International Journal of Applied Power Engineering (IJAPE)
Vol. 14, No. 4, December 2025, pp. 1071~1084
ISSN: 2252-8792, DOI: 10.11591/ijape.v14.i4.pp1071-1084

Portable solar photovoltaic systems for post-disaster emergency power supply: a comprehensive review

Tole Sutikno[1,2], Wahyu Sapto Aji[1], Mochammad Facta[3], Hendril Satrian Purnama[2], Tri Wahono[2]
[1]Faculty of Industrial Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[2]Embedded System and Power Electronics Research Group, Yogyakarta, Indonesia
[3]Department of Electrical Engineering, Faculty of Engineering, Universitas Diponegoro, Semarang, Indonesia

Article Info

Article history:

Received May 11, 2025
Revised Oct 20, 2025
Accepted Nov 8, 2025

Keywords:

DC-first system
Disaster response energy
Emergency power supply
Energy resilience
IoT-enabled energy monitoring
Modular energy storage
Portable solar PV

ABSTRACT

Natural disasters frequently disrupt electrical infrastructure, creating critical challenges for emergency response, healthcare delivery, and community recovery. Portable solar photovoltaic (PV) systems have emerged as a sustainable and rapidly deployable solution for off-grid energy provision in disaster-affected regions. This review provides a comprehensive synthesis of portable PV technologies for post-disaster applications, encompassing system architectures, component selection, deployment configurations, and operational performance. Particular emphasis is placed on DC-first designs, modular scalability, energy storage integration, and IoT-enabled monitoring, which collectively enhance efficiency, reliability, and usability under harsh environmental conditions. The analysis highlights persistent challenges related to energy efficiency, storage resilience, system standardization, and user accessibility, while underscoring the importance of integration into broader emergency energy ecosystems. Research gaps are identified in areas such as efficiency optimization, human-centered design, and scalability, providing guidance for the development of next-generation portable PV systems. By consolidating technical and operational insights, this review establishes a foundation for advancing portable PV systems as robust emergency energy solutions, bridging the gap between immediate relief and long-term resilience in disaster-prone regions.

Corresponding Author:

Tole Sutikno
Master Program of Electrical Engineering, Faculty of Industrial Technology, Universitas Ahmad Dahlan
UAD 4th Campus, South Ring Road, Tamanan, Banguntapan, Bantul, Yogyakarta 55166, Indonesia
Email: tole@te.uad.ac.id

1. INTRODUCTION

Natural disasters such as earthquakes, floods, hurricanes, volcanic eruptions, and tsunamis frequently cause severe damage to electrical infrastructure, leading to widespread and prolonged power outages [1]. Electricity is a critical enabler for emergency response activities, including lighting, communication, medical services, water supply, and coordination of humanitarian aid [2]. In the immediate aftermath of a disaster, the availability of reliable electrical power often determines the effectiveness of rescue operations and the resilience of affected communities [3]. In recent years, the increasing frequency and intensity of climate-related disasters have further amplified the importance of resilient and rapidly deployable energy systems [4], [5]. This has attracted significant attention from researchers, humanitarian organizations, and policymakers toward decentralized and renewable-based emergency power solutions [6]. Among the available alternatives, portable solar photovoltaic (PV) systems have emerged as a particularly attractive option due to their modularity, environmental sustainability, and ability to operate independently of damaged grid infrastructure [7]. Despite their importance, post-disaster energy supply systems face multiple technical and operational challenges [8]. Conventional solutions, such as diesel generators, remain widely used in emergency situations; however, they suffer from several limitations [9], [10]. Fuel supply chains are often disrupted after disasters, generators produce noise and emissions, and maintenance requires skilled operators and spare parts that may not be readily available. Moreover, the reliance on fossil fuels contradicts long-term sustainability and resilience goals [11]. Grid restoration, on the other hand, typically requires substantial time and resources, leaving affected populations without power during the most critical response period [12]. These challenges highlight the need for energy solutions that are rapidly deployable, easy to operate, scalable, and capable of supplying critical loads without external fuel dependency [12], [13]. However, designing such systems requires careful consideration of portability, energy storage, power conversion efficiency, user accessibility, and environmental robustness [14].

Advances in solar PV technology, energy storage, and power electronics have enabled the development of various portable solar power solutions for emergency applications [15]. Existing systems range from small solar charging kits and foldable PV panels to integrated portable power stations and modular off-grid microgrids [16]. These systems are commonly equipped with lithium-based batteries, charge controllers with maximum power point tracking (MPPT), and multiple DC and AC output interfaces to serve diverse emergency loads. Recent studies have demonstrated the feasibility of using portable PV systems to supply power for emergency shelters, communication devices, medical instruments, and lighting systems [17], [18]. Innovations such as DC-first architectures, flexible PV modules, and Internet of Things (IoT)-based monitoring have further improved system efficiency and operational awareness [18], [19]. Commercial products increasingly offer all-in-one solutions; meanwhile, academic research continues to explore optimized converter topologies, energy management strategies, and resilience-oriented system designs [20].

Although significant progress has been made, existing literature remains fragmented and lacks a comprehensive synthesis of portable solar PV systems specifically tailored for post-disaster emergency power supply. Many studies focus on isolated aspects, such as PV module performance, battery technologies, or converter efficiency, without addressing system-level integration and real-world deployment constraints. Furthermore, comparative analyses between different system architectures (e.g., DC-only, DC-first, and AC-centric designs) are limited, particularly in the context of emergency loads and non-technical users. Social and operational dimensions such as ease of use, deployment time, reliability under harsh conditions, and scalability for multiple shelters are often underrepresented. As a result, there is a clear need for a holistic review that bridges technical design considerations with operational and humanitarian requirements.

This paper presents a comprehensive review of portable solar photovoltaic systems for post-disaster emergency power supply, with the following key contributions: 1) Systematic classification of portable PV systems based on capacity, architecture, and deployment scenarios; 2) Integrated discussion of core components, including PV modules, energy storage, power electronics, and protection systems; 3) Comparative analysis of performance, reliability, and usability considerations relevant to disaster-response environments; 4) Examination of smart features and IoT-based monitoring for enhancing system operation and decision-making; and 5) Identification of research gaps and future directions toward resilient, scalable, and user-centered emergency energy solutions. By consolidating dispersed research findings into a unified framework, this review aims to support researchers, engineers, and practitioners involved in the design and deployment of emergency energy systems. The insights provided can inform the development of more efficient, modular, and human-centered portable solar PV systems, ultimately contributing to improved disaster preparedness and response capabilities. Moreover, the review establishes a strong theoretical foundation for applied research and prototype development, facilitating the transition from laboratory-scale designs to real-world humanitarian applications. In this way, the study contributes not only to academic discourse but also to the broader goal of enhancing energy resilience in disaster-prone regions.

2. CLASSIFICATION OF PORTABLE SOLAR PHOTOVOLTAIC SYSTEMS FOR EMERGENCY USE

Portable solar photovoltaic (PV) systems designed for post-disaster applications exhibit wide variations in scale, architecture, and functionality. Table 1 summarizes the main classification criteria for portable solar photovoltaic systems used in post-disaster emergency power supply, highlighting the trade-offs between capacity, deployment configuration, and electrical architecture [21]. A clear classification framework is essential to compare existing solutions, evaluate their suitability for different emergency scenarios, and identify optimal design pathways [22]. Based on a synthesis of recent literature and practical deployments, portable solar PV systems for emergency power supply can be classified according to power capacity and application scale, deployment configuration, and electrical system architecture.

