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Energy resilience in disaster-prone regions: the role of portable and modular solar power systems

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ABSTRACT

Energy resilience is a critical requirement in disaster-prone regions, where electrical infrastructure is highly vulnerable to natural hazards and prolonged power outages. Portable and modular solar power systems have emerged as promising solutions for enhancing resilience by enabling decentralized, rapidly deployable, and grid-independent energy supply. This paper presents a comprehensive review of the role of portable and modular photovoltaic-based power systems in improving energy resilience from a power electronics perspective. The review synthesizes recent literature on resilience concepts, system architectures, and converter-based control strategies relevant to emergency energy applications. Particular emphasis is placed on DC-first and hybrid AC/DC architectures, modular converter topologies, battery management systems, and energy management strategies that support reliable and fault-tolerant operation under variable and uncertain conditions. Practical deployment and performance considerations, including scalability, robustness, monitoring, and usability in disaster environments, are also discussed. The findings indicate that well-designed portable and modular solar power systems can significantly reduce recovery time, improve operational continuity, and decrease reliance on centralized grids and fuel-based generators. This review identifies key technical challenges and research opportunities to guide future development of resilient power electronic-based energy systems for disaster response and recovery.

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1. INTRODUCTION

Electric power systems play a fundamental role in supporting emergency response, public safety, and socio-economic recovery in disaster-prone regions [1], [2]. Natural hazards such as earthquakes, floods, hurricanes, and volcanic eruptions frequently damage transmission and distribution infrastructure, resulting in prolonged power outages and reduced operational capability of critical facilities [3], [4]. In such contexts, the ability of an energy system to withstand disturbances, recover rapidly, and continue supplying essential loads is commonly referred to as energy resilience and has become a central concern in modern power system design [5].

Traditional centralized power grids are inherently vulnerable to large-scale disruptions, as failures in key components can propagate across wide areas [6]. During disaster events, restoration of grid infrastructure often requires significant time, skilled labor, and logistical support, leaving affected communities without reliable electricity during the most critical response period [1], [3]. Diesel generator sets are commonly deployed as emergency power sources; however, their dependence on fuel supply chains, high maintenance requirements, emissions, and operational noise limit their effectiveness and sustainability in disaster environments [7], [8] These limitations have motivated growing interest in decentralized, renewable, and power-electronics-based energy solutions that can operate independently of the main grid [9], [10].

Among the available alternatives, portable and modular solar power systems have emerged as promising candidates for enhancing energy resilience in disaster-prone regions [11]. Advances in photovoltaic (PV) technology, battery energy storage, and power electronic converters have enabled the development of compact, scalable, and rapidly deployable systems capable of supplying critical loads such as lighting, communication equipment, medical devices, and emergency shelters [12]. From a power electronics perspective, these systems rely heavily on efficient DC–DC converters, inverters, battery management systems, and control strategies to ensure stable operation under highly variable generation and load conditions [13], [14].

Recent research has explored various aspects of portable and modular solar energy systems, including converter topologies, maximum power point tracking (MPPT) techniques, hybrid AC/DC architectures, and energy management strategies [15], [16]. In particular, DC-first and modular architectures have gained attention due to their potential to reduce conversion losses, improve system efficiency, and facilitate scalability [17], [18]. Nevertheless, much of the existing literature addresses these technologies in isolated contexts, such as standalone microgrids or rural electrification, without explicitly framing their contribution to energy resilience in disaster scenarios [19].

Moreover, resilience is often discussed at a high conceptual level, with limited linkage to the underlying power electronic components and system architectures that enable resilient operation. Key questions related to how converter design, control strategies, modularity, and protection mechanisms influence system robustness, adaptability, and recovery speed remain insufficiently synthesized in the literature. This gap is particularly relevant for portable systems, where constraints on size, weight, and usability impose additional design challenges.

In response to these issues, this paper presents a comprehensive review of energy resilience in disaster-prone regions from the perspective of portable and modular solar power systems, with a strong emphasis on power electronics and system integration. The review synthesizes recent advances in converter technologies, control, and energy management strategies, and modular system architectures that enable resilient emergency power supply. Both technical performance and practical deployment considerations are discussed to bridge the gap between theoretical design and real-world disaster response applications.

