints increases, the central challenge shifts from simply having flexible resources to coordinating them intelligently in real time. This creates the rationale for the third technological pillar of the proposed resilience architecture:

9. AI-Based Control and Energy Management

The increasing penetration of variable renewable energy resources is transforming power-system operation into a more data-intensive, uncertain, and computationally demanding task. While GFM provides a grid-support interface and ESS provides controllable energy and flexibility, neither technology alone determines how thousands of distributed resources should be forecast, scheduled, coordinated, or adapted to changing system conditions. Artificial Intelligence (AI) can address this coordination layer by transforming historical and real-time measurements into forecasts, classifications, control actions, maintenance decisions, and optimized schedules. Recent research therefore positions AI as an enabling technology for renewable forecasting, dispatch, stability control, energy management, and market operation rather than as an independent source of physical grid strength (Li et al., 2024; Alazemi et al., 2024).

9.1 AI Techniques

Several AI families are relevant to renewable-rich power systems, but their suitability varies according to the problem, timescale, available data, and required level of operational assurance.

Artificial Neural Networks (ANNs) are among the most established data-driven techniques in power engineering. Their ability to approximate nonlinear relationships makes them suitable for load forecasting, renewable-generation prediction, battery-state estimation, fault classification, and power-quality assessment. Unlike conventional linear statistical models, ANNs can represent complex relationships among meteorological, operational, and electrical variables. However, their predictive capability depends heavily on representative training data, and their performance may deteriorate when operating conditions depart significantly from the data used during training. Consequently, ANN accuracy under historical test conditions should not automatically be interpreted as evidence of robustness under extreme or previously unseen grid events (Li et al., 2024).

Deep Learning (DL) extends ANN capabilities through multi-layer architectures capable of extracting complex temporal and spatial patterns from large datasets. Architectures such as CNNs, RNNs, LSTMs, GRUs, and more recently attention-based models are increasingly applied to PV, wind, and load forecasting. Li et al. (2024) show that deep-learning approaches have become particularly important for renewable-generation forecasting because they can capture nonlinear and temporal dependencies that are difficult to represent using traditional models. Their advantage, however, comes with increased computational cost, greater data requirements, and reduced interpretability.

Reinforcement Learning (RL) is particularly relevant to sequential decision-making. Rather than learning only input-output relationships, an RL agent learns a control policy by interacting with an environment and receiving rewards or penalties. Applications include ESS scheduling, voltage control, frequency regulation, demand response, economic dispatch, and microgrid

energy management. Deep Reinforcement Learning (DRL) further extends this capability to high-dimensional nonlinear environments. Nevertheless, conventional RL creates an important conflict with power-system operation: trial-and-error exploration may generate unsafe actions. Recent safe-RL research therefore emphasizes constrained learning, safety layers, Lyapunov-based approaches, and other mechanisms designed to keep states and actions within acceptable operating regions (Su et al., 2025).

Fuzzy systems provide an alternative form of intelligent control based on linguistic rules and membership functions rather than exclusively on data-intensive training. Their ability to translate expert knowledge into rules such as IF frequency deviation is high AND battery SoC is sufficient, THEN increase active-power support makes them attractive for energy management, storage control, voltage regulation, and microgrid applications. Fuzzy systems offer comparatively high interpretability and can perform effectively when accurate mathematical models are unavailable. However, as system dimensionality increases, the number of rules and membership functions may grow substantially, making design, tuning, and scalability increasingly difficult.

Hybrid AI combines complementary techniques to overcome limitations inherent in individual algorithms. Examples include ANN–fuzzy architectures, deep learning combined with optimization, physics-informed machine learning, and forecasting models coupled with RL-based scheduling. Hybridization is particularly relevant to renewable power systems because forecasting, optimization, control, fault detection, and asset management represent fundamentally different computational tasks. Recent reviews indicate that AI integration across renewable-energy systems increasingly involves combinations of forecasting, monitoring, optimization, and control methods rather than reliance on a single universal algorithm (Ukoba et al., 2024).

Finally, predictive analytics provides an anticipatory intelligence layer by combining historical records, sensor measurements, statistical learning, and AI models to estimate future operating conditions. It can predict renewable generation, demand, equipment deterioration, battery degradation, congestion, or emerging system anomalies. Its resilience value is particularly important because it allows the system to move from reactive operation toward preventive and anticipatory operation.

TABLE IV. COMPARATIVE CHARACTERISTICS OF AI TECHNIQUES FOR RENEWABLE-RICH POWER SYSTEMS

Technique	Primary capability	Key advantage	Principal limitation	Resilience relevance
ANN	Nonlinear prediction/classification	Flexible nonlinear modeling	Data dependency	Forecasting and detection
Deep Learning	Complex temporal/spatial learning	High predictive capability	Computation and explainability	Anticipation and situational awareness
Reinforcement Learning	Sequential control/optimization	Adaptive decision-making	Safety during learning/deployment	Response and adaptation
Fuzzy Systems	Rule-based control	Interpretability	Scalability of rule base	Local control and decision support
Hybrid AI	Multi-method intelligence	Complementary capabilities	Architectural complexity	Multi-layer resilience
Predictive Analytics	Future-state estimation	Preventive decision-making	Forecast uncertainty	Preparation and prevention

Thus, the relevant engineering question is not which AI algorithm is universally best, but rather which method is appropriate for a particular grid function, timescale, safety requirement, and data environment.

9.2 Applications of AI in Renewable-Rich Power Systems

The contribution of AI to power-system operation extends from forecasting several hours ahead to real-time control occurring within seconds or fractions of a second. This functional diversity makes it particularly relevant to the coordination of GFM, ESS, renewable generation, and flexible demand.

Load forecasting is among the most mature applications. Accurate short-term and day-ahead demand forecasts improve unit scheduling, reserve allocation, ESS charging/discharging, and demand-response decisions. Deep neural architectures can capture nonlinear temporal patterns, weather sensitivity, consumer behavior, and calendar effects more effectively than many conventional forecasting approaches under suitable data conditions (Li et al., 2024).

PV forecasting is particularly important because rapid changes in solar irradiance can create significant power ramps. AI models can integrate irradiance, temperature, cloud information, historical PV output, and other meteorological variables to estimate future generation. Similarly, wind forecasting uses historical wind speed, direction, atmospheric conditions, and turbine data to estimate wind generation over different time horizons. Improved PV and wind forecasting reduces uncertainty and allows storage and reserve resources to be positioned proactively rather than reactively. AI-based renewable forecasting therefore has an indirect but important effect on grid stability and resilience (Alazemi et al., 2024).