Table 1. Classification of portable solar photovoltaic systems for post-disaster emergency power supply

Classification criterion	Category	Typical capacity	Key characteristics	Advantages	Limitations	Typical emergency applications
Power Capacity & Scale	Low-power solar kits	< 300 Wh/day	Small PV panel, basic charge controller, integrated battery, DC outputs	Lightweight, low cost, rapid distribution	Limited power, single-user focus	Phone charging, LED lamps, and personal communication
	Medium-capacity portable power stations	300 Wh-2 kWh	Integrated PV input, lithium battery, DC & AC outputs, enclosed unit	Balanced portability and functionality	Limited scalability, fixed configuration	Emergency shelters, medical devices, and command posts
	Modular & scalable PV systems	> 2 kWh (expandable)	Interconnected PV and battery modules, flexible configuration	High adaptability, scalable capacity, and redundancy	Higher setup complexity	Evacuation camps, field hospitals, multi-shelter operations
Deployment Configuration	Individual-use systems	Low	Plug-and-play, minimal setup	Easy to operate, fast deployment	Limited shared usage	Household-level disaster relief
	Shelter-based systems	Medium	Centralized storage, multiple outputs	Efficient shared energy use	Requires coordination	Emergency shelters, clinics
	Clustered/networked systems	Medium–High	Interconnected portable units	Improved resilience, energy sharing	More complex management	Large shelters, coordinated response centers
Electrical Architecture	DC-only systems	Low	USB/low-voltage DC outputs only	High efficiency, low losses	Limited load compatibility	Lighting, mobile devices
	DC-first systems	Low–Medium	DC prioritized, optional AC inverter	High efficiency, flexible load support	Requires careful design	Communication, lighting, and medical devices
	AC-centric systems	Medium	Inverter-dominant, AC distribution	Appliance compatibility	Higher losses, reduced efficiency	General-purpose emergency loads
System Origin	Commercial off-the-shelf products	Low–Medium	All-in-one, closed systems	User-friendly, readily available	Limited customization	Rapid deployment scenarios
	Research-based prototypes	Medium–High	Modular, open architecture, optimized design	High efficiency, adaptable	Limited immediate availability	Pilot projects, field trials

2.1. Classification based on power capacity and application scale

One of the most common classification criteria for portable solar PV systems is their power capacity, which directly determines the types of loads that can be supported during emergency operations.

a) Low-power solar kits typically provide power in the range of a few tens to several hundred watt-hours per day. These systems often consist of small rigid or foldable PV panels combined with basic charge controllers and integrated battery packs. Their primary applications include charging mobile phones, powering LED lamps, and supporting small communication devices. Due to their simplicity and low cost, such systems are widely used in household-level disaster relief and rapid humanitarian distribution.

b) Medium-capacity portable power stations represent a more advanced category, with energy capacities generally ranging from several hundred to a few kilowatt-hours. These systems integrate PV input, lithium-based energy storage, power conversion stages, and multiple output ports (DC and AC) within a single enclosure. They are capable of supplying power to emergency shelters, medical devices with low-to-moderate power demand, and coordination centers. This category has received increasing attention in both commercial markets and academic research due to its balance between portability and functional versatility.

c) Modular and scalable portable PV systems constitute the highest-capacity category within portable solutions. Rather than relying on a single unit, these systems are composed of multiple interconnected modules, allowing capacity expansion according to situational needs. Modular systems are particularly suitable for large evacuation camps, field hospitals, and clustered shelters, where energy demand varies over time. Their scalability makes them an attractive alternative to temporary diesel-based microgrids in disaster response contexts.

2.2. Classification based on deployment configuration

Portable solar PV systems can also be categorized according to how they are deployed and integrated into emergency settings [23].

a) Individual-use systems are designed for personal or household-level applications. These systems prioritize extreme portability, minimal setup requirements, and ease of use by non-technical users. Their deployment typically involves a simple plug-and-play operation, making them ideal for rapid distribution immediately after a disaster.

b) Shelter-based systems are installed at specific locations such as emergency shelters, command posts, or temporary healthcare facilities. These systems often involve larger PV arrays, centralized battery storage, and multiple distribution points. While still portable, their deployment may require basic planning and coordination, particularly for load management and system protection [24].
c) Clustered or networked systems involve the interconnection of multiple portable PV units to form a localized energy network. This approach allows energy sharing among shelters and supports redundancy in case of component failure. Clustered systems bridge the gap between fully portable units and larger emergency microgrids, offering improved resilience and flexibility while maintaining relatively fast deployment.

2.3. Classification based on electrical system architecture

Electrical architecture plays a crucial role in determining the efficiency, complexity, and reliability of portable solar PV systems [25].

a) DC-only systems supply power exclusively in direct current form, typically through USB or low-voltage DC outputs. These systems minimize conversion losses and component count, making them highly efficient and lightweight. However, their application is limited to DC-compatible loads and low-power devices.
b) DC-first systems represent an evolution of DC-only designs by prioritizing DC power delivery for critical loads while optionally incorporating AC outputs through dedicated inverters. In these systems, energy is primarily managed and distributed in DC form, reducing unnecessary conversions. DC-first architectures are increasingly favored for emergency applications due to their improved efficiency, adaptability, and suitability for common disaster-response loads such as LED lighting, communication equipment, and medical devices.
c) AC-centric systems are designed around traditional alternating current distribution, often emulating conventional household power supplies. While they offer compatibility with a wide range of appliances, AC-centric systems generally suffer from higher conversion losses, increased system complexity, and reduced overall efficiency. In emergency contexts where energy availability is limited, these drawbacks can significantly affect system performance.

2.4. Commercial products versus research-based prototypes

From an implementation perspective, portable solar PV systems can be divided into commercial off-the-shelf products and research-driven prototypes. Commercial products typically emphasize user convenience, integrated design, and aesthetic appeal, but they often function as closed systems with limited modularity and restricted monitoring capabilities [26]. In contrast, research-based prototypes focus on architectural optimization, open monitoring platforms, and adaptability to specific disaster scenarios. While commercial solutions offer immediate availability, research prototypes contribute critical innovations such as advanced energy management strategies, modular expansion mechanisms, and resilience-oriented design features. Understanding the strengths and limitations of both categories is essential for guiding future development toward deployable yet adaptable emergency energy systems [27].

2.5. Summary of classification and implications for emergency applications

The classification presented in this section highlights the diversity of portable solar PV systems and underscores the importance of aligning system design with specific emergency requirements [23]. Low-power kits are suitable for rapid individual support, medium-capacity power stations address shelter-level needs, and modular systems enable scalable energy provision for larger operations. Similarly, deployment configuration and electrical architecture significantly influence system efficiency, usability, and resilience. In particular, DC-first and modular approaches emerge as promising pathways for achieving efficient, flexible, and user-friendly emergency power supply systems. These insights provide a foundation for the subsequent sections, which examine system components, performance evaluation, and future research directions in greater detail.

3. CORE COMPONENTS AND SYSTEM ARCHITECTURES

The performance, reliability, and usability of portable solar photovoltaic (PV) systems for post-disaster emergency power supply are determined by the integration of several key components and the overall system architecture. Unlike conventional stationary PV installations, emergency-oriented portable systems must balance energy efficiency, portability, robustness, and operational simplicity. This section reviews the core subsystems commonly employed in portable solar PV systems and examines architectural approaches that influence system effectiveness in disaster-response environments [23]. Figure 1 presents the conceptual architecture of a portable solar photovoltaic system designed for post-disaster emergency power supply. The system utilizes a DC-first configuration, where energy captured by portable PV modules is regulated through an MPPT-enabled charge controller and stored in a lithium-based battery system. Direct current loads are powered via DC–DC converters to optimize efficiency, while an optional DC–AC inverter supports selected AC emergency devices. Integrated monitoring and control systems ensure safe, reliable, and user-friendly operation under disaster conditions.