The main contributions of this review can be summarized as follows:

a) A structured discussion of energy resilience concepts and metrics relevant to power-electronics-based systems.
b) A systematic review of portable and modular solar power system architectures, with emphasis on DC-first and scalable designs.
c) An analysis of power electronic converters and control strategies that support reliable and resilient operation under disaster conditions.
d) Identification of technical challenges and research opportunities for improving resilience through advanced power electronics.

The remainder of this paper is organized as follows: i) Section 2 introduces energy resilience concepts and their relevance to power-electronic-based systems; ii) Section 3 reviews portable and modular solar power system architectures suitable for disaster-prone regions; iii) Section 4 discusses power electronics and control strategies that enhance resilient operation; iv) Section 5 examines deployment, performance, and practical considerations; v) and Finally, Section 6 concludes the paper and outlines future research directions.

2. ENERGY RESILIENCE CONCEPTS IN POWER ELECTRONIC–BASED SYSTEMS

Energy resilience has emerged as a key performance objective in modern electrical energy systems, particularly in applications exposed to extreme operating conditions and external disturbances [1]. In disaster-prone regions, resilience extends beyond conventional reliability metrics by emphasizing the ability of a system to withstand disruptions, adapt to degraded conditions, and recover rapidly while maintaining supply to critical loads [20]. For power electronic–based systems, energy resilience is closely linked to converter design, control strategies, and system-level architecture [21]. Figure 1 conceptually illustrates the key attributes of energy resilience and their relationship to power electronic components and control functions in decentralized and modular energy systems.

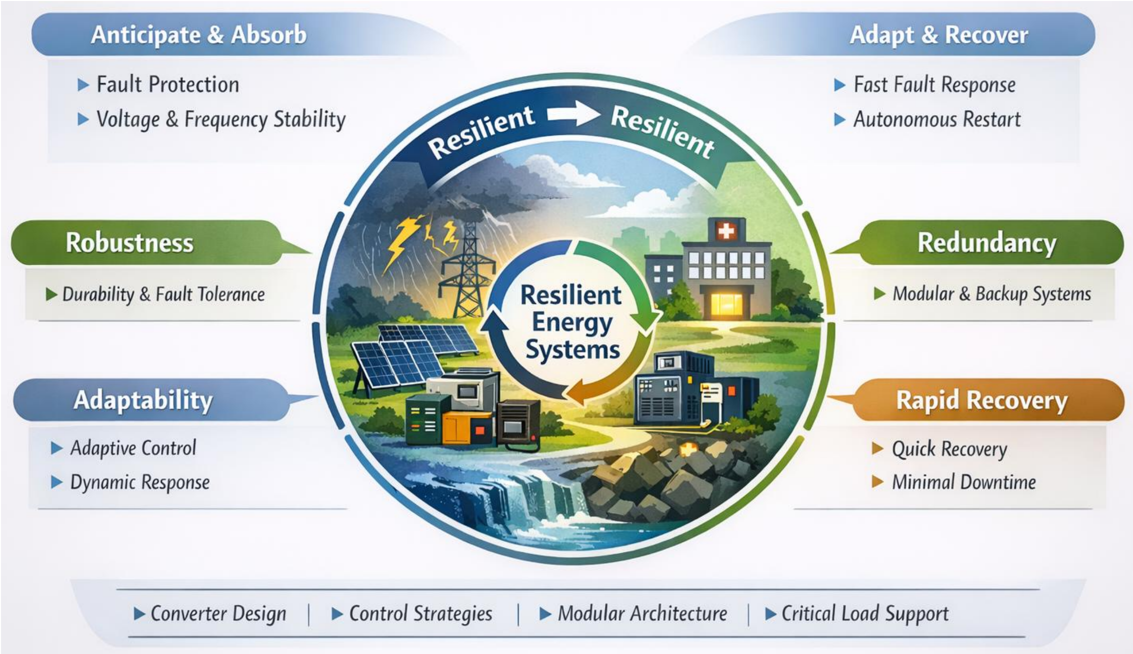

Figure 1. Energy resilience in power electronic-based systems

2.1. Definition of energy resilience in electrical systems

Energy resilience in electrical systems can be defined as the capability to anticipate, absorb, adapt to, and rapidly recover from disruptive events while preserving essential functionality [22], [23]. Unlike reliability, which focuses on the probability of failure under normal operating conditions, resilience explicitly considers high-impact, low-probability events such as natural disasters and extreme environmental stress [24].