ESS scheduling represents a more decision-oriented application. AI can determine when a battery should charge, discharge, maintain reserve, or preserve state-of-charge headroom based on expected renewable generation, demand, electricity-system conditions, and resilience requirements. RL is particularly relevant because storage operation is sequential: aggressive discharge at one time may leave insufficient stored energy for a subsequent contingency.

AI can also support fault detection and classification by identifying abnormal patterns in voltage, current, frequency, harmonics, or equipment measurements. Data-driven detection can potentially recognize complex signatures that are difficult to encode using fixed thresholds. However, fault-detection algorithms must be validated against rare and severe events, because high classification accuracy on routine historical datasets does

not necessarily imply reliable performance during previously unseen faults.

Closely related is predictive maintenance. AI can analyze temperature, vibration, electrical measurements, alarms, degradation indicators, and maintenance records to estimate emerging failures in transformers, converters, batteries, wind turbines, and other critical assets. The resilience contribution is significant: avoiding a failure before it occurs is generally more valuable than merely improving recovery after the failure.

AI methods have also been investigated for frequency control and voltage regulation. RL-based controllers can learn corrective actions from system states and potentially coordinate distributed resources under nonlinear and uncertain conditions. Safe-RL literature specifically identifies frequency regulation, voltage control, and energy management as major application areas while simultaneously emphasizing that safety constraints must be embedded into the learning and deployment process (Yu et al., 2024; Su et al., 2025).

Demand response provides another important flexibility resource. AI can forecast consumption patterns, identify flexible loads, optimize scheduling, and coordinate customer-side resources with renewable availability and grid conditions. At a higher level, AI-based energy management systems (EMS) can integrate forecasts, storage states, generation limits, network constraints, flexible demand, and economic objectives into coordinated operational decisions. Li et al. (2024) identify forecasting, dispatch, control, and market decision-making as interconnected AI application domains within renewable power-system operation.

These applications can be summarized functionally as:

Forecast → Detect → Schedule → Optimize → Control → Learn

rather than treating AI as a single-purpose technology.

9.3 Artificial Intelligence for Grid Resilience

The resilience contribution of AI becomes clearer when its functions are mapped onto the previously defined resilience cycle:

Prepare → Absorb → Respond → Recover → Adapt

During the Prepare stage, AI can improve renewable and load forecasting, contingency prediction, weather-risk assessment, ESS reserve scheduling, and predictive maintenance. This may enable the system operator to identify potential stress conditions before they develop into major disturbances.

During Absorb, AI can support rapid situational awareness, anomaly detection, adaptive resource allocation, and identification of emerging instability. However, the physical ability to withstand a disturbance still depends primarily on network infrastructure and resources such as GFM, ESS, synchronous machines, protection systems, and transmission capacity.

During Respond, AI-based control can potentially coordinate BESS dispatch, demand response, voltage support, and other controllable resources. RL and other adaptive approaches are particularly relevant here, although safety requirements become correspondingly more stringent as decision timescales shorten.

During Recover, intelligent systems can assist restoration sequencing, microgrid coordination, load prioritization, storage management, and decision support following outages.

Finally, during Adapt, predictive analytics and machine learning can analyze previous disturbances, update models, identify recurring vulnerabilities, and improve future operational strategies.

The relationship can therefore be conceptualized as:

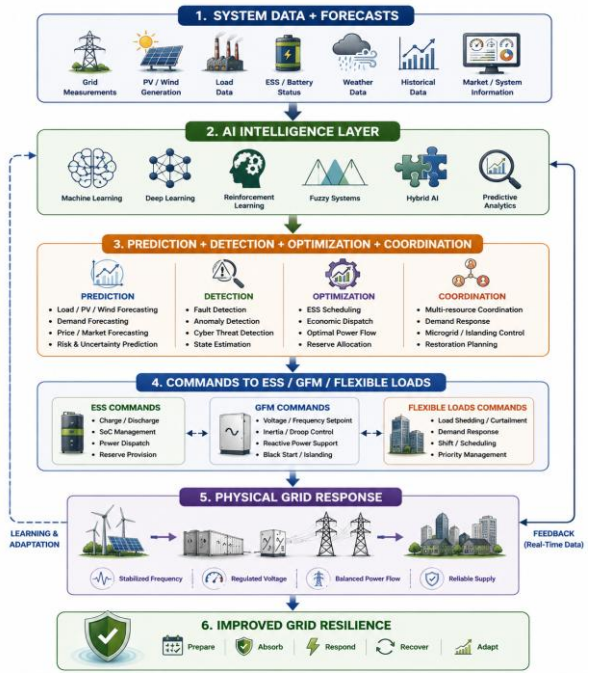


Figure 3. AI-Enabled Grid Resilience Framework for Renewable-Rich Power Systems

This distinction is critical to the central argument of the paper. AI does not directly provide inertia, stored energy, voltage strength, or fault current. Instead, it can improve how resources possessing those physical capabilities are anticipated, allocated, coordinated, and controlled. Therefore, presenting AI as an alternative to GFM or ESS would be conceptually misleading.

The integrated architecture proposed in this review can instead be expressed as:

ESS = Energy and Flexibility Layer → GFM = Electrical Grid-Support Interface → AI = Intelligence and Coordination Layer

This three-layer interpretation provides a stronger theoretical basis for the proposed **GFM–ESS–AI resilience** architecture than treating the technologies as independent alternatives.

9.4 Critical Limitations of AI-Based Power-System Control

Despite its considerable potential, AI should not be presented as a technological panacea for grid resilience. Its use in safety-critical electricity infrastructure introduces several limitations that become particularly

important when algorithms move from offline forecasting toward autonomous real-time control.

The first limitation is data dependency. Supervised AI models require sufficiently large, accurate, representative, and well-labelled datasets. Missing measurements, sensor errors, inconsistent sampling, limited disturbance records, or fragmented databases can substantially reduce model performance. This problem is particularly severe for rare high-impact events because the historical datasets needed to train algorithms on such conditions are inherently limited.

A related challenge is generalization. A model trained on one grid configuration, weather regime, renewable penetration level, or operating condition may not retain equivalent performance when these conditions change. This means that successful validation using historical data from one environment cannot automatically establish robustness under another.

This leads directly to dataset shift. Renewable-rich power systems evolve continuously as PV, wind, batteries, EVs, GFM resources, loads, and network configurations change. The statistical distribution encountered during deployment may therefore differ from the training distribution. AI performance must consequently be monitored and models periodically retrained or adapted.

Another major limitation is explainability. Complex deep-learning and RL models can produce highly accurate outputs without providing operators with a transparent explanation of why a particular action was recommended. This creates a serious challenge in safety-critical grid environments where operators, regulators, and engineers need to understand and verify control decisions.