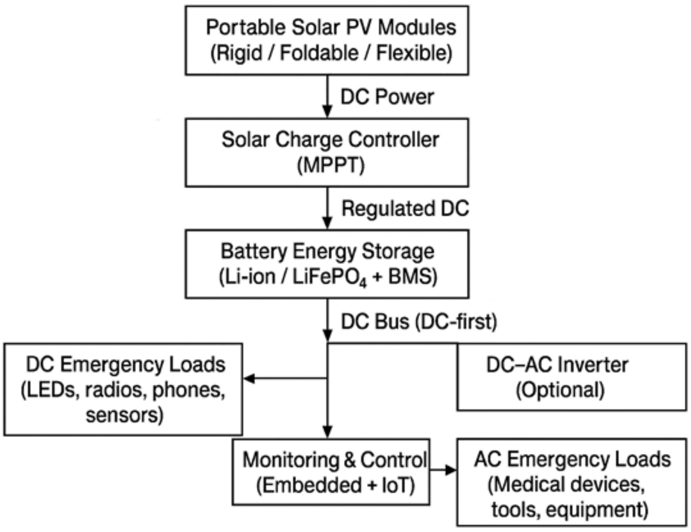

Figure 1. Conceptual architecture of a portable solar photovoltaic system for post-disaster emergency power supply

3.1. Solar energy harvesting units

The solar energy harvesting unit is the primary power source of portable PV systems and significantly influences deployment flexibility and energy yield. Portable systems typically employ rigid, foldable, or flexible PV modules, each offering distinct advantages [28]. Rigid PV panels provide higher efficiency and mechanical durability but are relatively heavy and bulky, which can limit portability. Foldable PV panels, often based on monocrystalline silicon cells, offer a compromise between efficiency and transportability, making them popular in emergency applications. Flexible PV panels, fabricated using thin-film or lightweight crystalline technologies, enable compact storage and rapid deployment on uneven surfaces such as tents or temporary shelters. However, flexible modules generally exhibit lower conversion efficiency and may be more susceptible to mechanical degradation. In disaster scenarios, the selection of PV modules must consider not only peak efficiency but also ease of installation, resistance to dust and moisture, and performance under partial shading, which is common in temporary shelter environments [29].

3.2. Energy storage technologies

Energy storage is crucial for providing power at night and during periods of low sunlight. Portable solar PV systems mainly use lithium-based batteries, such as lithium-ion and lithium iron phosphate ($LiFePO_4$), because they are lightweight, store more energy, last longer, and charge faster than lead-acid batteries. They also allow deeper discharge, making them more suitable for portable use. However, safety is especially important in emergency situations, as systems may be used by non-technical users. Battery management systems (BMS) are therefore essential to monitor voltage, temperature, and state of charge to ensure safe operation. Battery sizing is another important factor: too little storage limits usage time, while too much increases weight and cost. For emergency applications, storage is typically sized to support critical loads rather than continuous high-power use [30], [31].

3.3. Energy storage technologies

Power electronics are essential in portable solar PV systems because they manage energy conversion, control, and distribution. Key components include solar charge controllers, DC–DC converters, inverters, and protection circuits. Solar charge controllers, often using maximum power point tracking (MPPT), regulate power from the PV panels to the batteries and improve energy capture under changing sunlight. DC–DC converters adjust voltage levels for different DC loads with minimal energy loss. When AC power is needed, inverters convert DC power to standard AC output [32]. The selection and setup of these components strongly affect system efficiency and heat generation. In emergency applications, where energy is limited, minimizing conversion steps and using high-efficiency converters is critical to maximize available power [33], [34].

3.4. DC-first and hybrid system architectures

System architecture determines how energy moves between PV panels, batteries, and loads. Traditional portable systems often use an AC-centric design, where DC power from the PV and batteries is first converted to AC. While this allows easy use of standard appliances, it increases energy losses and system complexity [30]. DC-first architectures, on the other hand, distribute DC power directly to compatible loads such as LED lights, communication devices, and medical equipment, using inverters only when AC power is necessary. This reduces unnecessary conversions, improves efficiency, and increases reliability. For these reasons, DC-first designs are well-suited to disaster-response applications, where simplicity and efficient energy use are critical. Hybrid architectures combine DC-first operation with optional AC outputs, offering flexibility while maintaining high efficiency. They also support modular designs, allowing systems to be expanded easily and loads to be prioritized as needed.

3.5. Protection, enclosure, and environmental robustness

Portable solar PV systems used in disaster areas face harsh conditions such as dust, moisture, temperature changes, and physical impacts. As a result, system protection and enclosure design are very important. Common protection features include overcurrent, short-circuit, overvoltage, and thermal shutdown protection. Enclosures are typically compact, lightweight, and weather-resistant, using durable materials and suitable ingress protection (IP) ratings for outdoor use. Proper ventilation or thermal management is also needed to prevent overheating of batteries and power electronics. A robust system design improves reliability and reduces downtime, which is especially critical in emergency situations where maintenance options are limited [35].

3.6. Implications for emergency power system design

The review of core components and system architectures highlights the importance of integrated, efficiency-oriented design in portable solar PV systems for disaster response. The selection of PV modules, batteries, and power electronics must be guided by operational constraints such as portability, ease of use, and environmental resilience. Architectural choices, particularly the adoption of DC-first and modular configurations, play a decisive role in maximizing system efficiency and adaptability. These considerations provide a foundation for evaluating system performance and operational effectiveness, which are examined in the next section [36], [37].

4. PERFORMANCE EVALUATION AND OPERATIONAL CONSIDERATIONS

Evaluating the performance of portable solar photovoltaic (PV) systems for post-disaster emergency power supply requires a multidimensional approach that extends beyond conventional electrical efficiency metrics. In disaster-response contexts, system effectiveness is determined not only by energy yield but also by reliability, robustness, ease of deployment, and usability under constrained conditions [38]. This section reviews key performance indicators and operational considerations commonly used to assess portable solar PV systems in emergency applications [39], [40].

4.1. Implications for emergency power system design

Energy yield is a key performance metric for portable PV systems in emergency operations, where available energy is limited. It is influenced by daily energy output, conversion efficiency, and environmental factors such as irradiance variability, shading, dust, and temperature [41]. Systems using MPPT-based charge controllers achieve higher energy harvesting efficiency under non-ideal conditions. In addition, DC-first architectures reduce conversion losses by minimizing DC–AC–DC transitions, allowing more usable energy to be delivered to critical loads for a given PV and battery capacity [42].

4.2. Reliability and operational continuity

Reliability is essential in emergency power systems, where outages can threaten safety and critical services. Performance evaluation, therefore, focuses on system uptime, fault tolerance, and continuous operation under prolonged use. Reliability is affected by component quality, thermal management, battery aging, and protection features. Disaster-response PV systems must operate stably despite load fluctuations and irregular charging. To improve reliability, designers often use redundancy, modular configurations, and load prioritization to ensure critical loads remain powered when system capacity is limited [20], [40].