From a power electronics perspective, resilience involves maintaining stable voltage and frequency, protecting components from fault conditions, and enabling controlled degradation rather than complete system shutdown [21]. Portable and modular systems further require resilience to be achieved under constraints related to size, weight, energy availability, and user operation [25].

2.2. Key attributes of resilient power electronic systems

Resilient energy systems are commonly characterized by four core attributes: robustness, redundancy, adaptability, and rapid recovery [3]. In power electronic–based systems, these attributes are directly influenced by hardware and control design choices [21]:

a) Robustness refers to the ability of converters and control systems to tolerate disturbances such as voltage fluctuations, load transients, and environmental stress without failure. This includes thermal robustness, overcurrent tolerance, and protection against short circuits and component degradation [26].
b) Redundancy is achieved through modular converter structures, parallel operation of power modules, and distributed energy storage. In portable solar systems, modularity enables continued operation even if individual units fail [27].
c) Adaptability involves the capability of control algorithms to adjust operating points in response to changing generation, load demand, or system configuration. Adaptive MPPT, dynamic load prioritization, and reconfigurable DC buses contribute significantly to this attribute [21].
d) Rapid recovery is enabled by fast control response, fault isolation, and autonomous restart mechanisms, allowing the system to resume operation quickly after disturbances without manual intervention [28].

2.3. Resilience metrics and evaluation criteria

Quantifying energy resilience remains challenging due to its multidimensional nature. However, for power electronic–based systems, several metrics are commonly used to assess resilience performance [29]. These include voltage stability margins, fault ride-through capability, recovery time after disturbance, system efficiency under degraded operation, and availability of critical loads [30].

In portable and modular systems, resilience evaluation also considers deployment-related metrics such as time to energization, flexibility in load connection, and operational continuity under partial system failure

[31]. Unlike large grid-connected systems, resilience metrics in portable systems must account for limited energy resources and the need for prioritized load supply [32].

2.4. Role of power electronics in enhancing energy resilience

Power electronics play a central role in enabling resilience by providing fast, flexible, and precise control of energy flow [33]. DC–DC converters regulate voltage levels and isolate disturbances between subsystems, while inverters ensure stable AC output where required [34]. Advanced control techniques allow power electronic interfaces to operate autonomously, making them particularly suitable for disaster-response applications where grid support is unavailable [35].

In DC-first and hybrid AC/DC systems, power electronics reduce conversion stages and improve efficiency, thereby extending operational duration under constrained energy availability [36]. Furthermore, digital control platforms enable the implementation of protective and adaptive functions that enhance system survivability during abnormal operating conditions [37].

2.5. Resilience in decentralized and modular architectures

Decentralized and modular architectures inherently support energy resilience by reducing dependence on centralized infrastructure. In such architectures, power electronic interfaces act as the enabling technology that allows multiple generation and storage units to operate in a coordinated manner [38].

Modular converter-based systems facilitate scalability and reconfiguration, allowing capacity to be increased or redistributed as needed [39]. In disaster scenarios, this flexibility supports staged deployment and localized energy autonomy, which are critical for emergency shelters and field operations [40]. The combination of modular hardware and distributed control thus represents a key strategy for achieving resilient energy systems in disaster-prone regions [41], [42].

2.6. Implications for portable solar power systems

The resilience concepts discussed in this section provide a conceptual foundation for evaluating portable and modular solar power systems [43]. By linking resilience attributes directly to power electronic components and control strategies, it becomes possible to assess how design choices influence system behavior under extreme conditions [3].

In the context of disaster-prone regions, energy resilience is not an abstract property but an outcome of efficient conversion, intelligent control, and modular architecture [42]. These principles guide the review of portable and modular solar power systems presented in the subsequent sections, where specific system configurations and control strategies are examined in greater detail [44].