Closely associated is black-box behavior. High predictive accuracy alone does not guarantee physically meaningful or operationally safe decisions. AI models can exploit statistical correlations that do not reflect power-system physics. This supports growing interest in explainable, physics-informed, and hybrid AI rather than unconstrained black-box models.

Cybersecurity introduces an additional vulnerability. AI systems depend on measurements, communication infrastructure, and digital control signals that may be manipulated through false-data injection, adversarial examples, compromised sensors, or communication attacks. Research on learning-based power-system operation demonstrates that adversarial manipulation can affect safety-critical tasks such as voltage regulation and topology control. Thus, increasing intelligence can simultaneously increase the digital attack surface unless cybersecurity is integrated into system design.

Computational requirements also matter. Large deep-learning models and optimization-intensive AI architectures may require substantial processing capacity, memory, communication bandwidth, and specialized hardware. This becomes particularly relevant for distributed grids or regions with limited digital infrastructure.

Furthermore, real-time constraints create a fundamental engineering boundary. An algorithm that produces an excellent solution after several seconds may be unsuitable for a control problem requiring action within milliseconds. AI algorithms should therefore be evaluated not only by prediction accuracy or optimization quality but also by latency, determinism, computational reliability, and compatibility with the timescale of the physical phenomenon.

The most serious limitation concerns safety-critical control. Conventional RL learns partly through exploration, but a real power system cannot safely tolerate arbitrary experimental actions. Unsafe voltage, frequency, thermal, or current conditions can damage equipment or initiate cascading failures. Recent safe-RL reviews therefore argue that traditional unconstrained RL cannot simply be transferred directly into operational power-system control; safety layers, constraint enforcement, offline training, digital twins, formal verification, or other mechanisms are required (Yu et al., 2024; Su et al., 2025).

TABLE V. CRITICAL LIMITATIONS OF AI FOR GRID-RESILIENCE APPLICATIONS

Limitation	Engineering consequence	Required response
Data dependency	Poor data can produce unreliable decisions	Data governance and validation
Generalization	Performance may decline under unseen conditions	Cross-condition testing
Dataset shift	Models become outdated as grid conditions evolve	Monitoring and retraining
Explainability	Operators cannot readily justify decisions	XAI / interpretable models
Black-box behavior	Statistically valid but physically unsafe outputs	Physics-informed/hybrid AI
Cybersecurity	Manipulated data can corrupt decisions	Secure sensing and adversarial robustness
Computational requirements	Excessive hardware/communication burden	Edge computing/model reduction
Real-time constraints	Decisions may arrive too late	Latency-aware algorithm design
Safety-critical control	AI actions may violate physical constraints	Safe RL, safety layers, formal constraints

The appropriate conclusion is therefore deliberately conditional:

The value of AI for grid resilience is determined not only by predictive accuracy, but by robustness, explainability, cybersecurity, computational feasibility, real-time performance, and demonstrable operational safety.

This point is particularly relevant to Libya. Advanced AI control should not precede the development of reliable measurements, communication infrastructure, digital databases, validated grid models, and cybersecurity mechanisms. A realistic Libyan pathway would therefore involve progressive AI maturity: beginning with forecasting, condition monitoring, and predictive maintenance; progressing toward ESS scheduling and decision support; and only subsequently considering increasingly autonomous frequency, voltage, and

resilience control after adequate simulation, digital-twin, hardware-in-the-loop, and field validation.

10. Critical Comparative Analysis of GFM, ESS, and AI-Based Control

The preceding sections demonstrate that Grid-Forming Inverters (GFM), Energy Storage Systems (ESS), and AI-based control address fundamentally different dimensions of grid resilience. Accordingly, their comparison should not be framed as a search for a universally superior technology. GFM primarily modifies the electrical behavior of inverter-based resources at the grid interface; ESS provides controllable physical energy and flexibility across multiple timescales; and AI provides forecasting, optimization, detection, and coordination capabilities. Experimental and hardware-based studies show that GFM-controlled resources can improve frequency response, system strength, islanded operation, and black-start capability, particularly under weak-grid conditions, while BESS can provide fast frequency and voltage regulation, renewable smoothing, reserve, peak shaving, and restoration support (Wang et al., 2024; Yan et al., 2024).

The comparison therefore needs to distinguish between physical grid-support functions and supervisory intelligence functions. GFM directly affects voltage-angle and frequency dynamics, making its contribution particularly important when system strength or synchronous inertia is inadequate. Hardware experiments involving multiple commercial GFM inverters have demonstrated their potential to support weak-grid stability and grid-connected operation, although such studies also emphasize the continuing need for wider hardware validation and interoperability testing (Wang et al., 2024). By contrast, AI does not itself supply energy, inertia, or voltage strength. Its principal value lies in interpreting system data and generating improved forecasts, control policies, or coordination decisions. Studies on autonomous grid control, for example, demonstrate the potential of machine-learning-based controllers to improve adaptive grid operation, while cyber-resilient reinforcement-learning environments illustrate how intelligent decision-making can also be extended to network reconfiguration under compromised conditions (Obert et al., 2023; Sahu et al., 2023).

10.1 Frequency Stability and Inertia Support

Among the three technologies, GFM provides the most direct contribution to frequency-forming behavior. Unlike conventional GFL resources that generally respond to an externally established waveform, GFM can establish an internal voltage-frequency reference and modify active-power output in response to disturbances. Experimental work comparing GFL- and GFM-controlled BESS found that GFM operation can more directly support frequency stability and can operate autonomously during black-start sequences, whereas GFL operation requires an already energized network reference (Yan et al., 2024).

ESS can also make a strong contribution to frequency stability because batteries can rapidly absorb or inject active power. However, the battery itself does not determine the dynamic frequency-forming behavior; this depends on the inverter and its control architecture. The U.S. Department of Energy identifies frequency regulation as one of the principal BESS applications because battery systems can respond on millisecond-to-second timescales (U.S. Department of Energy, 2025). Consequently, the statement that ESS provides "inertia support" requires qualification: ESS can provide inertia-like or fast-frequency response when coupled with an appropriate control strategy, including GFM or synthetic-inertia control.

AI contributes to frequency stability mainly indirectly or through control optimization. Machine-learning and reinforcement-learning controllers can adapt power-system control policies, but their effectiveness ultimately depends on physical resources capable of injecting or absorbing power. Thus, AI may improve the dispatch or control of BESS and GFM, but it cannot replace the physical energy and electrical-interface requirements associated with frequency support.