4.3. Load profiling and energy management

Understanding and managing load demand is essential for optimizing portable solar PV systems in emergency situations. Common loads include LED lighting, communication devices, medical equipment, and mobile charging, each with different power needs. Performance evaluation focuses on how effectively the system supports these loads through profiling and prioritization. Energy management strategies such as scheduled operation, load shedding, and priority-based distribution help prevent battery depletion and extend system operation. Intelligent energy management improves efficiency and service duration under limited energy conditions [43].

4.4. Deployment time and portability

In post-disaster situations, rapid deployment is as important as energy capacity. Performance evaluation therefore, considers portability, setup time, and ease of handling [24]. Lightweight components, compact enclosures, and simple connectors allow faster installation with less logistical effort. Foldable PV modules and plug-and-play power stations enable use by non-technical users, which is vital in humanitarian settings. In contrast, systems requiring complex wiring or configuration can delay response and reduce practical effectiveness despite good electrical performance.

4.5. Usability and human factors

Operational success in disaster environments depends heavily on system usability. Many portable solar PV systems are operated by volunteers or affected individuals with limited technical background. As such, performance evaluation must account for human factors, including interface clarity, ease of operation, and safety [7].

4.6. Environmental robustness and durability

Portable solar PV systems deployed in disaster zones are exposed to harsh environmental conditions, including moisture, dust, mechanical shocks, and temperature extremes. Performance evaluation, therefore, includes durability testing and assessment of environmental robustness. Ingress protection ratings, impact-resistant enclosures, and secure mounting solutions enhance system longevity and operational safety. Systems that demonstrate consistent performance under adverse conditions are better suited for prolonged emergency deployment and repeated use across multiple disaster events [44].

4.7. Environmental robustness and durability

The evaluation of portable solar PV systems for post-disaster emergency power supply must integrate technical performance metrics with operational and human-centered considerations. High energy efficiency alone is insufficient if systems are difficult to deploy, unreliable, or challenging to operate. DC-first, modular, and user-oriented designs consistently emerge as effective solutions, offering improved energy utilization, adaptability, and resilience. These insights highlight the need for holistic evaluation frameworks that reflect real-world emergency conditions, providing a basis for future system optimization and innovation [45], [46].

5. SMART FEATURES, MONITORING, AND INTEGRATION IN EMERGENCY SYSTEMS

The integration of smart features and digital monitoring has become an increasingly important aspect of portable solar photovoltaic (PV) systems for post-disaster emergency power supply. In emergency environments characterized by uncertainty, limited technical support, and dynamic energy demand, real-time system awareness and adaptive control can significantly enhance reliability, safety, and operational effectiveness. This section reviews key smart functionalities, monitoring approaches, and system integration strategies employed in portable solar PV systems for disaster-response applications [47].

5.1. Role of smart monitoring in emergency energy systems

Smart monitoring enables continuous observation of system status and performance, allowing operators to make informed decisions regarding energy usage and maintenance. In portable PV systems, monitoring typically focuses on critical parameters such as battery state-of-charge, PV voltage and current, load consumption, temperature, and fault conditions. In post-disaster contexts, monitoring serves both technical and operational purposes. Technically, it helps prevent system failures through early detection of abnormal conditions such as overheating, overcurrent, or battery degradation. Operationally, it supports energy allocation decisions, ensuring that limited energy resources are directed toward critical loads. The ability to visualize system status in a simple and intuitive manner is particularly important for non-technical users operating under stressful conditions [48].

5.2. IoT-based architectures and communication technologies

Internet of Things (IoT) technologies enable smart monitoring in portable solar PV systems through scalable and flexible architectures. Typical setups include embedded controllers, sensors, communication interfaces, and local or cloud data platforms. Common communication options are Wi-Fi, Bluetooth, cellular networks, and LPWANs, selected based on deployment conditions and power availability. In disaster areas with poor connectivity, systems often rely on local data storage and short-range communication, using cloud services when networks are available. Low power consumption and robust operation are essential to ensure reliable monitoring without reducing energy supply performance [49].

5.3. Embedded control and intelligent energy management

Beyond passive monitoring, smart portable PV systems increasingly include embedded control and intelligent energy management. These features enable automated decisions such as load prioritization, charge control, and fault response without constant user input. Energy management algorithms adjust power distribution based on battery status, load demand, and expected energy availability. For instance, non-critical loads can be disconnected when battery levels drop, preserving power for essential services. This automation improves system resilience and reduces operator workload during emergency response [49], [50].

5.4. User interfaces and human–system interaction

Effective human–system interaction is crucial for deploying smart portable solar PV systems in disaster environments. User interfaces should present system information clearly and simply, avoiding technical complexity. Common interfaces include onboard displays, LED indicators, and mobile apps, with color-coded visuals and simple icons to quickly convey system status. Multilingual support and offline operation further improve usability in emergencies. Human-centered design enhances efficiency, builds user confidence, and supports long-term adoption in humanitarian settings [51].

5.5. Integration with emergency energy ecosystems

Portable solar PV systems rarely operate alone during large-scale disaster response. They are typically integrated into broader emergency energy ecosystems such as shelters, healthcare facilities, communication networks, and coordination centers. Integration may involve linking multiple portable units, sharing monitoring data, or coordinating with temporary microgrids and backup generators. Smart features enable standardized communication, remote monitoring, and coordinated energy management across systems. This system-level integration improves energy resilience by pooling resources, balancing loads, and reducing failures through redundancy and adaptive control [52], [53].

5.6. Implications for future emergency power systems

The adoption of smart features and monitoring marks a major advancement in portable solar PV systems for post-disaster power supply. Although these technologies add complexity, they significantly improve reliability, safety, and operational awareness. Future systems are expected to focus on low-power intelligent monitoring, open communication protocols, and user-centered design to support seamless integration into disaster-response frameworks. By aligning innovation with practical needs, smart portable PV systems can greatly enhance energy resilience and effectiveness in emergency situations [54].

6. CHALLENGES AND RESEARCH GAPS IN PORTABLE SOLAR PHOTOVOLTAIC SYSTEMS FOR EMERGENCY POWER SUPPLY

Portable solar photovoltaic (PV) systems have emerged as a promising alternative to conventional emergency power solutions in post-disaster contexts. Their ability to provide clean, modular, and rapidly deployable energy makes them attractive for humanitarian operations. However, widespread adoption remains constrained by a range of technical, operational, and institutional challenges [55]. Addressing these gaps is critical to ensure that portable PV systems can deliver reliable, scalable, and sustainable energy under the demanding conditions of disaster response [56]. This section synthesizes the principal limitations and highlights areas where further research and development are required.

6.1. Technical challenges

Despite notable advances, several technical barriers continue to limit the performance and resilience of portable PV systems:

a) Energy efficiency and variability: PV modules are highly sensitive to environmental factors such as shading, dust accumulation, and temperature fluctuations, which can significantly reduce energy yield in disaster environments.
b) Storage limitations: Lithium-ion and $LiFePO_4$ batteries, while widely used, remain costly and prone to degradation under extreme temperatures or irregular charging cycles, undermining long-term reliability.
c) System standardization: The absence of standardized connectors, voltage levels, and modular interfaces complicates interoperability between units and hinders rapid deployment in multi-system scenarios.
d) Robustness and durability: Many prototypes lack sufficient ruggedization, making them vulnerable to damage during transport, handling, and exposure to adverse weather conditions.