3. PORTABLE AND MODULAR SOLAR POWER SYSTEM ARCHITECTURES

Portable and modular solar power systems are increasingly recognized as effective solutions for enhancing energy resilience in disaster-prone regions [45]. Their ability to operate independently of centralized grids, combined with rapid deployment and scalability, makes them well suited for emergency power supply applications [46]. From a power electronics perspective, system architecture plays a critical role in determining efficiency, reliability, and adaptability under highly variable operating conditions [47], [48]. Figure 2 illustrates the principal architectural configurations of portable and modular solar power systems, including stand-alone, clustered, and hybrid arrangements, as well as the associated DC-first and hybrid AC/DC power distribution structures.

3.1. Overview of portable and modular solar power systems

Portable solar power systems are typically designed as compact, self-contained units that integrate photovoltaic (PV) modules, energy storage, power electronic converters, and control interfaces [49]. Modular systems extend this concept by enabling multiple units or subsystems to be interconnected, allowing capacity expansion and functional reconfiguration [46]. In disaster-response contexts, portability ensures fast deployment, while modularity supports adaptability to changing load demands and operational priorities [50].

These systems are commonly deployed in applications such as emergency shelters, temporary medical facilities, communication hubs, and field operations [51], [52]. Their architectural design must therefore balance competing requirements, including power density, efficiency, ease of use, and environmental robustness [50].

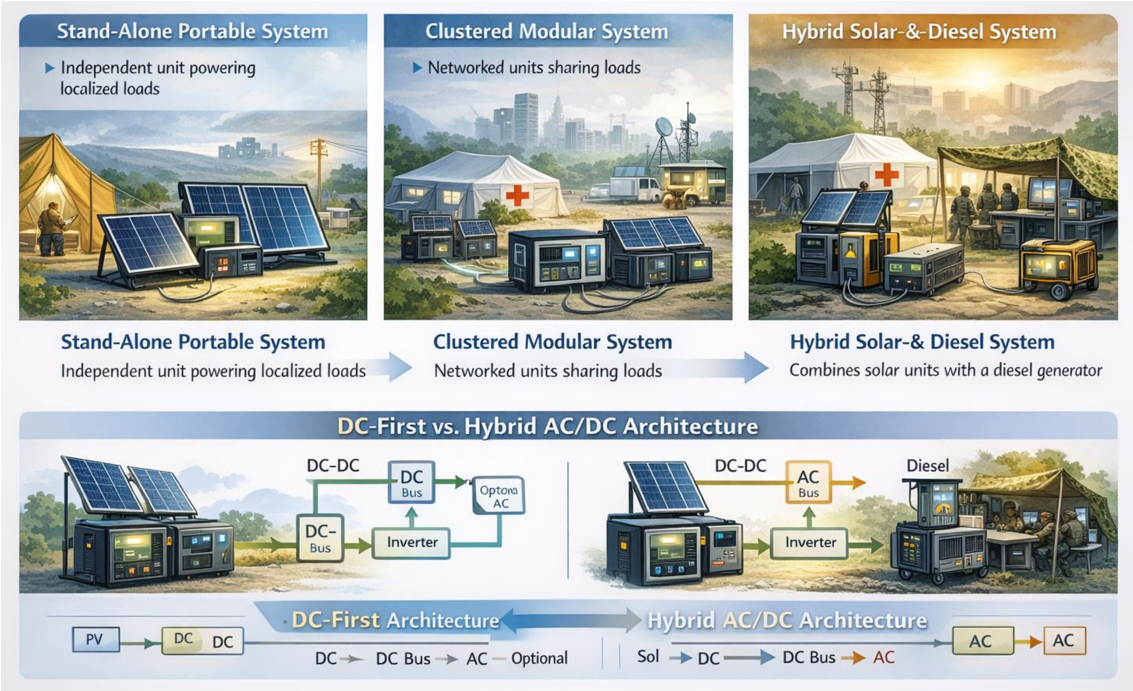

Figure 2. Portable and modular solar power system architectures

3.2. System configurations and deployment models

Portable and modular solar power systems can be classified into several architectural configurations based on deployment scale and interconnection strategy.

a) Stand-alone portable systems operate independently and supply power to localized loads. They prioritize simplicity and ease of operation, often using integrated DC–DC converters and limited AC outputs. These systems are well-suited for individual shelters or mobile emergency units [53], [54].

b) Clustered or interconnected systems involve the parallel or networked operation of multiple portable units. Power electronic interfaces enable load sharing, redundancy, and coordinated control among units. This configuration enhances resilience by allowing energy resources to be pooled and redistributed as needed [55]–[57].

c) Hybrid systems integrate portable solar units with other energy sources such as diesel generators or temporary grid connections. Power electronic converters facilitate seamless source integration and load management, reducing fuel consumption and improving overall system efficiency during disaster recovery phases [58], [59].

