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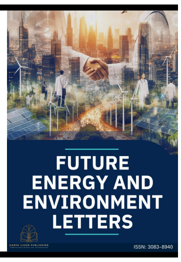

Digital Twin Integration for Photovoltaic–Battery Energy Storage Systems: A Systematic Review of Architectures, Intelligent Control and Deployment Pathways

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ABSTRACT

The rapid growth of renewable energy technologies, particularly photovoltaic generation coupled with battery energy storage, has introduced new challenges in maintaining efficiency, stability, and cost-effectiveness under variable operating conditions. Traditional monitoring and control strategies are often insufficient to manage the complex dynamics and multi-layer interactions of these hybrid systems. To address these challenges, the digital twin concept has emerged as a promising solution that bridges the physical and virtual environments. It enables real-time data synchronization, predictive analysis, and intelligent decision-making for improved energy management. However, its practical implementation in photovoltaic–battery systems remain fragmented, with many models focused on simulation rather than full cyber-physical integration. This gap highlights the need to identify current trends, strengths, and limitations in existing digital twin research. This study aims to systematically review recent developments in digital twin applications for photovoltaic and battery energy storage systems, outlining the key technological focus areas and research directions. The review follows the PRISMA methodology to ensure a structured and transparent selection of relevant literature. The analysis identifies four focus areas. The first, architecture and integration, emphasizes system modelling and real-time synchronization between sensors, IoT devices, and digital environments. The second, intelligent control and optimization, explores how artificial intelligence and predictive algorithms improve

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forecasting, scheduling, and operational efficiency. The third, reliability and predictive maintenance, focuses on diagnostics, degradation management, and fault prevention within hybrid energy systems. The fourth, sustainability and deployment, assesses techno-economic performance, carbon mitigation, and scalability for industrial and urban applications. Results show that integrating digital twin frameworks with artificial intelligence and optimization techniques enhances energy utilization, operational reliability, and cost efficiency. Nonetheless, further progress is required to standardize architecture, ensure secure data communication, and validate large-scale industrial deployment. In conclusion, digital twin integration provides a vital pathway toward intelligent, adaptive, and low-carbon energy infrastructures, enabling the transition from traditional management systems to real-time, data-driven operation in renewable energy networks.

Keywords:
Digital Twin; Renewable energy; Energy management system

1. Introduction

The transition toward cleaner electricity and industrial decarbonization has accelerated global interest in integrating solar photovoltaic (PV) systems and battery energy storage systems (BESS) as essential components of sustainable energy infrastructure [1], [2]. These technologies play a vital role in mitigating grid instability, enhancing energy reliability, and reducing dependence on fossil fuel-based generation [3]. Digital transformation of energy systems through Digital Twin technology presents new opportunities for intelligent control, predictive maintenance, and system-level optimization [4]. A Digital Twin represents a virtual replica of a physical asset or process that continuously exchanges data through sensors and communication networks. This real-time synchronization supports performance analysis, operational forecasting, and fault detection in energy systems [5], [6]. In the context of solar PV and BESS, digital twins enable efficient monitoring of system degradation, environmental impacts, and control decisions that improve energy utilization [7]. Advanced studies demonstrate how data-driven models and neural networks have been embedded in PV and BESS twins to enhance prediction accuracy and cost efficiency [8], [9]. Although significant progress has been made in the development of digital twin models, their application within renewable energy systems remains fragmented. Most implementations concentrate either on PV fault diagnostics or battery state estimation without providing an integrated model that combines both components under dynamic load and tariff conditions [10]. The lack of interoperability between digital twin models and industrial energy management frameworks further limits their adoption at the building or microgrid scale [11]. Recent works have demonstrated that digital twin models can simulate the spatio-temporal behavior of PV generation at neighborhood and city levels [12]. Other studies show that hybrid neural network approaches and cloud-based architectures improve PV power prediction accuracy and enhance inverter operation [13]. For BESS, twin-based frameworks have been successfully applied to monitor real-time degradation, frequency regulation, and capacity estimation in microgrids [14], [15]. However, these studies are typically focused on system design or laboratory validation, not on techno-economic applications or tariff-based performance analysis for industrial users. Despite rapid technological advancement, there is limited systematic synthesis of how digital twin approaches are applied to PV–BESS systems in industrial energy management. Key gaps include the absence of standardized modeling architectures, unclear validation strategies, and limited integration of economic and environmental indicators such as cost of energy and emission reduction [16], [17]. Existing reviews have focused on electric vehicles and manufacturing, but not specifically on hybrid PV–BESS energy systems for grid-interactive buildings [18]. In Southeast Asia, particularly Malaysia, industrial buildings represent a major share of electricity demand and carbon emissions. While national energy policies emphasize renewable integration, challenges remain regarding energy data management, load forecasting, and system optimization. Incorporating digital twin concepts could enhance operational visibility and support effective tariff selection under variable time-based pricing schemes [19]. This direction aligns with Malaysia's energy transition roadmap and supports the objective of achieving a low-carbon manufacturing sector. This paper aims to perform a systematic review of recent research on the implementation of digital twin technology for Solar PV and BESS systems. It synthesizes studies from 2021 to 2024 focusing on model architectures, data-driven algorithms, validation approaches, and practical deployment in grid-connected and stand-alone applications. The study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) methodology to ensure transparency, reproducibility, and comprehensive coverage. The findings are categorized into three key areas: digital twin frameworks for PV, digital twin frameworks for BESS, and integrated PV–BESS applications for energy management. The results highlight emerging research themes, industrial applications, and future directions for digitalized energy systems.