6.2. Operational and social challenges

Beyond technical constraints, several operational and social factors affect the effective deployment of portable PV systems:

a) User training and acceptance: Non-technical users often face difficulties in system setup, monitoring, and maintenance. Simplified interfaces and accessible training materials are frequently inadequate.
b) Logistics and supply chains: Transporting, distributing, and maintaining portable PV units in disaster zones is logistically complex, particularly when infrastructure is severely disrupted.
c) Cultural and social acceptance: Communities accustomed to conventional diesel generators may initially distrust solar-based solutions, necessitating awareness campaigns and demonstration projects to build confidence.
d) Maintenance and spare parts: Limited availability of replacement components and technical support remains a major barrier to long-term sustainability and reliability.

6.3. Scalability and system integration

While portable PV systems are effective at the household or shelter level, scaling them to community-wide applications introduces additional challenges:

a) Coordination of multiple units: Integrating several portable systems into a temporary microgrid requires advanced energy management strategies and standardized communication protocols.
b) Load balancing and prioritization: Scaling increases complexity in distributing energy fairly among critical and non-critical loads, particularly under resource-constrained conditions.
c) Interoperability with existing infrastructure: Seamless integration with backup generators, grid restoration efforts, and humanitarian logistics remains underdeveloped, limiting system flexibility.

6.4. Policy, standardization, and humanitarian deployment

Institutional and policy frameworks play a decisive role in enabling the adoption of portable PV systems, yet several gaps persist:

a) Absence of standards: International standards tailored to portable PV systems in disaster contexts are limited, resulting in inconsistent designs and deployment practices.
b) Procurement and funding: Humanitarian organizations often operate under short-term procurement cycles, which may discourage investment in durable and modular PV solutions.
c) Regulatory barriers: Import restrictions, certification requirements, and the lack of harmonized policies can delay deployment in affected regions.
d) Ethical considerations: Ensuring equitable access, avoiding dependency, and aligning deployment strategies with humanitarian principles are essential for responsible and sustainable implementation.

As summarized in Table 2, technical, operational, scalability, and policy-related barriers collectively hinder the widespread adoption of portable solar PV systems in emergency contexts. Technically, systems face limitations in energy efficiency, storage reliability, and ruggedization, which compromise performance under harsh disaster conditions [57]. Operationally, challenges such as user unfamiliarity, logistical constraints, and maintenance gaps reduce system effectiveness and sustainability. At the scalability level, difficulties in coordinating multiple units, balancing loads, and integrating with existing infrastructure limit expansion beyond individual shelters. Institutionally, the absence of international standards, fragmented procurement practices, and regulatory hurdles further delay deployment and reduce interoperability across regions. These interconnected challenges underscore the need for holistic solutions that address not only hardware and design, but also training, policy alignment, and system-level integration to ensure portable PV systems can fulfill their potential as resilient energy solutions in post-disaster scenarios.

Table 2. Summary of challenges and research gaps in portable solar PV systems for emergency power supply

Challenge	Description	Implication for disaster response
Energy efficiency and variability	PV modules are sensitive to shading, dust, and temperature fluctuations, reducing energy yield.	Lower and unpredictable energy output may compromise critical load supply in unstable environments.
Storage limitations	Lithium-ion and $LiFePO_4$ batteries are costly and prone to degradation under extreme conditions.	Reduced reliability and shorter system lifespan hinder sustained operation in prolonged emergencies.
System standardization	Lack of standardized connectors, voltage levels, and modular interfaces limits interoperability.	Slows rapid deployment and complicates integration of multiple units in coordinated relief efforts.
Robustness and durability	Many prototypes are fragile and not ruggedized for harsh transport or weather exposure.	Increased risk of system failure during field use, reducing trust and adoption in humanitarian contexts.
User training and acceptance	Non-technical users struggle with setup, monitoring, and maintenance; training materials are limited.	Misuse or underutilization of systems reduces effectiveness in disaster response operations.
Logistics and supply chains	Transporting and maintaining units is complex when infrastructure is damaged.	Delays in deployment and difficulties in sustaining energy supply across affected regions.
Cultural and social acceptance	Communities accustomed to diesel generators may distrust solar-based solutions.	Slower adoption and reliance on conventional, less sustainable alternatives.
Maintenance and spare parts	Limited availability of replacement components and technical support.	System downtime and reduced resilience in long-term disaster recovery.
Scalability and integration	Coordinating multiple units into microgrids requires advanced management and protocols.	Limits expansion from household-level to community-wide energy solutions.
Load balancing and prioritization	Scaling introduces complexity in distributing energy among critical and non-critical loads.	Risk of inequitable energy allocation, undermining humanitarian objectives.
Interoperability with infrastructure	Integration with generators, grid restoration, and logistics is underdeveloped.	Reduces flexibility and efficiency of hybrid emergency energy ecosystems.
Absence of standards	Few international standards exist for portable PV in disaster contexts.	Inconsistent designs and deployment practices hinder global adoption.
Procurement and funding	Short-term procurement cycles discourage investment in durable systems.	Limits availability of robust solutions during emergencies.
Regulatory barriers	Import restrictions and certification requirements delay deployment.	Slows humanitarian response and reduces scalability across regions.
Ethical considerations	Need to ensure equitable access and avoid dependency.	Risk of unequal distribution of energy resources, undermining humanitarian principles.

7. CONCLUSION

This review has critically examined the role of portable solar photovoltaic (PV) systems in delivering emergency power during post-disaster scenarios. Beginning with the challenges of energy disruption in disaster contexts, the paper classified portable PV systems by capacity, deployment type, and electrical architecture, and analyzed their core components, performance considerations, and smart monitoring features. Particular emphasis was placed on DC-first architectures, modularity, and IoT-enabled monitoring, which emerge as key enablers of efficiency, reliability, and usability in humanitarian settings. The synthesis of findings highlights that portable PV systems represent a sustainable and scalable alternative to conventional diesel generators, especially when designed with resilience, simplicity, and user-centered interfaces. Smart monitoring and embedded control substantially enhance operational awareness and reduce the burden on non-technical users, while integration into broader emergency energy ecosystems enables coordinated and adaptive resource management. Nonetheless, significant barriers remain, including technical limitations in energy storage, lack of standardization, and operational challenges in deployment and maintenance, which currently constrain widespread adoption. To address these challenges and advance the field, future research should prioritize: 1) Resilient energy storage-development of low-cost, thermally stable, and long-life batteries tailored for disaster environments; 2) Modular and plug-and-play architectures-standardized interfaces enabling rapid scaling from single units to coordinated microgrids; 3) AI-driven energy management-intelligent algorithms for predictive load prioritization, fault detection, and adaptive control; d) Low-power IoT monitoring-energy-efficient communication protocols and embedded systems that minimize overhead while ensuring reliability; 4) Human-centered design-interfaces that emphasize simplicity, multilingual support, and accessibility for non-technical users; 5) Policy frameworks and standards-collaborative efforts to establish international guidelines for portable PV deployment in humanitarian contexts; and 6) Hybrid systems-integration of PV with complementary renewable sources (e.g., portable wind, fuel cells) to enhance resilience and energy diversity. In conclusion, portable solar PV systems hold transformative potential for strengthening energy resilience in disaster contexts. Realizing this potential will require coordinated advances in technology, operations, and policy, alongside a commitment to humanitarian integration. By overcoming current limitations and embracing innovation in storage, modularity, intelligent monitoring, and system interoperability, future portable PV systems can evolve into robust, scalable, and trusted solutions. Ultimately, they may serve as a cornerstone of sustainable disaster-response strategies, bridging the gap between immediate relief and long-term recovery.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Universitas Ahmad Dahlan (UAD), Universitas Diponegoro, and the Embedded Systems and Power Electronics Research Group (ESPERG) for their invaluable support and contributions to this research. The facilities, guidance, and collaborative environment provided by these institutions were instrumental in the successful completion and publication of this work.