3.3. DC-first and hybrid AC/DC architectures

Architectural choice significantly influences system performance and resilience [60]. Traditional emergency power systems often adopt AC-centric architectures to ensure compatibility with standard appliances. However, in portable solar systems, this approach introduces additional conversion losses and increases system complexity [36].

a) DC-first architectures prioritize DC power distribution, supplying compatible loads directly from the DC bus while using inverters only when AC power is required. This reduces the number of conversion stages, improves efficiency, and enhances system reliability attributes that are particularly important under limited energy availability [42], [60], [61].

b) Hybrid AC/DC architectures combine DC-first principles with selective AC distribution, offering a compromise between efficiency and load compatibility. Power electronic interfaces play a central role in managing energy flow between DC and AC domains, ensuring stable operation and flexible load support [62]–[64].

3.4. Modular converter topologies and scalability

Modularity in portable solar power systems is largely enabled by power electronic converter design [65]. Modular DC–DC converters and inverter units can be connected in parallel or series to increase power capacity or adapt voltage levels [66]. This approach supports scalability while maintaining manageable component sizes.

Modular converter topologies also improve fault tolerance by allowing individual modules to be isolated or bypassed without disabling the entire system [67], [68]. In disaster scenarios, such capability is critical for maintaining operation despite partial system failures. Furthermore, modular designs simplify maintenance and facilitate incremental upgrades [69].

3.5. Integration of energy storage and load interfaces

Energy storage is a central component of portable and modular solar systems, enabling continuous operation during periods of low solar availability [70]. Batteries are typically interfaced with the system through bidirectional DC–DC converters that regulate charging and discharging while protecting battery health [71], [72].

Load interfaces are designed to support a range of DC and AC loads, with power electronic converters ensuring voltage regulation and load isolation [73]. Priority-based load interfaces enable critical services to be maintained even under constrained energy conditions [74], [75]. The integration of storage and load interfaces through a common DC bus is a defining characteristic of resilient portable system architectures [73].

3.6. Architectural implications for energy resilience

The architectural features discussed in this section demonstrate how portable and modular solar power systems inherently support energy resilience in disaster-prone regions [45]. Decentralized deployment reduces dependence on vulnerable grid infrastructure, while modularity and DC-first design enhance efficiency, adaptability, and fault tolerance [60], [76].

By leveraging power electronic interfaces and scalable architectures, portable solar systems can be tailored to a wide range of emergency applications [45], [77]. These architectural principles form the foundation for the control strategies and performance considerations discussed in the subsequent sections, where system operation under disaster conditions is examined in greater detail [78].

4. POWER ELECTRONICS AND CONTROL STRATEGIES FOR RESILIENT OPERATION

Power electronics and control strategies form the foundation of resilient operation in portable and modular solar power systems. In disaster-prone regions, these systems must operate autonomously under highly variable generation, load, and environmental conditions, often without external grid support [79], [80]. Efficient energy conversion, stable control, and rapid fault response are therefore essential to ensure continuous supply to critical loads [81]. Figure 3 provides an overview of the key power electronic components and control strategies that collectively enable resilient operation in portable and modular solar power systems.

