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Review

Pathways to 100% Renewable Energy in Island Systems: A Systematic Review of Challenges, Solutions Strategies, and Success Cases

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Abstract: The transition to 100% renewable energy systems is critical for achieving global sustainability and reducing dependence on fossil fuels. Island power systems, due to their geographical isolation, limited interconnectivity, and reliance on imported fuels, face unique challenges in this transition. These systems' vulnerability to supply–demand imbalances, voltage instability, and frequency deviations necessitates tailored strategies for achieving grid stability. This study conducts a systematic review of the technical and operational challenges associated with transitioning island energy systems to fully renewable generation, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. Out of 991 identified studies, 81 high-quality articles were selected, focusing on key aspects such as grid stability, energy storage technologies, and advanced control strategies. The review highlights the importance of energy storage solutions like battery energy storage systems, hydrogen storage, pumped hydro storage, and flywheels in enhancing grid resilience and supporting frequency and voltage regulation. Advanced control strategies, including grid-forming and grid-following inverters, as well as digital twins and predictive analytics, emerged as effective in maintaining grid efficiency. Real-world case studies from islands such as El Hierro, Hawai'i, and Nusa Penida illustrate successful strategies and best practices, emphasizing the role of supportive policies and community engagement. While the findings demonstrate that fully renewable island systems are technically and economically feasible, challenges remain, including regulatory, financial, and policy barriers.

Keywords: 100% renewable energy systems; islanded power systems; systematic literature review; microgrids

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1. Introduction

The transition to 100% renewable energy systems has become a primary objective to ensure energy sustainability and mitigate the environmental impact of fossil fuel-based generation. However, this process faces multiple technical and operational challenges, particularly in island systems that rely on weak and isolated power grids [1]. The reduction in system inertia due to the high penetration of inverter-based renewable sources compromises frequency and voltage stability, necessitating the implementation of advanced control

and energy storage strategies [2]. Additionally, the optimal design of storage configurations is crucial to ensuring a reliable power supply, as evidenced by studies modeling the transition in different geographical contexts [3]. Despite these challenges, various island systems have demonstrated that achieving 100% renewable energy integration is feasible through innovative grid management and storage solutions, leading to cost reductions and improved energy security [4,5].

The transition towards fully integrated renewable energy systems has been extensively explored in the literature, with a focus on different technological, economic, and policy strategies. Initial studies on energy transition pathways describe a phased approach, where renewable electricity is first integrated alongside conventional fossil fuel-based power plants, later supplemented by flexible renewable thermal power stations, and finally expanded to other sectors through power-to-X technologies [6]. A major challenge in this transition is the stability of low-carbon power systems with high shares of inverter-based renewable generation. The shift from traditional synchronous generators to renewable resources reduces system inertia and short circuit levels, leading to significant deviations in frequency and voltage during disturbances [1]. Studies have demonstrated that a transition to 100% renewable energy is technically feasible and economically viable. Research on isolated communities in Upper Michigan, USA, has shown that localized renewable generation using wind, solar, hydropower, and battery storage can result in lower electricity costs compared to fossil-fuel-based centralized grids [4]. Similar findings have been reported in large-scale case studies in countries such as Indonesia, where optimizing storage solutions is critical for maintaining grid stability and ensuring a reliable renewable energy supply [3]. The role of biomass as a flexible power generation alternative has also been analyzed, highlighting its potential to support energy transition scenarios by providing grid stability and load balancing [7].

Grid resilience and modernization are two focal points for achieving high renewable penetration. Some studies propose new grid architectures, such as decentralized renewable and resilient grids with enhanced power electronics-based control strategies, to overcome the challenges posed by the intermittency of renewable sources [8]. The integration of energy storage technologies has been identified as a critical factor, with research indicating that hybrid energy systems combining different storage solutions—such as batteries, hydrogen, methane, and ammonia—can enhance economic and operational efficiency in 100% renewable grids [9]. Additionally, a comprehensive analysis of the US energy system has demonstrated that a fully renewable power grid, relying on wind, water, and solar energy, can achieve stable operation with reduced overall energy costs [10]. One of the most critical aspects of high-renewable penetration systems is frequency control. With the increasing deployment of inverter-based resources, maintaining system frequency has become a challenge as traditional synchronous generators are being phased out. Studies have reviewed different frequency control strategies, emphasizing the need for new grid support mechanisms, such as fast frequency response services and grid-forming inverters, to ensure stability in renewable-dominated power systems [2]. Another significant challenge is the scarcity of reactive power reserves, which, if not addressed, could lead to voltage instability and operational constraints in future power grids [11].

Isolated and island power systems present additional challenges due to their limited interconnections and reliance on local generation. Research on fully renewable island grids has focused on optimal energy management strategies, including the integration of battery and supercapacitor storage systems, to enhance grid reliability and mitigate supply–demand imbalances [12]. Studies on power grid synchronization with 100% inverter-based renewable generation suggest that system stability can be improved through advanced control architectures that account for generator heterogeneity and damping factors [13].

Furthermore, the performance of grid-following converters in low-inertia systems has been extensively analyzed, with findings indicating that their effectiveness diminishes as the share of renewables increases, making it necessary to develop new control strategies and grid codes for enhanced grid support [14]. Addressing frequency stabilization in fully renewable power systems requires coordinated approaches, such as distributing inertia and frequency containment reserves across multiple technologies. Research has shown that a joint provision of these services can significantly improve redundancy and reduce the technological and economic burden of maintaining grid stability [15]. The role of hydrogen storage in supporting large-scale renewable deployments has also been investigated, with the results indicating that hydrogen-based storage solutions can provide cost-effective alternatives to batteries in long-term energy storage applications [16].