FUNDING INFORMATION

The research was funded by PT. Intelektual Pustaka Media Utama (IPMU) under contract number 01/RST-E/IPMU/I/2025, which supported the facilitation of this work.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Tole Sutikno	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Wahyu Sapto Aji	✓	✓		✓	✓	✓			✓	✓		✓		
Mochammad Facta	✓	✓		✓	✓	✓			✓	✓				
Hendril Satrian Purnama	✓	✓				✓			✓					
Tri Wahono		✓		✓						✓	✓		✓	

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.

REFERENCES

[1] J.-H. Lin and Y.-K. Wu, "Review of power system resilience concept, assessment, and enhancement measures," *Appl. Sci.*, vol. 14, no. 4, p. 1428, Feb. 2024, doi: 10.3390/app14041428.

[2] E. Yulianto, P. Utari, and I. A. Satyawan, "Communication technology support in disaster-prone areas: Case study of earthquake, tsunami and liquefaction in Palu, Indonesia," *Int. J. Disaster Risk Reduct.*, vol. 45, p. 101457, May 2020, doi: 10.1016/j.ijdrr.2019.101457.

[3] J. A. Casey, M. Fukurai, D. Hernández, S. Balsari, and M. V. Kiang, "Power outages and community health: a narrative review," *Curr. Environ. Heal. Reports*, vol. 7, no. 4, pp. 371–383, Dec. 2020, doi: 10.1007/s40572-020-00295-0.

[4] H. Ashrafi and T. Parhizkar, "Electricity sector resilience in response to extreme weather and climate-related events: Tools and

datasets," *Electr. J.*, vol. 36, no. 6, p. 107290, Jul. 2023, doi: 10.1016/j.tej.2023.107290.
[5] S. W. Monie, M. Gustafsson, S. Önnered, and K. Guruvita, "Renewable and integrated energy system resilience-A review and generic resilience index," *Renew. Sustain. Energy Rev.*, vol. 215, p. 115554, Jun. 2025, doi: 10.1016/j.rser.2025.115554.
[6] A. Oshiobugie and P. Adeel, "Building Resilient and Sustainable Energy Infrastructure: Enhancing renewable integration and emergency power management," *Int. J. Energy Environ. Res.*, vol. 12, no. 3, pp. 20–39, Nov. 2024, doi: 10.37745/ijeer.2013/vol12n12039.
[7] M. Widyartono, W. Aribowo, R. Rahmadian, A. L. Wardani, and A. C. Hermawan, "Designing a portable solar generator for emergencies," *E3S Web Conf.*, vol. 513, p. 02006, Apr. 2024, doi: 10.1051/e3sconf/202451302006.
[8] M. Rouholamini, C. Wang, S. Magableh, and X. Wang, "Resiliency of electric power distribution networks: a review," *J. Infrastruct. Preserv. Resil.*, vol. 6, no. 1, p. 39, Nov. 2025, doi: 10.1186/s43065-025-00154-y.
[9] C. Lawrie and C. Stubenberg, "Friend or foe? Diesel generators and the global energy transition," *Energy Res. Soc. Sci.*, vol. 126, p. 104124, Aug. 2025, doi: 10.1016/j.erss.2025.104124.
[10] J. Marqusee and D. Jenket, "Reliability of emergency and standby diesel generators: Impact on energy resiliency solutions," *Appl. Energy*, vol. 268, p. 114918, Jun. 2020, doi: 10.1016/j.apenergy.2020.114918.
[11] A. Felice, J. Barbieri, A. Martinez Alonso, M. Messagie, and T. Coosemans, "Challenges of phasing out emergency diesel generators: the case study of Lacor Hospital's energy community," *Energies*, vol. 16, no. 3, p. 1369, Jan. 2023, doi: 10.3390/en16031369.
[12] J. Xia, F. Xu, and G. Huang, "Research on power grid resilience and power supply restoration during disasters-a review," in *Flood Impact Mitigation and Resilience Enhancement*, IntechOpen, 2020.
[13] M. U. Aslam, M. S. Miah, B. M. R. Amin, R. Shah, and N. Amjady, "Application of energy storage systems to enhance power system resilience: a critical review," *Energies*, vol. 18, no. 14, p. 3883, Jul. 2025, doi: 10.3390/en18143883.
[14] M. Doostizadeh, H. Jalili, and A. Babaee, "A decentralized framework for economic-resilient operation of networked microgrids, considering demand response program," *IET Renew. Power Gener.*, vol. 18, no. 8, pp. 1428–1454, Jun. 2024, doi: 10.1049/rpg2.12984.
[15] A. Ghosh, D. Gamage, A. Ukil, and A. P. Hu, "Emergency power supply enabling solar PV integration with battery storage and wireless interface," *J. R. Soc. New Zeal.*, vol. 55, no. 4, pp. 1028–1050, Aug. 2025, doi: 10.1080/03036758.2024.2314476.
[16] Q. Fitriyah, E. P. Saragi, N. Lusi, G. S. Prayogo, and M. P. E. Wahyudi, "Portable solar photovoltaic suitcase," *J. Integr.*, vol. 13, no. 2, pp. 158–161, Oct. 2021, doi: 10.30871/ji.v13i2.3460.
[17] S. Sulistiyanto, M. J. IsroAfifi, and A. F. AlBasyi, "Designing a solar power plant emergency box for rapid disaster response in bucor wetan village," *J. Electr. Eng. Comput.*, vol. 7, no. 2, pp. 445–451, Oct. 2025, doi: 10.33650/jeecom.v7i2.12682.
[18] S. Shadvar and A. Rahman, "Performance evaluation of off-grid solar systems for critical medical instruments in remote regions," *J. Emerg. Sci. Eng.*, vol. 2, no. 2, p. e22, May 2024, doi: 10.61435/jese.2024.e22.
[19] N. Rouibah *et al.*, "Smart monitoring of photovoltaic energy systems: An IoT-based prototype approach," *Sci. African*, vol. 30, p. e02973, Dec. 2025, doi: 10.1016/j.sciaf.2025.e02973.
[20] D. Raveendhra *et al.*, "Part-I: State-of-the-art technologies of solar powered DC microgrid with hybrid energy storage systems-architecture topologies," *Energies*, vol. 16, no. 2, p. 923, Jan. 2023, doi: 10.3390/en16020923.
[21] M. Ahmed, M. Rashel, M. Islam, A. Islam, and M. Tlemcani, "Classification and Parametric analysis of solar hybrid PVT system: a review," *Energies*, vol. 17, no. 3, p. 588, Jan. 2024, doi: 10.3390/en17030588.
[22] A. Herez, H. Jaber, H. El Hage, T. Lemenand, M. Ramadan, and M. Khaled, "A review on the classifications and applications of solar photovoltaic technology," *AIMS Energy*, vol. 11, no. 6, pp. 1102–1130, 2023, doi: 10.3934/energy.2023051.
[23] J. Franceschi, J. Rothkop, and G. Miller, "Off-grid solar PV power for humanitarian action: From emergency communications to refugee camp micro-grids," *Procedia Eng.*, vol. 78, pp. 229–235, 2014, doi: 10.1016/j.proeng.2014.07.061.
[24] Q. Li, T. Li, and A. Zanelli, "Performance evaluation of flexible photovoltaic panels for energy supply in post-disaster emergency shelters," *J. Build. Eng.*, vol. 98, p. 111285, Dec. 2024, doi: 10.1016/j.jobe.2024.111285.
[25] J. J. Justo, F. Mwasilu, J. Lee, and J.-W. Jung, "AC-microgrids versus DC-microgrids with distributed energy resources: A review," *Renew. Sustain. Energy Rev.*, vol. 24, pp. 387–405, Aug. 2013, doi: 10.1016/j.rser.2013.03.067.
[26] Z. Kou and H. Wang, "Transient pressure analysis of a multiple fractured well in a stress-sensitive coal seam gas reservoir," *Energies*, vol. 13, no. 15, p. 3849, Jul. 2020, doi: 10.3390/en13153849.
[27] S. Okamoto, N. Denis, Y. Kato, M. Ieki, and K. Fujisaki, "Core loss reduction of an interior permanent-magnet synchronous motor using amorphous stator core," *IEEE Trans. Ind. Appl.*, vol. 52, no. 3, pp. 2261–2268, May 2016, doi: 10.1109/TIA.2016.2532279.
[28] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, "Solar cell efficiency tables (version 48)," *Prog. Photovoltaics Res. Appl.*, vol. 24, no. 7, pp. 905–913, Jul. 2016, doi: 10.1002/pip.2788.
[29] Y.-J. Kim, J.-W. Ha, K.-S. Park, and Y.-H. Song, "A study on the energy reduction measures of data centers through chilled water temperature control and water-side economizer," *Energies*, vol. 14, no. 12, p. 3575, Jun. 2021, doi: 10.3390/en14123575.
[30] G. Ding, Q. Wu, L. Zhang, Y. Lin, T. A. Tsiftsis, and Y.-D. Yao, "An Amateur drone surveillance system based on the cognitive internet of things," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 29–35, Jan. 2018, doi: 10.1109/MCOM.2017.1700452.
[31] F. Altobelli, M. Condorí, G. Duran, and C. Martinez, "Solar dryer efficiency considering the total drying potential. Application of this potential as a resource indicator in north-western Argentina," *Sol. Energy*, vol. 105, pp. 742–759, Jul. 2014, doi: 10.1016/j.solener.2014.04.029.
[32] N. Ahmed and Maher Faeq, "A review of single phase transformer-less inverter topologies for grid-tied photovoltaic system and control strategy methods," *NTU J. Renew. Energy*, vol. 7, no. 1, pp. 84–97, Nov. 2024, doi: 10.56286/m55ayy76.
[33] A. Z. Arsad, A. W. M. Zuhdi, A. D. Azhar, C. F. Chau, and A. Ghazali, "Advancements in maximum power point tracking for solar charge controllers," *Renew. Sustain. Energy Rev.*, vol. 210, p. 115208, Mar. 2025, doi: 10.1016/j.rser.2024.115208.
[34] V. C. Tella, B. Agili, and M. He, "Advanced MPPT Control Algorithms: A comparative analysis of conventional and intelligent techniques with challenges," *Eur. J. Electr. Eng. Comput. Sci.*, vol. 8, no. 4, pp. 6–20, Jul. 2024, doi: 10.24018/ejece.2024.8.4.623.
[35] J.-H. Ahn and B. K. Lee, "High-efficiency adaptive-current charging strategy for electric vehicles considering variation of internal resistance of lithium-ion battery," *IEEE Trans. Power Electron.*, vol. 34, no. 4, pp. 3041–3052, Apr. 2019, doi: 10.1109/TPEL.2018.2848550.
[36] G. Shabbir, A. Hasan, M. Yaqoob Javed, K. Shahid, and T. Mussenbrock, "Review of DC Microgrid design, optimization, and control for the resilient and efficient renewable energy integration," *Energies*, vol. 18, no. 23, p. 6364, Dec. 2025, doi: 10.3390/en18236364.
[37] A. W. Adegboyega, S. Sepasi, H. O. R. Howlader, B. Griswold, M. Matsuura, and L. R. Roose, "DC microgrid deployments and challenges: a comprehensive review of academic and corporate implementations," *Energies*, vol. 18, no. 5, p. 1064, Feb. 2025, doi: 10.3390/en18051064.