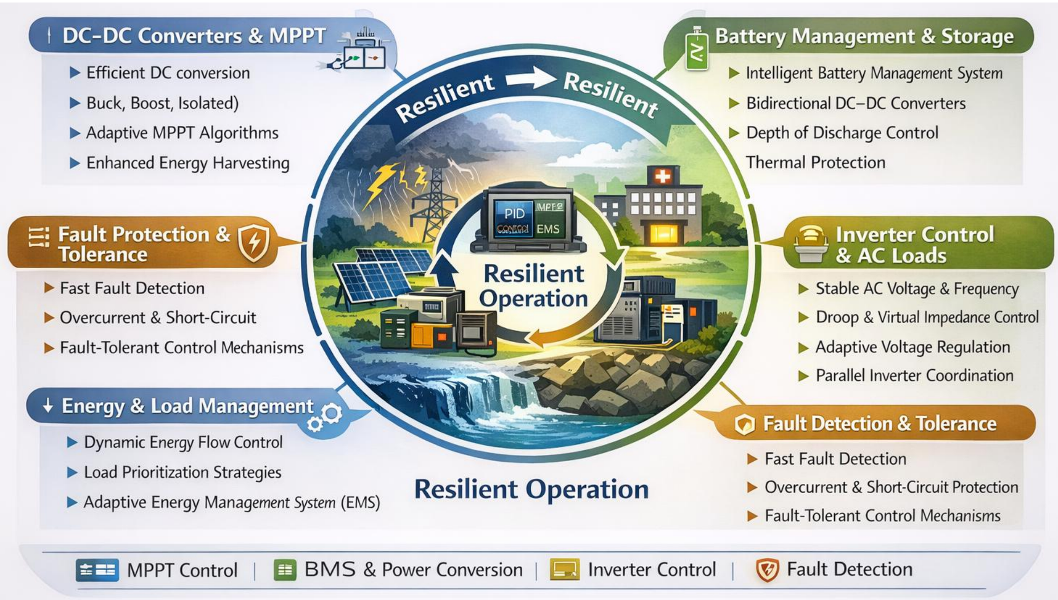

Figure 3. Power electronics and control strategies for resilient operation

4.1. DC–DC converters and maximum power point tracking

DC–DC converters are key components in portable solar power systems, regulating voltage levels and enabling efficient energy transfer between photovoltaic (PV) modules, energy storage, and loads [82], [83]. Common converter topologies include buck, boost, buck–boost, and isolated converters, selected based on voltage requirements, power levels, and safety considerations [84]–[86].

Maximum power point tracking (MPPT) algorithms are employed to maximize energy harvesting from PV modules under varying irradiance and temperature conditions [87], [88]. Traditional methods such as perturb and observe and incremental conductance, remain widely used due to their simplicity and robustness [89]. More advanced techniques, including adaptive and model-based MPPT, offer improved tracking performance under rapidly changing conditions, which are common in disaster environments with partial shading and frequent repositioning of PV modules [90].

4.2. Battery management and bidirectional power conversion

Energy storage systems in portable solar architectures rely on bidirectional DC–DC converters to manage battery charging and discharging [91]. These converters regulate current and voltage while ensuring safe operation across varying load and generation profiles [92]. Battery management systems (BMS) monitor state-of-charge, temperature, and health parameters, providing protection against overcharge, deep discharge, and thermal runaway [93].

From a resilience perspective, intelligent battery management enables controlled degradation and prioritization of critical loads when energy availability is limited [94]. Advanced control strategies can dynamically adjust charging rates and discharge limits to extend operational duration and preserve battery lifespan during prolonged emergency use [95].

4.3. Inverter control for emergency loads

Although DC-first architectures are increasingly adopted, many emergency applications still require AC power [96]. Inverter design and control are therefore critical for supplying a stable AC voltage and frequency under islanded operation [97]. Voltage-source inverters with closed-loop control are commonly used to support diverse load types, including nonlinear and transient loads [98].

Control strategies such as droop control, virtual impedance, and adaptive voltage regulation enhance inverter stability and load-sharing capability, particularly in clustered or modular systems. These techniques enable multiple inverters to operate in parallel without centralized coordination, improving system redundancy and fault tolerance [99]–[101].

4.4. Energy management and load prioritization strategies

Energy management systems (EMS) coordinate power flow among PV sources, storage, and loads to optimize system performance and resilience. In portable solar systems, EMS algorithms must balance efficiency with simplicity, ensuring reliable operation without excessive computational complexity [102]–[104].

Load prioritization is a key resilience feature, allowing essential services to remain powered during energy shortages [105]. Priority-based control schemes disconnect non-critical loads when battery levels fall below predefined thresholds, thereby preserving energy for critical applications such as medical equipment and communication devices [106]. Automated load management reduces operator burden and enhances system survivability under prolonged emergency conditions [107].