10.2 *Voltage Regulation and Weak-Grid Operation*

GFM also possesses a distinctive advantage in voltage support and weak-grid operation because its control philosophy treats the converter more directly as a voltage-forming resource. Hardware testing of commercial GFM inverters has specifically targeted their behavior under grid-connected and weak-grid conditions, supporting the view that GFM is increasingly important as renewable penetration rises and system strength declines (Wang et al., 2024).

ESS can provide strong voltage support through its inverter by supplying or absorbing reactive power. The DOE identifies voltage regulation as a major BESS grid service, with inverter-based storage capable of responding quickly to transient and local voltage deviations (U.S. Department of Energy, 2025). Nevertheless, the degree to which ESS enhances weak-grid stability again depends strongly on whether its converter operates in GFL, grid-supporting, or GFM mode. This illustrates why storage capacity and inverter functionality should not be treated as equivalent technical characteristics.

AI-based voltage control may offer significant optimization potential, particularly where many distributed resources must be coordinated, but it remains dependent on measurements, communications, computational infrastructure, and available controllable assets. Therefore, AI can enhance voltage-management decisions, but it does not independently increase short-circuit strength or create a voltage-forming source.

10.3 Renewable Smoothing and System Flexibility

In contrast to GFM, ESS is clearly the strongest technology for renewable-energy smoothing and temporal flexibility. Batteries can store excess solar and wind generation and release it when renewable output declines or demand rises. The DOE identifies renewable smoothing, ramping support, load following, reserve provision, peak shaving, and congestion relief among the major applications of BESS (U.S. Department of Energy, 2025).

GFM provides little renewable smoothing by itself because it does not inherently store energy. Its contribution depends on the DC-side resource. A GFM inverter connected to BESS can provide both dynamic grid formation and temporal flexibility, whereas GFM connected to a renewable source without sufficient headroom or storage may have limited capacity to sustain prolonged active-power support.

AI contributes strongly to renewable smoothing at the supervisory level by improving forecasting and coordinating storage dispatch. This means that ESS supplies the physical flexibility while AI may improve how effectively that flexibility is used. Therefore, for renewable smoothing, the technologies are more appropriately represented as:

AI Forecasting → ESS Scheduling → GFM/Converter Dispatch → Smoother Grid Injection

rather than as three competing alternatives.

10.4 Black Start and Restoration Capability

Black-start capability illustrates particularly clearly why the three technologies should be analyzed as complementary. GFM can establish the voltage and frequency reference required to energize a de-energized network. BESS can provide the stored energy necessary to sustain that process. In real-world and power-hardware-in-the-loop testing, Yan et al. (2024) demonstrated that a BESS operating in GFM mode could independently energize part of a network and support regional restoration, whereas the same BESS in GFL mode could not operate independently without an energized grid reference.

This finding demonstrates that neither the battery nor the inverter function alone explains black-start capability. It is their functional integration that creates the restoration resource.

AI can support restoration by determining energization sequences, prioritizing loads, coordinating distributed resources, and adapting restoration strategies to evolving system conditions. Its role should therefore be classified as supporting or coordinating, rather than as an independent black-start source.

10.5 Forecasting and Real-Time Optimization

Forecasting represents the clearest area in which AI is dominant. GFM and ESS do not inherently predict renewable generation, load, equipment condition, or disturbances. AI-based forecasting architectures can use meteorological and operational data to anticipate renewable output and demand, enabling more informed scheduling of storage and reserves.

Likewise, AI has the greatest potential for real-time and near-real-time optimization, particularly when large numbers of distributed resources and operational constraints must be considered simultaneously. Nevertheless, "very high" optimization capability should not be interpreted as unconditional superiority. Machine-learning control remains affected by data quality, latency, generalization, and safety constraints. Obert et al. (2023), for example, demonstrated autonomous grid-control techniques while explicitly addressing measurement noise, illustrating that data-driven controllers must remain robust to imperfect operating information. Sahu et al. (2023) further demonstrated a reinforcement-learning environment specifically designed around cyber-resilient distribution-system operation, showing that intelligent control must be assessed alongside cyber-physical vulnerabilities rather than solely by optimization performance.

10.6 Capital, Data, and Cybersecurity Requirements

ESS generally entails the highest direct capital requirement because large-scale deployment requires battery modules, power-conversion systems, thermal management, civil infrastructure, protection, and balance-of-system equipment. GFM may require lower incremental capital when implemented as a control capability within an already required inverter or BESS platform, although hardware upgrades, converter oversizing, control validation, and protection modifications may still be necessary.

AI-based systems can appear less capital-intensive than physical storage infrastructure, but this comparison must be treated cautiously. AI may require extensive sensing, communication networks, computing infrastructure, data management, cybersecurity, and integration with control centers. Therefore, "moderate capital cost" should be interpreted as lower physical-energy infrastructure requirements but potentially significant digital-infrastructure requirements.

The trade-off reverses for data dependency. GFM and ESS rely primarily on electrical measurements and local controllers for core grid-support functions, whereas AI is inherently dependent on historical and/or real-time datasets. Consequently, AI has the greatest exposure to data quality, missing measurements, dataset shift, and adversarial manipulation.

Cybersecurity exposure follows a similar pattern. GFM and ESS can face cybersecurity threats, especially when remotely monitored or coordinated, but AI-based control typically depends more extensively on communications, datasets, and computational pipelines. Sahu et al. (2023) explicitly demonstrated how reinforcement-learning environments can be used to investigate cyber-resilient network reconfiguration, reinforcing the idea that cyber resilience must become an integral component of AI-enabled power-system design.

10.7 Evidence-Informed Comparative Matrix

Based on the engineering evidence synthesized above, the three technologies can be compared using a common resilience-oriented framework. The ratings below should be interpreted as qualitative evidence-informed assessments rather than universal numerical rankings, because performance changes according to control architecture, ESS sizing, network strength, operating conditions, data quality, and implementation design.