[38] M. A. Hawks and S. Cho, "Review and analysis of current solutions and trends for zero energy building (ZEB) thermal systems," *Renew. Sustain. Energy Rev.*, vol. 189, p. 114028, Jan. 2024, doi: 10.1016/j.rser.2023.114028.

[39] P. Johnstone, K. S. Rogge, P. Kivimaa, C. Farné Fratini, and E. Primmer, "Exploring the re-emergence of industrial policy: Perceptions regarding low-carbon energy transitions in Germany, the United Kingdom and Denmark," *Energy Res. Soc. Sci.*, vol. 74, p. 101889, Apr. 2021, doi: 10.1016/j.erss.2020.101889.

[40] Q. Cheng, L. You, N. Jia, Y. Kang, C. Chang, and W. Xie, "New insight into enhancing organic-rich shale gas recovery: shut-in performance increased through oxidative fluids," *Energies*, vol. 16, no. 11, p. 4325, May 2023, doi: 10.3390/en16114325.

[41] P. J. M. Thomas, P. Sandwell, S. J. Williamson, and P. W. Harper, "A PESTLE analysis of solar home systems in refugee camps in Rwanda," *Renew. Sustain. Energy Rev.*, vol. 143, p. 110872, Jun. 2021, doi: 10.1016/j.rser.2021.110872.

[42] A. Purkayastha and A. T. Mallajosyula, "Optical modelling of tandem solar cells using hybrid organic-inorganic tin perovskite bottom sub-cell," *Sol. Energy*, vol. 218, pp. 251–261, Apr. 2021, doi: 10.1016/j.solener.2021.01.054.

[43] C. Schulze and K. P. Birke, "Method for analyzing in-situ volume change of large format lithium-ion hard case cells," *J. Energy Storage*, vol. 55, p. 105736, Nov. 2022, doi: 10.1016/j.est.2022.105736.

[44] R. Cristobal, "Mobile Solar Generator: A disaster resilient power source," *Business, Educ. Soc. Sci. Technol.*, vol. 1, no. 2, pp. 27–32, Jul. 2025, doi: 10.69478/BEST2025v1n2a004.

[45] M. M. Rahman, S. Khan, and J. M. Pearce, "Open-source hardware design of modular solar DC nanogrid," *Technologies*, vol. 12, no. 9, p. 167, Sep. 2024, doi: 10.3390/technologies12090167.

[46] F. C. Ogbuonwu, K. C. Owuama, and V. C. Ezechukwu, "Performance evaluation of a reliable portable solar power system," *IPS J. Eng. Technol.*, vol. 1, no. 2, pp. 75–90, Apr. 2025, doi: 10.54117/ijet.v1i2.16.

[47] C. K. Rao, S. K. Sahoo, and F. F. Yanine, "A review of IoT enabled intelligent smart energy management for photovoltaic power forecasting and generation," *Unconv. Resour.*, vol. 9, p. 100279, Jan. 2026, doi: 10.1016/j.uncres.2025.100279.

[48] M. A. T. Pojas, J. M. M. Magayon, A. D. B. Balamad, J. T. Dellosa, and L. M. Dagsa, "Real-time monitoring and adaptive control of solar panel cooling for enhanced power harvest through IoT integration," *Proc. Int. Exch. Innov. Conf. Eng. Sci.*, vol. 10, pp. 312–318, Oct. 2024, doi: 10.5109/7323279.