4.5. Fault detection, protection, and fault-tolerant control

Fault detection and protection mechanisms are essential for preventing component damage and ensuring safe operation in harsh disaster environments. Power electronic systems typically incorporate overcurrent protection, short-circuit detection, thermal monitoring, and isolation mechanisms [108], [109].

Fault-tolerant control strategies further enhance resilience by enabling continued operation under partial system failure. Modular converter designs allow faulty modules to be isolated or bypassed, while remaining units continue to supply power [28]. Fast control response and autonomous restart capabilities minimize downtime and support rapid recovery after disturbances [110].

4.6. Implications for resilient system design

The power electronics and control strategies reviewed in this section demonstrate that resilience in portable and modular solar power systems is fundamentally enabled by intelligent converter design and adaptive control [60]. By combining efficient DC–DC conversion, robust inverter control, and intelligent energy management, these systems can maintain stable operation under highly uncertain conditions [111]. For disaster-prone regions, the integration of modular power electronic architectures with fault-tolerant control strategies offers a practical pathway toward resilient emergency power supply [112]. These technical foundations support the deployment and performance considerations discussed in the following section, where real-world operational challenges are examined [113].

5. DEPLOYMENT, PERFORMANCE, AND PRACTICAL CONSIDERATIONS

While power electronic design and control strategies are fundamental to resilient operation, the effectiveness of portable and modular solar power systems in disaster-prone regions ultimately depends on their real-world deployment and operational performance [45]. Practical considerations such as efficiency under field conditions, ease of installation, environmental robustness, and usability play a critical role in determining system success during emergency response and recovery phases [50].

5.1. Deployment and installation considerations

Rapid deployment is a key requirement for emergency power systems. Portable solar power systems are typically designed for plug-and-play installation, enabling deployment by personnel with limited technical expertise. Lightweight system components, standardized connectors, and integrated enclosures contribute to reduced setup time and lower logistical burden [11], [49], [51].

Modular architectures further support flexible deployment by allowing capacity to be scaled according to situational needs [114], [115]. In disaster environments, systems may be deployed incrementally, with additional modules added as load demand increases or as recovery efforts expand. Power electronic interfaces facilitate seamless integration of new modules without disrupting ongoing operation [39].

5.2. Performance under variable operating conditions

Performance evaluation of portable solar systems must account for highly variable operating conditions, including fluctuating solar irradiance, changing load profiles, and environmental stress [116]. Power electronic converters and control algorithms play a central role in maintaining stable operation despite these uncertainties [117].

Efficiency metrics such as energy conversion efficiency, battery utilization, and thermal performance are commonly used to assess system performance. DC-first architectures generally demonstrate higher overall efficiency due to reduced conversion stages, which translates into longer operational duration for a given energy capacity. Performance evaluation also considers the system’s ability to maintain voltage and frequency stability under transient loads and partial shading conditions [42], [60], [61].

5.3. Reliability, durability, and environmental robustness

Reliability is a critical performance criterion in disaster-response applications, where system failure can have serious consequences. Portable solar power systems must be designed to withstand harsh environmental conditions, including moisture, dust, temperature extremes, and mechanical shocks [4], [45], [50].

Durability is influenced by enclosure design, thermal management, and component selection [118]. Adequate ingress protection, shock-resistant materials, and passive or active cooling strategies enhance system longevity and reduce maintenance requirements. Power electronic components must be selected and designed to operate reliably under wide temperature ranges and irregular duty cycles [119].

5.4. Monitoring, diagnostics, and user interaction

Effective monitoring and diagnostics support both performance optimization and operational safety. Many portable solar systems incorporate basic monitoring features such as battery state-of-charge indicators, fault alarms, and load status displays. More advanced systems integrate digital monitoring and communication interfaces that provide real-time system information [49], [51], [52].

User interaction is an important practical consideration, as emergency systems are often operated by non-specialists. Clear visual indicators, intuitive interfaces, and automated protection features reduce the risk of misuse and improve system reliability. Human-centered design enhances user confidence and supports sustained operation under stressful conditions [120].