TABLE VI. MULTI-CRITERIA COMPARATIVE ASSESSMENT OF GRID-FORMING INVERTERS, ENERGY STORAGE SYSTEMS, AND AI-BASED CONTROL FOR GRID RESILIENCE

Criterion	GFM	ESS	AI-Based Control
Frequency stability	Very High	High	High / Indirect
Voltage	Very High	High	High /

support			Coordinating
Inertia-like support	High	High with suitable control	Indirect
Renewable smoothing	Low alone	Very High	High through coordination
Black-start capability	High	High when suitably interfaced	Supporting / Coordinating
Forecasting capability	None	None	Very High
Real-time optimization	Moderate	Moderate	Very High, subject to computational limits
Capital requirements	Moderate	High	Moderate / digitally intensive
Data dependency	Low–Moderate	Low–Moderate	Very High
Cybersecurity exposure	Moderate	Moderate	High
Weak-grid suitability	Very High potential	High with suitable inverter control	Context-dependent
Physical energy provision	None by itself	Very High	None
Restoration support	Very High	High	High as supervisory support
Technological role	Grid-forming/stability layer	Energy/flexibility layer	Intelligence/coordination layer

The matrix highlights a critical finding: the strengths of the three technologies are largely non-substitutable. GFM performs best where the problem is electrical formation and dynamic stability; ESS performs best where the problem is energy flexibility and temporal balancing; and AI performs best where the problem is information processing, forecasting, optimization, and coordination. This explains why a simple ranking of GFM, ESS, and AI from "best" to "worst" would be technically misleading.

10.8 Critical Interpretation: Competition or Complementarity?

The comparative evidence challenges the assumption that future grid planners should choose GFM or ESS or AI. A more technically defensible conclusion is that the three technologies operate at different layers of the resilience problem.

GFM determines how a converter interacts dynamically with the AC network. ESS determines how much controllable energy and power are physically available. AI determines how information is interpreted and how resources are scheduled or coordinated.

Accordingly, their functional relationship can be represented as:

ESS provides energy → GFM converts that energy into grid-forming support → AI optimizes when, where, and how the combined resource should respond.

Experimental BESS–GFM restoration results strongly support this complementarity: the same stored-energy resource provides fundamentally different resilience services depending on whether its inverter operates as GFL or GFM (Yan et al., 2024). At the same time, learning-based autonomous control research suggests that increasingly complex distributed networks can benefit from intelligent decision-making, provided that robustness and cybersecurity are incorporated into the architecture (Obert et al., 2023; Sahu et al., 2023).

The critical conclusion of this comparison is therefore:

No single technology provides the complete set of capabilities required for renewable-rich grid resilience.

More specifically:

GFM provides stability, ESS provides flexibility and energy, and AI provides intelligence and coordination.

Their integration may therefore offer greater system-level value than independently maximizing the deployment of any single technology. This conclusion provides the conceptual basis for the following section of the review, which examines the synergies among GFM, ESS, and AI and develops an integrated architecture suitable for weak-grid and Libyan power-system conditions.

11. SYNERGIES AMONG GFM, ESS, AND AI

The critical comparison presented in the previous section suggests that Grid-Forming Inverters (GFM), Energy Storage Systems (ESS), and AI-based control should not be treated as competing alternatives but as complementary layers of a unified grid-resilience architecture. GFM provides the electrical behavior required to establish and support voltage and frequency, ESS provides the controllable energy and fast flexibility needed to sustain that response, while AI adds forecasting, optimization, coordination, and adaptive decision-making. Recent work on Grid-Forming Battery Energy Storage Systems confirms that combining storage with grid-forming control is particularly relevant in renewable-rich and weak-grid environments because the storage resource provides the physical energy reserve while the GFM converter determines how that reserve interacts dynamically with the grid (Zhu, 2024; Wang et al., 2024).

The integrated operating logic can therefore be represented as:

Renewable Generation → BESS → Grid-Forming Converter → Weak Grid

with an upper supervisory layer:

AI Supervisory Control → Forecasting + Dispatch + SoC Management + Stability Coordination + Predictive Maintenance

Within this structure, forecasting anticipates renewable generation and load conditions; dispatch optimization determines when storage should charge, discharge, or preserve reserve; State-of-Charge (SoC) management ensures adequate energy remains available for contingencies; stability coordination adjusts operating decisions to support frequency and voltage requirements; and predictive maintenance identifies emerging faults or degradation before they compromise availability. AI-based energy-management studies increasingly demonstrate the value of integrating forecasting,

decentralized decision-making, and optimization in renewable microgrids, while broader reviews show that intelligent control can improve reliability and resilience when linked to physical grid resources (Safari et al., 2024; Khanna et al., 2025).

This synergy is particularly important because each technology compensates for limitations in the others. GFM without adequate storage may be unable to sustain prolonged active-power support; ESS without GFM may possess energy flexibility but lack voltage- and frequency-forming capability; and AI without physical grid-support resources cannot directly provide inertia, energy, or voltage strength. Their integration therefore creates a layered architecture in which physical energy, dynamic grid support, and intelligent coordination reinforce one another. Experimental and restoration studies involving GFM-based battery systems further support this complementarity, particularly for black start and operation in weak or islanded networks (Seo et al., 2024; Yan et al., 2024).

Accordingly, the principal conceptual contribution of this review is to shift the analytical perspective from "GFM vs. ESS vs. AI" toward "GFM + ESS + AI." This integrated perspective provides a more realistic basis for future resilient power-system design, particularly in Libya, where renewable integration will require simultaneous improvement in grid stability, energy flexibility, forecasting, operational coordination, and asset management.

12. THE LIBYAN POWER-SYSTEM CONTEXT

12.1 Renewable Energy Potential

Libya possesses substantial solar and wind resources, making renewable-energy integration strategically attractive. Solar energy is particularly promising because of the country's high irradiation levels and large available land area, while wind resources are more location-dependent but remain significant in several coastal and eastern regions. Previous assessments consistently identify solar PV and wind as the most accessible renewable options for diversifying Libya's electricity mix and reducing dependence on fossil-fuel generation (Almaktar & Shaaban, 2021; Maka et al., 2021). IRENA also identifies North Africa, including Libya, as a region with strong solar and wind potential that could support both domestic decarbonization and broader regional energy transitions.

12.2 Characteristics of the Libyan Grid

The Libyan electricity system combines a geographically dispersed transmission network with concentrated generation and long-distance power transfers between major demand and generation areas. This configuration creates operational challenges in regions with weaker network support and makes voltage control, protection coordination, and reliability particularly important when new inverter-based generation is introduced. A grid-impact study of a 10-MW PV plant in Kufra showed that renewable integration can influence voltage profiles, power losses, harmonics, short-circuit behavior, and protection-system performance, confirming that renewable expansion must be accompanied by detailed grid-strength and protection assessments (Alasali et al., 2023).

Reliability is also a major concern. Almaktar (2021) explicitly examined distributed PV and microgrids as possible non-wires alternatives for improving operational reliability and reducing vulnerability to system-wide outages. Libya's location additionally provides opportunities for regional electricity cooperation within North Africa, although interconnection benefits depend on network reinforcement, regulatory coordination, and operational compatibility.