2. Methodology

2.1 Overview

This study applies a systematic literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The method ensures a transparent and replicable process for identifying, screening, and synthesizing research on digital twin applications for photovoltaic (PV) and battery energy storage systems (BESS). The process involved four phases: identification, screening, eligibility, and inclusion. Scientific databases Scopus and Web of Science (WOS) were selected as the primary data sources due to their comprehensive indexing of engineering and energy research. The search string used across both databases was:

Table 1
Search String for PRISMA method

Search String	"digital twin" AND ("battery energy storage" OR BESS OR "energy storage") AND ("solar PV" OR "solar photovoltaic") AND ("energy management" OR optimization OR control)

The search focused on peer-reviewed journal articles published in English from 2023 to 2025. Non-journal sources such as conference papers, book chapters, and review articles were excluded to maintain consistency and research quality. In total, 35 studies were initially identified (18 from Scopus and 17 from Web of Science). After duplicate removal and preliminary screening, 30 records remained for detailed evaluation. Titles, abstracts, and keywords were examined, resulting in 29 eligible full-text papers. Following final assessment, 27 articles met all inclusion criteria and were accepted for synthesis. The PRISMA flow in Figure 1 summarizes this process, highlighting the exclusion of studies that did not meet publication scope, language requirements, or research relevance:

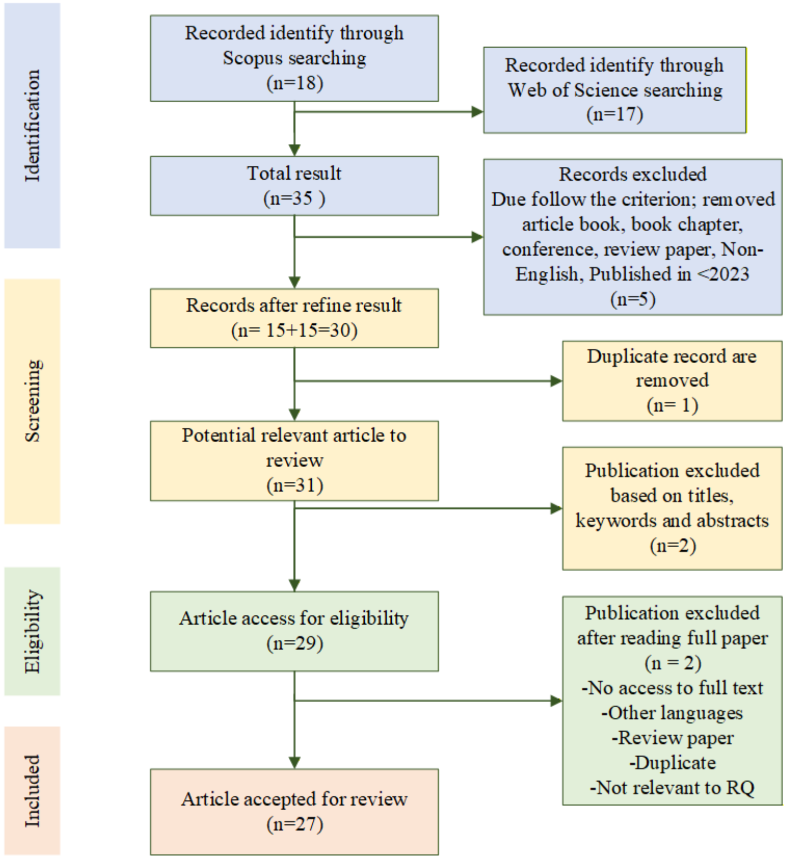

Fig. 1. Research flow using PRISMA method

3. Methodology

3.1 Overview of the Selected Studies

The systematic synthesis of the 27 reviewed studies from 2023 to 2025 revealed four primary research focuses in the development and application of digital twin (DT) technology for photovoltaic (PV) and battery energy storage systems (BESS). These focus areas are: (1) architecture and integration frameworks, (2) intelligent control and optimization, (3) reliability and predictive maintenance, and (4) sustainability, economic performance, and scalability. Together, these areas reflect the evolving maturity of DT research in renewable energy systems.

Across the selected papers, the convergence of artificial intelligence (AI), Internet of Things (IoT) connectivity, and cloud–edge computing emerged as the central foundation for DT implementation [2], [20], [21]. Several studies demonstrated how DT platforms enable synchronized physical–virtual interaction by integrating real-time sensor data, digital replicas, and predictive models to enhance operational visibility [4], [5]. Advanced simulation tools such as MATLAB/Simulink and Python were frequently used to validate these models and replicate field conditions before deployment [6].

Recent research trends also indicate a shift from conceptual modeling to fully functional prototypes capable of self-learning, fault prediction, and energy dispatch optimization. Such developments have redefined DTs from static monitoring tools to dynamic decision-making agents that contribute directly to energy efficiency and grid stability. The following subsections discuss the four identified themes in detail, illustrating the distinct technical contributions and limitations observed across the reviewed literature. Figure 2 illustrates the digital twin research focus area:

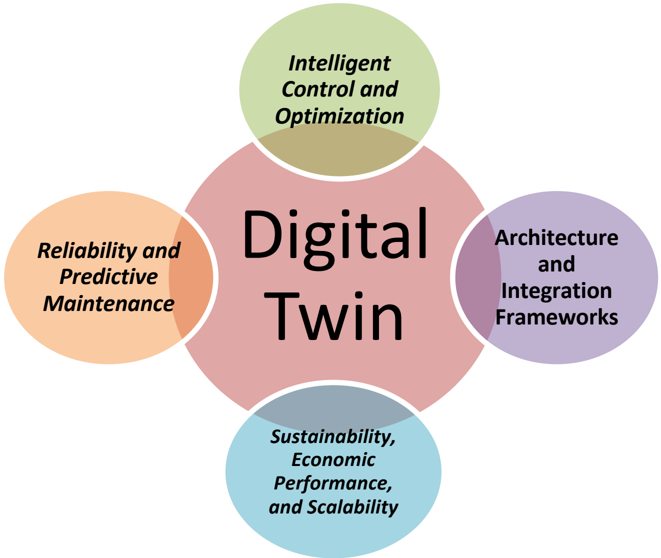

Fig. 2. Conceptual framework illustrating the four primary focus areas of Digital Twin applications for photovoltaic and battery energy storage (PV–BESS) systems

3.2 Focus Area 1: Architecture and Integration Frameworks

Significant progress has been achieved in developing digital twin architectures that combine cyber-physical connectivity with high-fidelity modeling. Recent frameworks establish bi-directional data exchange between the physical PV–BESS units and virtual counterparts through multi-protocol communication and sensor fusion [4], [5]. The study [6] introduced a MATLAB-based unified DT platform that supports real-time modeling and system validation. Similarly, [8] emphasized modular DT structures that merge physical-based and data-driven models for improved flexibility.

Agent-based and hybrid neural network architectures have emerged as key enablers for dynamic representation of distributed energy resources (DER). These architectures support interoperability across layers such as PV inverters, storage controllers, and supervisory management systems [9]. The integration of these models with IoT sensors and 5G-based data transmission further enhances the responsiveness of DT frameworks for grid-connected applications [10].