5.5. Lessons from field deployments and case studies

Field deployments and reported case studies provide valuable insights into the practical performance of portable and modular solar power systems [49], [52]. These experiences highlight the importance of balancing technical sophistication with operational simplicity. Systems that perform well in laboratory environments may encounter unforeseen challenges when deployed in disaster settings, such as logistical constraints, user behavior, and environmental exposure [121], [122]. Lessons learned from field applications emphasize the value of modularity, robust protection, and adaptive control strategies. These findings reinforce the need for close alignment between power electronic design and real-world deployment requirements.

5.6. Practical challenges and limitations

Despite their advantages, portable and modular solar power systems face several practical challenges. Limited energy density of storage systems constrains operational duration, particularly during extended periods of low solar availability. Cost considerations may also limit large-scale deployment, especially in resource-constrained regions [123], [124]. Additionally, interoperability and standardization remain ongoing challenges, as systems from different manufacturers or research platforms may not be easily integrated [124]. Addressing these limitations requires continued research in power electronics, energy storage technologies, and system-level integration.

5.7. Implications for resilient emergency power systems

The deployment and performance considerations discussed in this section demonstrate that resilience is achieved not only through advanced power electronics and control but also through thoughtful system design and practical implementation [43]. Portable and modular solar power systems that combine efficiency, robustness, and usability offer a viable pathway for enhancing energy resilience in disaster-prone regions [45], [122].

These practical insights provide a foundation for the concluding section by illustrating how deployment, performance, and usability considerations directly influence system resilience in real-world disaster scenarios. As summarized in Figure 4, resilient field operation emerges from the combined effects of rapid deployment, stable performance under variable conditions, environmental robustness, effective monitoring, and user-centered design. Together, these factors link power electronic design choices with operational outcomes, thereby informing the synthesis of key findings and guiding the identification of future research directions presented in the concluding section.

Figure 4. Deployment, performance, and practical considerations for portable and modular solar power systems

6. CONCLUSION

Energy resilience has become a critical requirement for electrical power systems operating in disaster-prone regions, where infrastructure damage and prolonged outages can severely disrupt emergency response and recovery efforts. This review has examined the role of portable and modular solar power systems in enhancing energy resilience, with a particular focus on power electronics, system architecture, and control strategies that enable reliable operation under extreme conditions. The review highlighted that decentralized, photovoltaic-based systems offer significant advantages over conventional emergency power solutions by reducing dependence on centralized grids and fuel supply chains. DC-first and hybrid AC/DC architectures, supported by efficient DC–DC converters, robust inverters, and intelligent energy management systems, were identified as key enablers of resilient operation. Modular system designs further enhance adaptability, scalability, and fault tolerance, allowing energy capacity to be tailored to evolving emergency needs. From a control perspective, advanced MPPT techniques, battery management systems, and load prioritization strategies play a central role in maximizing energy utilization and maintaining supply to critical loads. Fault detection and fault-tolerant control mechanisms contribute to rapid recovery and operational continuity, which are essential attributes of resilience in disaster-response applications. The integration of these power electronic functions enables portable solar systems to operate autonomously and reliably in the absence of grid support. Practical deployment considerations, including ease of installation, environmental robustness, monitoring capabilities, and user interaction, were also shown to be decisive factors influencing system performance. Field experiences demonstrate that resilience is achieved not only through technical sophistication but also through simplicity, reliability, and human-centered design. Despite substantial progress, several challenges remain. Limitations in energy storage capacity, interoperability between modular systems, and the need for standardized architectures continue to constrain large-scale deployment. Future research should focus on improving power electronic efficiency, enhancing fault-tolerant and adaptive control strategies, and developing standardized modular interfaces that facilitate interoperability and scalability. Advances in battery technologies and low-power digital monitoring are also expected to further strengthen system resilience. In conclusion, portable and modular solar power systems, when designed with appropriate power electronic architectures and control strategies, represent a viable and effective approach to enhancing energy resilience in disaster-prone regions. Continued research and development in this area will be essential for translating technological advances into practical, resilient energy solutions capable of supporting emergency response and sustainable recovery.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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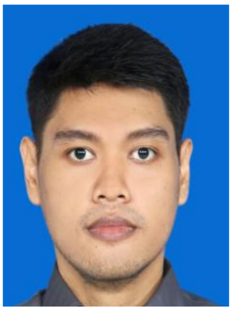

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