12.3 Barriers to Renewable Integration

The barriers can be classified into five interacting groups. Technical barriers include network weakness, protection challenges, renewable variability, limited flexibility, and the need for improved voltage and frequency support. Economic barriers include high investment requirements for grid reinforcement, storage, and advanced power electronics. Institutional barriers relate to coordination among energy institutions and implementation capacity. Digital barriers include limited monitoring, data availability, advanced control infrastructure, and cybersecurity readiness. Finally, regulatory barriers concern grid codes, market frameworks, interconnection requirements, and mechanisms for renewable investment. Libya has adopted renewable-energy strategic targets, but the gap between resource potential, policy ambition, and practical deployment remains significant (IEA, 2025; Almaktar & Shaaban, 2021).

12.4 Suitability of GFM for Libya

GFM technology appears most relevant in weak-grid areas, renewable plants connected through long transmission corridors, islandable microgrids, and locations requiring enhanced black-start or restoration capability. In such applications, GFM could improve voltage-frequency formation and reduce dependence on a strong external grid reference. However, deployment should follow detailed short-circuit-strength, protection, and transient-stability studies rather than assuming that GFM is universally required.

12.5 Suitability of ESS

ESS could provide particularly high value where Libya faces renewable variability, peak demand, transmission constraints, weak-grid operation, and restoration requirements. BESS located near PV or wind plants could provide ramp-rate control, frequency support, renewable smoothing, reserve, and—when paired with GFM—black-start and islanding capability. Storage should therefore be located according to grid-service needs rather than simply colocated with renewable generation.

12.6 Role of AI

AI is most realistically introduced as a progressive supervisory layer. Initial applications could include solar and wind forecasting, load prediction, predictive maintenance, and fault detection. More advanced stages could support ESS scheduling, dispatch optimization, congestion management, voltage control, and coordinated GFM–ESS operation. For Libya, AI deployment should

therefore evolve in parallel with improved measurement systems, communication networks, data governance, and digital grid models.

Overall, Libya's central challenge is not a shortage of renewable resources but the creation of a grid capable of integrating them securely. This reinforces the logic of the proposed architecture: GFM for dynamic stability, ESS for flexibility and energy support, and AI for forecasting **and coordination.**

13. Proposed Integrated Framework for Libya

The central conceptual contribution of this review is the development of a GFM–ESS–AI Integrated Resilience Framework for Libya, designed to connect physical energy resources, grid-forming capability, and intelligent coordination within a single resilience-oriented architecture. Rather than treating Grid-Forming Inverters, Energy Storage Systems, and AI-based control as separate technological solutions, the proposed framework positions them as mutually reinforcing layers that address different but interdependent requirements of a renewable-rich and potentially weak power system.

The first layer, the Physical Energy Layer, comprises solar PV, wind generation, conventional generation, and Battery Energy Storage Systems (BESS). This layer provides the actual sources of electrical energy and operational flexibility. Renewable resources contribute low-carbon generation, conventional units continue to provide firm capacity during the transition period, while BESS supplies fast active-power support, renewable smoothing, reserve capability, and energy balancing. For Libya, this layer is particularly important because increasing renewable penetration must be accompanied by sufficient flexibility to manage solar and wind variability without compromising supply adequacy.

The second layer is the Grid-Forming and Stability Layer, built around Grid-Forming Inverters (GFM) and associated functions such as voltage regulation, frequency support, virtual inertia, islanded operation, and potentially black-start capability. Its role is to convert the energy and flexibility available in the first layer into dynamic grid-support services. This distinction is fundamental: BESS provides the stored energy, whereas GFM determines how that energy interacts with the AC network during normal operation and disturbances. In weak-grid areas, this layer can therefore contribute directly to improving dynamic stability and reducing dependence on a strong external voltage and frequency reference.

The third layer, the Intelligent Coordination Layer, incorporates AI-based forecasting, optimization, predictive maintenance, energy management, and coordinated dispatch. Its function is not to replace physical grid-support resources, but to improve how they are scheduled and coordinated. AI can forecast PV and wind generation, predict load conditions, optimize BESS State-of-Charge, identify emerging equipment failures, coordinate GFM and ESS dispatch, and support preventive rather than purely reactive grid operation. In this way, the AI layer provides the intelligence required to connect short-term stability decisions with longer-term operational planning.

The interaction among the three layers creates a sequential pathway from energy availability to resilience. The Physical Energy Layer provides generation and flexibility; the Grid-Forming and Stability Layer translates these resources into voltage and frequency support; and the Intelligent Coordination Layer optimizes their use according to forecast conditions, network constraints, and system risks. The expected system-level outcome is a progressive improvement from **Grid Stability → Flexibility → Reliability → Resilience → Higher Renewable Penetration.**

For the Libyan context, the framework should be understood as a staged modernization architecture rather than a single-step technological replacement. Renewable generation and BESS can first be introduced at strategically selected locations; GFM functionality can then be deployed where system-strength, islanding, or restoration requirements justify it; and AI-based coordination can progressively expand as measurement, communication, digital modeling, and cybersecurity capabilities mature. This sequencing makes the framework technically more realistic for Libya because it links technological ambition with infrastructure readiness and operational capability.

The framework therefore reframes Libya's renewable-energy transition from a narrow generation-expansion problem into an integrated grid-resilience transformation. Its principal proposition is that higher renewable penetration is sustainable only when renewable resources are supported simultaneously by physical flexibility, grid-forming stability, and intelligent coordination.

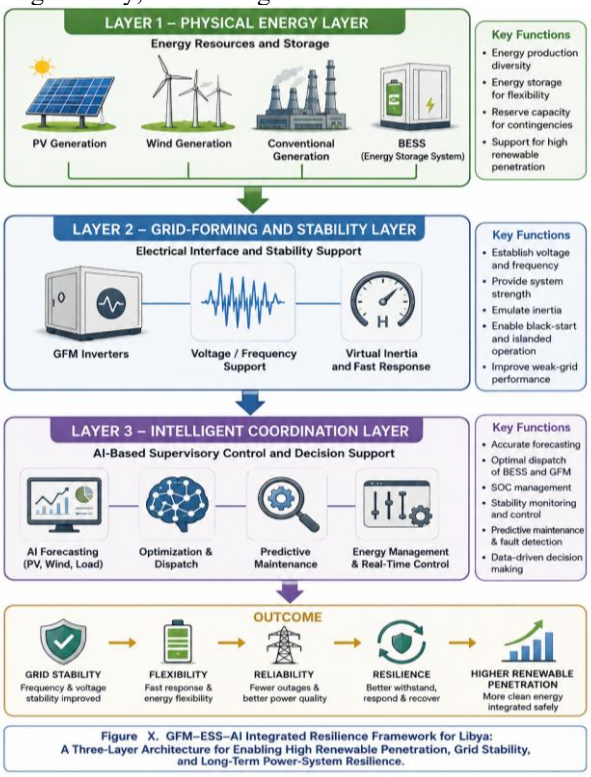


Figure 4. Proposed GFM–ESS–AI Integrated Resilience Framework for Renewable Energy Integration in the Libyan Power System