3.2 Focus Area 2: Intelligent Control and Optimization

Digital twins have shown strong potential in adaptive control and operational optimization for PV–BESS systems. Machine learning algorithms such as long short-term memory (LSTM), convolutional neural networks, and genetic algorithms are employed to improve forecasting, maximum power point tracking (MPPT), and load balancing [11], [12].

Furthermore, reinforcement learning and predictive control have been implemented within DT frameworks for real-time voltage and frequency regulation [22]. Cloud-edge coordination enables these models to make decentralized decisions while maintaining synchronization with grid parameters. Compared with static control strategies, DT-based optimization reduces energy losses, enhances peak shaving, and improves state-of-charge accuracy under variable irradiance conditions [15], [16].

3.2 Focus Area 3: Reliability and Predictive Maintenance

Reliability assessment is a dominant theme across the reviewed studies. DT-enabled predictive maintenance facilitates early identification of component degradation, thermal imbalance, and converter faults through continuous model comparison. [17] demonstrated research prioritizes adaptive Human-Robot Collaboration Disassembly (HRCD) strategies, leveraging transfer learning and genetic algorithms for Disassembly Sequence Planning (DSP), to efficiently and flexibly address the complexity and environmental threat posed by the diverse, retired lithium-ion batteries from new energy vehicles. Futhermore, Cappellen et al. employed a real-time physics-based digital twin to monitor power converter health, showing superior fault localization precision.

Other studies highlight hybrid monitoring frameworks combining hardware sensors and software-based diagnostics [19], [23], [24]. These systems support preventive maintenance scheduling and reduce downtime through automated fault classification. The ability of digital twins to merge physical modeling and data analytics makes them an essential reliability layer for future PV–BESS plants.

3.2 Focus Area 4: Sustainability, Economic Performance, and Scalability

Beyond operational benefits, digital twins contribute significantly to sustainability and techno-economic optimization. [2]used DT-aided models to simulate hybrid energy systems with varying renewable penetration, demonstrating potential operational cost reductions of up to 20 percent. [5] integrated DTs with distributed control schemes to enhance frequency regulation and system resilience.

Recent works focus on large-scale deployment using cloud or edge architectures. These implementations improve scalability and facilitate integration with utility grid systems while maintaining real-time synchronization. However, challenges such as data interoperability, cybersecurity, and lack of standardization continue to hinder full-scale adoption. Despite these constraints, digital twins have proven to be an enabling technology for low-carbon, high-resilience energy systems [25], [26], [27].

4. Conclusions

This systematic review analyzed 27 journal articles published between 2023 and 2025 that explored the integration of digital twin technology within photovoltaic and battery energy storage systems. The findings demonstrate that DT frameworks have progressed from conceptual discussions to practical implementations capable of real-time synchronization, adaptive control, and predictive performance assessment.

The review identified four dominant focus areas that represent the current research landscape. The first concerns architecture and integration, emphasizing cyber-physical connectivity, sensor fusion, and multi-layer communication for seamless data exchange. The second, intelligent control and optimization, focuses on data-driven algorithms that enhance forecasting accuracy, operational flexibility, and energy dispatch efficiency. The third, reliability and predictive maintenance, highlights DTs as diagnostic tools that enable early fault detection, condition monitoring, and life-cycle management of PV and BESS assets. The fourth, sustainability and scalability, underscores the role of DTs in techno-economic evaluation and system upscaling, contributing to carbon mitigation and cost reduction objectives.

Collectively, these studies confirm that digital twin technology offers a transformative framework for the next generation of renewable energy management systems. The integration of AI, IoT, and edge computing enables DTs to operate as intelligent agents that bridge simulation and reality, optimizing both performance and reliability. However, technical and institutional challenges remain, particularly in model interoperability, standardization, and data security.

Future research should therefore concentrate on developing unified DT architectures with open communication standards, exploring federated or distributed DT systems for multi-site energy networks, and enhancing cyber-physical resilience through secure data protocols. Experimental validation using hardware-in-the-loop and field-scale deployments is also recommended to bridge the gap between simulation fidelity and real-world performance.

In summary, digital twin technology is emerging as a cornerstone of sustainable energy transition, offering predictive, adaptive, and resilient control mechanisms for integrated PV–BESS infrastructures. As research advances, DT-enabled systems are expected to accelerate the realization of intelligent, low-carbon, and economically optimized power networks.

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