[49] C. M. Nkinyam, C. O. Ujah, C. O. Asadu, B. Anyaka, and P. A. Olubambi, "Development of a low-cost monitoring device for solar electric (PV) system using internet of things (IoT)," *Results Eng.*, vol. 28, p. 107324, Dec. 2025, doi: 10.1016/j.rineng.2025.107324.

[50] A. Mimouni, Y. Chahet, A. El Amrani, M. El Amraoui, and L. Bejjit, "Internet of things technology for an autonomous photovoltaic solar energy system monitoring," *E3S Web Conf.*, vol. 601, p. 00056, Jan. 2025, doi: 10.1051/e3sconf/202560100056.

[51] M. L. Tan, R. Prasanna, K. Stock, E. E. H. Doyle, G. Leonard, and D. Johnston, "Understanding end-users' perspectives: Towards developing usability guidelines for disaster apps," *Prog. Disaster Sci.*, vol. 7, p. 100118, Oct. 2020, doi: 10.1016/j.pdisas.2020.100118.

[52] M. Ali, Y. Guan, J. C. Vasquez, J. M. Guerrero, F. D. Wijaya, and A. P. Perdana, "Microgrids for energy access in remote and islanded communities under natural disasters-Context of Lombok Island Indonesia," *Renew. Energy Focus*, vol. 54, p. 100705, Sep. 2025, doi: 10.1016/j.ref.2025.100705.

[53] S. Punitha, N. P. Subramaniam, and P. A. D. V. Raj, "A comprehensive review of microgrid challenges in architectures, mitigation approaches, and future directions," *J. Electr. Syst. Inf. Technol.*, vol. 11, no. 1, p. 60, Dec. 2024, doi: 10.1186/s43067-024-00188-4.

[54] L. Jia, Z. Li, and Z. Hu, "Applications of the internet of things in renewable power systems: A Survey," *Energies*, vol. 17, no. 16, p. 4160, Aug. 2024, doi: 10.3390/en17164160.

[55] D. Bammeke, J. D. Nixon, J. Brusey, and E. Gaura, "Multi-objective energy management model for stand-alone photovoltaic-battery systems: application to refugee camps," 2023, pp. 81–91.

[56] A. A. Firoozi, A. A. Firoozi, and M. R. Maghami, "Harnessing photovoltaic innovation: Advancements, challenges, and strategic pathways for sustainable global development," *Energy Convers. Manag. X*, vol. 27, p. 101058, Jul. 2025, doi: 10.1016/j.ecmx.2025.101058.

[57] S. L. Lewis, D. P. Edwards, and D. Galbraith, "Increasing human dominance of tropical forests," *Science (80-.).*, vol. 349, no. 6250, pp. 827–832, Aug. 2015, doi: 10.1126/science.aaa9932.

BIOGRAPHIES OF AUTHORS

Tole Sutikno is a lecturer and the head of the Master Program of Electrical Engineering at the Faculty of Industrial Technology, Universitas Ahmad Dahlan (UAD) in Yogyakarta, Indonesia. In addition to leading the Master Program, he also lectures in the Ph.D. Program in Informatics and the Undergraduate Program in Electrical Engineering at UAD. He received his Bachelor of Engineering from Universitas Diponegoro in 1999, Master of Engineering from Universitas Gadjah Mada in 2004, and Doctor of Philosophy in Electrical Engineering from Universiti Teknologi Malaysia in 2016. All three degrees are in the Electrical Engineering area. He has been a Professor at UAD in Yogyakarta, Indonesia, since July 2023, following his tenure as an associate professor in June 2008. He is the Editor-in-Chief of TELKOMNIKA and Head of the Embedded Systems and Power Electronics Research Group (ESPERG). He is listed as one of the top 2% of researchers worldwide, according to Stanford University and Elsevier BV's list of the most influential scientists from 2021 to the present. His research interests cover digital design, industrial applications, industrial electronics, industrial informatics, power electronics, motor drives, renewable energy, FPGA applications, embedded systems, artificial intelligence, intelligent control, digital libraries, and information technology. He can be contacted at email: tole@te.uad.ac.id or tole@ee.uad.ac.id.

Wahyu Sapto Aji is a Senior Lecturer and researcher in Electrical and Computer Engineering, affiliated with Universitas Ahmad Dahlan, Yogyakarta, Indonesia, and Universiti Malaysia Pahang (UMP), Malaysia. He earned his Bachelor's degree in Electrical Engineering from Universitas Gadjah Mada (UGM) in 1999, his Master's degree in Electrical Engineering from UGM in 2008, and his Ph.D. in Electrical and Electronic Engineering from UMP in 2025. As a certified professional engineer (Insinyur Profesional Madya-IPM), Dr. Aji has developed expertise in robotics, control systems, embedded systems, and industrial automation, with specialties in bacteria detection, control theory, and machine learning applications. His scholarly portfolio includes more than 26 publications, 15 of which are indexed in Scopus, with over 34 citations. Notable works include Oil Palm USB Detector Trained on Synthetic Images Generated by PGGAN, Irrigation Sluice Control System Using Algorithm-Based DC Motor PID and Omron PLC, and Rapid Bacterial Colony Classification Using Deep Learning. Earlier contributions in TELKOMNIKA (2007–2009) focused on fire detection, mobile alarm systems, and robotic prototypes. Dr. Aji continues to advance interdisciplinary research while mentoring students and contributing to engineering education and professional development in Indonesia and Malaysia. He can be contacted at email: wahyusa@ee.uad.ac.id or wahyusaji@gmail.com.

Mochammad Facta is an associate professor in the Department of Electrical Engineering at Universitas Diponegoro (UNDIP), Semarang, Indonesia, where he has served since 1999. He earned his B.S. in Electrical Engineering from Universitas Hasanuddin, his M.Eng. from Institut Teknologi Sepuluh Nopember (ITS), and his Ph.D. in Electrical Engineering from Universiti Teknologi Malaysia in 2012. With more than two decades of academic and research experience, Dr. Facta has established expertise in electrical machines, power system protection, relay systems, renewable energy, hybrid power generation, embedded systems, and optimization techniques for energy systems. He has authored and co-authored over 100 Scopus-indexed publications, contributing significantly to international journals and conferences, and his work has been cited more than 500 times, reflecting his impact in advancing electrical engineering research. Beyond his publications, he actively mentors students, collaborates with international researchers, and contributes to the development of innovative solutions for modern power and energy systems. He can be contacted at email: facta@lecturer.undip.ac.id.

Hendril Satrian Purnama received his B.Eng. degree in Electrical Engineering from Universitas Ahmad Dahlan, Yogyakarta, Indonesia, in 2017. After receiving his degree, he became a member of the Embedded Systems and Power Electronics Research Group (ESPERG) and worked there as a researcher. In addition, he is also active as an assistant editor in several international journals in the field of electrical engineering, computer, and informatics. His research interests include power electronics, renewable energy technology, robotics, and the internet of things. He can be contacted at email: lfriyan220@gmail.com.

Tri Wahono is a researcher at the Embedded Systems and Power Electronics Research Group (ESPERG), Indonesia. He earned his bachelor's degree in Electrical Engineering from Ahmad Dahlan University, Yogyakarta, Indonesia, in 2017, and his master's degree in the Master of Electrical Engineering Program, Faculty of Industrial Technology, Ahmad Dahlan University, Indonesia, in 2025. His research interests include power electronics, renewable energy technology, robotics, and the internet of things. He can be contacted at email: triwahono060@gmail.com.