14. Implementation Roadmap for Libya

The proposed GFM–ESS–AI framework should be implemented through a phased pathway that aligns technological deployment with the technical readiness of the Libyan power system. Rather than assigning fixed calendar years that may not correspond to formally adopted national plans, this review proposes three implementation horizons: **short-, medium-, and long-term.**

- **Phase I – Short-Term:** Assessment and Pilot Deployment. The first phase should focus on establishing the technical and digital foundations required for advanced renewable integration. Priority actions include comprehensive grid-strength and stability assessments, identification of weak-grid locations, pilot PV/wind projects integrated with BESS, renewable and load forecasting systems, improved measurement infrastructure, and demonstration projects for storage-based frequency and voltage support. This phase should also generate reliable operational datasets for subsequent AI applications.
- **Phase II – Medium-Term:** GFM–ESS Integration and Digitalization. Following successful pilot validation, deployment should progress toward GFM-enabled BESS, particularly at renewable plants, weak-grid locations, and strategically important substations. Smart substations, advanced monitoring, wide-area measurements, improved communication infrastructure, and AI-based renewable forecasting and ESS scheduling should be progressively introduced. Hardware-in-the-loop and field validation should precede large-scale deployment of advanced GFM and AI control.
- **Phase III – Long-Term:** Integrated Resilient Smart Grid. The final phase should target a power system capable of accommodating substantially higher renewable penetration through coordinated fleets of GFM-enabled renewable and storage resources. AI-assisted national energy management could integrate renewable forecasting, ESS dispatch, predictive maintenance, demand response, stability monitoring, and system restoration. The ultimate objective is a digitally coordinated, flexible, and resilient Libyan smart grid capable of maintaining secure operation under high shares of inverter-based renewable generation.

- The proposed pathway can therefore be summarized as:
- **Assessment & Pilots → GFM‑BESS Integration & Digitalization → AI-Coordinated Resilient Smart Grid**
- Importantly, these phases are readiness-based rather than tied to predetermined years. Specific implementation dates should be aligned with official Libyan electricity-sector and renewable-energy strategies once formally verified, avoiding unsupported assumptions about national deployment timelines.

15. Research Gaps and Future Research Agenda

Despite rapid progress in GFM, ESS, and AI-based control, several research gaps must be addressed before their integrated deployment can be considered technically and economically mature for Libya. The most important gaps concern the limited field validation of GFM under African weak-grid conditions, optimal BESS sizing and siting, coordination between GFM and BESS, and the robustness of AI models when operating with incomplete or heterogeneous grid data. Further research is also required on cyber-resilient AI control, protection coordination in GFM-dominated networks, techno-economic feasibility, digital twins of the Libyan grid, hybrid physics-informed AI models, and regulatory standards for inverter-dominated power systems. These gaps indicate that future research should move beyond isolated technology assessment toward integrated, experimentally validated, and context-sensitive solutions.

TABLE VII. PROPOSED RESEARCH AGENDA FOR GFM–ESS–AI INTEGRATION IN LIBYA

Research Gap	Key Research Question	Recommended Method	Expected Contribution
GFM field validation	How does GFM perform under weak-grid conditions representative of Libya?	HIL/PHIL + field pilots	Validated GFM performance
BESS sizing and siting	What BESS capacity and locations maximize resilience benefits?	Optimization + EMT/power-flow studies	Optimal investment strategy
GFM–BESS coordination	How should storage and GFM controls be coordinated?	Dynamic simulation + experimental validation	Improved stability and flexibility
Incomplete grid data	Can AI remain reliable with missing/noisy measurements ?	Robust ML + sensitivity testing	Data-resilient AI
Cyber-resilient AI	How can AI control withstand cyberattacks?	Adversarial testing + safe RL	Secure intelligent control
Techno-economic feasibility	When are GFM–ESS–AI solutions economically justified?	LCOE/LCOES + cost-benefit analysis	Investment guidance
Protection with GFM	How should protection adapt to converter-dominated grids?	EMT + relay/HIL testing	Adaptive protection schemes
Libyan digital twin	Can a digital twin support planning and real-time	Digital-twin modeling	National simulation platform

	operation?		
Physics-informed AI	Can physical grid models improve AI reliability?	Physics-informed ML/Hybrid AI	More explainable and robust AI
Regulatory framework	What standards are required for high-IBR operation?	Grid-code benchmarking + policy analysis	Libya-specific technical standards

The research agenda therefore suggests a progression from **simulation → experimental validation → pilot deployment → system-wide integration**. Most importantly, future studies should investigate GFM – ESS – AI as an integrated cyber-physical architecture, rather than continuing to evaluate each technology independently. This shift would provide stronger evidence for translating the conceptual framework proposed in this review into a practical resilience strategy for the Libyan power system.

16. Policy and Engineering Implications

The findings of this review generate distinct but interconnected engineering and policy implications for transitioning the Libyan power system toward higher renewable penetration and greater resilience. Separating these implications is important because technological capability alone cannot ensure successful implementation without an enabling institutional and regulatory environment.

16.1 *Engineering Implications*

From an engineering perspective, renewable expansion should be accompanied by updated grid-code requirements for inverter-based resources, including clearly defined GFM performance specifications for frequency response, voltage regulation, fault ride-through, current limiting, and black-start capability. BESS deployment should be based on system-specific sizing and siting studies rather than uniform capacity targets, considering grid strength, renewable variability, congestion, and restoration requirements. Protection schemes should also be reassessed for networks with high GFM and IBR penetration because converter fault behavior differs substantially from that of synchronous generators. Finally, AI architectures should initially complement rather than replace deterministic protection and control systems, with progressive deployment supported by digital twins, hardware-in-the-loop validation, explainability, and fail-safe mechanisms.

16.2 Policy Implications

At the policy level, Libya requires an enabling framework linking renewable-energy policy, storage deployment, grid modernization, digitalization, and resilience. National standards should establish technical requirements for GFM, BESS interconnection, interoperability, data exchange, and cybersecurity. Investment policies should prioritize pilot projects in technically strategic locations and encourage coordinated renewable–storage deployment rather than isolated generation expansion. Equally important is the development of data-governance and cybersecurity frameworks covering ownership, quality, accessibility, privacy, and protection of grid data used by AI systems. Finally, sustained investment in R&D, university–industry collaboration, professional training, and experimental testing facilities will be necessary to build domestic capability for GFM, ESS, AI, digital twins, and advanced power-system operation.

Overall, the transition should follow a coordinated principle:

Engineering readiness + regulatory readiness + digital readiness + institutional capacity → secure renewable integration and long-term grid resilience.

17. Conclusions

This critical comparative review demonstrates that the transition from renewable-energy integration to genuine grid resilience cannot be achieved through the deployment of a single enabling technology. The evidence examined throughout the study shows that the principal challenges created by increasing penetration of inverter-based resources are multidimensional: declining synchronous inertia, weaker system strength, renewable variability, altered fault characteristics, converter-control interactions, protection constraints, and increasing requirements for real-time coordination. Consequently, framing the technological choice as GFM versus ESS versus AI is conceptually inadequate. The more relevant engineering question is how their fundamentally different capabilities can be combined to address complementary dimensions of power-system resilience. This conclusion is consistent with the conceptual foundation adopted in this review, which distinguishes stability, reliability, and resilience and defines resilience through the interconnected capacities to prepare, absorb, respond, recover, and adapt.

The comparative analysis indicates that Grid-Forming Inverters (GFM) provide the most direct contribution to the stability dimension of this architecture. Their capacity to establish or actively regulate voltage and frequency makes them particularly relevant as synchronous generation is progressively displaced by inverter-based renewable resources. Their potential value is especially significant for low-inertia, weak-grid, islanded, and restoration conditions. Nevertheless, the review does not support the simplistic conclusion that GFM is universally superior to conventional grid-following operation. Its effectiveness remains highly conditional on controller architecture, grid strength, current-limiting strategy, DC-side energy availability, protection coordination, and interactions with other converters. Indeed, the reviewed evidence highlights unresolved problems involving transient stability, fault behavior and current limitation. Therefore, GFM provides a stability-enabling interface, but it cannot independently guarantee system resilience.

Energy Storage Systems (ESS), particularly BESS, address a different limitation: the availability and controllability of energy and flexibility. Storage can provide rapid active-power response, renewable smoothing, reserve, ramp-rate management, frequency regulation, and restoration support. More importantly, the comparison reveals an essential interdependence between

ESS and GFM: a grid-forming controller can determine how a converter responds to grid conditions, but it cannot indefinitely deliver active-power support without an adequate DC-side energy resource. BESS can therefore supply the physical flexibility that enables many GFM functions to become operationally meaningful. Yet storage is likewise not a stand-alone resilience solution. Capital costs, degradation, state-of-charge constraints, lifetime, sizing and safety introduce temporal and economic limitations to the services it can provide. The paper's evidence consequently challenges the assumption that increasing storage capacity automatically translates into proportional resilience gains; benefits depend on where storage is located, how it is sized, what services it is assigned, and how it is controlled. The reviewed literature already identifies these trade-offs as central constraints on ESS deployment.

The contribution of AI-based control is more indirect but potentially system-wide. AI can improve renewable and load forecasting, ESS scheduling, fault detection, predictive maintenance, optimization, and adaptive energy management, thereby creating an intelligent coordination layer above the physical system. However, a critical interpretation is necessary. AI does not generate inertia, establish voltage by itself, or supply reserve energy; these remain physical functions that must ultimately be delivered by converters, storage, generation, or other grid assets. Moreover, dependence on high-quality data, limited explainability, cybersecurity exposure, dataset shift, computational requirements, and uncertain generalization under previously unseen disturbances create particular concerns for safety-critical applications. The reviewed literature itself identifies explainability, transparency, trust and technical interpretability as barriers to wider deployment. Thus, AI should augment physical grid control rather than be interpreted as a substitute for it.

The central conclusion emerging from the comparison is therefore not simply that the three technologies are beneficial, but that their weaknesses explain why their integration is necessary. GFM can provide grid-forming and dynamic stability functions but requires an adequate energy source; ESS supplies energy and flexibility but requires effective converter control and dispatch; and AI can optimize and coordinate these resources but remains dependent on physical assets, reliable data, secure communications, and deterministic safety mechanisms. Their complementarity can therefore be expressed as:

GFM → Stability

ESS → Flexibility

AI → Intelligence and Coordination

GFM + ESS + AI → Integrated Resilience Architecture

This systems-level interpretation constitutes the principal conceptual contribution of the review. Rather than treating resilience as the additive effect of three independent technologies, the proposed GFM–ESS–AI Integrated Resilience Framework conceptualizes resilience as an emergent outcome of interactions between physical energy availability, converter-based stability, and intelligent coordination. This directly addresses the fragmentation identified in the existing literature, where GFM research has largely concentrated on converter stability and synchronization, ESS research on flexibility and energy management, and AI research on forecasting and optimization, with comparatively limited attention to their coordinated application.

For Libya, this conclusion has particularly important implications. The country's substantial renewable-resource potential should not be confused with its technical capacity to accommodate high levels of inverter-based generation. Evidence from the Libyan grid already indicates that renewable integration can affect voltage profiles, losses, short-circuit behavior, fault ride-through, and protection performance. Consequently, rapidly expanding PV and wind capacity without parallel investments in flexibility, stability support, protection modernization, monitoring, digital infrastructure, and operational coordination could shift rather than solve system vulnerabilities. The proposed framework therefore argues against technology-led deployment and instead supports a grid-needs-driven strategy, in which GFM, ESS, and AI are introduced according to local system strength, renewable penetration, operational requirements, data readiness, and economic constraints.

Ultimately, the review suggests that Libya's renewable-energy transition should be conceived not merely as a process of adding renewable generation, but as a transformation of the architecture through which the electricity system maintains security under increasing uncertainty and converter penetration. The appropriate pathway is therefore neither GFM alone, storage alone, nor AI alone, but their staged and technically justified integration. Under this perspective, the long-term objective shifts from maximizing installed renewable capacity toward maximizing secure renewable hosting capability. The proposed GFM–ESS–AI architecture provides a conceptual pathway toward that objective, but its value remains a proposition derived from comparative literature rather than field-validated evidence for Libya. Accordingly, the next research step should be to test this framework through Libyan grid models, EMT and dynamic simulations, optimal BESS sizing and siting, hardware-in-the-loop experiments, techno-economic assessment, cybersecurity analysis, and ultimately carefully designed pilot projects. This qualification is essential: it prevents the conceptual framework from being presented as an already validated solution and instead establishes it as a testable engineering architecture for advancing Libya from renewable-energy potential toward measurable grid resilience.

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