Among studies focusing specifically on island power systems, reference models such as the hybrid power grid of Cape Verde have been proposed to analyze different grid stability scenarios and evaluate the optimal placement of battery storage systems [17]. Case studies from Australia provide insights into how high-inertia synchronous condensers and grid-forming converters can support the integration of up to 75% renewable energy, demonstrating practical solutions to enhance grid resilience and operational security [18]. Research in Malaysia has further highlighted the critical role of battery energy storage systems in accelerating the transition to renewable energy, emphasizing the need for robust regulations and grid integration strategies to ensure successful deployment [19]. One of the most relevant studies to the present research is a multi-scenario analysis conducted in Morocco, which assesses the feasibility of large-scale photovoltaic-powered hydrogen production units. By combining the Analytical Hierarchy Process with Geographic Information Systems, the study identifies optimal locations for renewable energy infrastructure based on technical, economic, and environmental criteria [20].

Despite significant advancements in research on fully integrated renewable energy systems, several critical gaps remain, particularly concerning island power systems. While numerous studies have addressed the technical feasibility of renewable energy integration, most have focused on mainland grids or large-scale interconnected systems, leaving island systems underrepresented in the broader discussion of energy transition strategies [3,4,8]. Unlike continental networks, island grids operate under unique constraints such as limited interconnections, high dependence on imported fuels, and pronounced instability due to the variability of renewable resources, making them more vulnerable to supply–demand imbalances [12,17]. Existing studies on island energy systems often focus on specific case studies rather than proposing generalized frameworks that are adaptable to different geographical, technical, and economic conditions, limiting their applicability in diverse island contexts. A fundamental technical challenge in high-renewable penetrated grids is the maintenance of system stability in the absence of conventional thermal synchronous generators. As renewable penetration increases, the reduction in system inertia has led to concerns over frequency deviations and voltage instability, requiring advanced control strategies and grid support mechanisms [1,2,13]. Various solutions, including grid-forming inverters and high-inertia synchronous condensers, have been proposed to mitigate these issues, yet their implementation in isolated island networks remains insufficiently explored [14,18]. The effectiveness of these technologies in real-world scenarios requires further analysis, particularly regarding their capacity to enhance frequency stability and improve voltage regulation in renewable-dominated power systems.

As was mentioned before, energy storage is vital for achieving fully renewable island grids, but research on its implementation remains fragmented. While multiple studies discuss battery storage, hydrogen, and other long-duration storage solutions, comparative analyses of their long-term reliability, scalability, and economic feasibility in island contexts

are scarce [9,16,19]. Furthermore, much of the literature prioritizes technical feasibility and cost assessments without sufficiently addressing operational challenges, grid resilience, and the potential for large-scale deployment [3,11]. Given that storage technologies are essential for mitigating the intermittency of renewable resources, a comprehensive synthesis of their application in island energy systems is needed to establish a coherent framework for decision-making in storage investments. Policy and regulatory frameworks also represent a significant gap in existing research. Although several studies acknowledge the importance of government support in accelerating the transition to 100% renewable energy, few offer detailed analyses of the specific policies that have successfully facilitated these transitions in island environments [4,7,10]. Regulatory challenges such as outdated grid codes, lack of financial incentives for energy storage deployment, and insufficient support for demand-side management continue to obstruct large-scale renewable energy adoption. A structured review of policy strategies, incorporating lessons from successful island case studies, would provide valuable insights for policymakers seeking to implement effective energy transition frameworks in similar contexts. Beyond technical and policy considerations, a major limitation in the current literature is the lack of systematic methodologies for synthesizing challenges, solutions, and success cases in island energy transitions. Many reviews rely on qualitative and narrative-based approaches, which, while informative, often lack transparency and reproducibility in the selection of studies. Structured methodologies such as Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), which enhance the rigor of literature reviews by ensuring comprehensive and unbiased data collection, are rarely applied in research on island renewable energy systems [20]. This methodological gap reduces comparability between studies and limits the ability to extract generalizable findings applicable across different island networks.

Addressing these research gaps, this study conducts a systematic review of the challenges, solutions, and success stories associated with achieving 100% renewable energy transitions in island power systems using the PRISMA 2020 methodology. This research aims to explore and identify technological, economic, regulatory, and legislative solutions that have enabled significant progress toward fully integrating renewable energy generation in island power systems. It seeks to uncover effective strategies for enhancing grid stability, optimizing energy storage solutions, and analyzing the role of policy incentives and regulatory frameworks in supporting the transition to 100% renewable energy in insular environments.

The remainder of this article is organized as follows: Section 2 outlines the systematic methodology employed in this review, including the study selection process and evaluation criteria; Section 3 presents a comprehensive analysis of the results, discussing major challenges, technological solutions, and insights from successful island case studies; and Section 4 provides the main conclusions, practical recommendations, and potential research directions to facilitate fully renewable energy systems in island contexts.

2. Methodology for Literature Review

This review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses—PRISMA 2020 guidelines [21], a rigorous and structured approach that is well suited for synthesizing the literature in technical fields like renewable energy. PRISMA is widely adopted due to its transparency, reproducibility, and ability to minimize bias compared to traditional review methods. Several alternative methodologies exist, such as the *Cochrane Handbook* for healthcare reviews or MOOSE for epidemiological studies, but PRISMA's versatility makes it particularly effective in interdisciplinary research. Its structured framework is highly applicable to fields like engineering and energy, enabling the thorough evaluation of diverse study types, from technical innovations to socioeconomic

analyses. The methodology in this review follows four essential phases (see Figure 1): identification, screening, eligibility and inclusion, and synthesis. In the identification phase, relevant studies are retrieved using a well-defined search strategy across selected databases. The screening phase reviews titles and abstracts to ensure alignment with predefined inclusion and exclusion criteria. During the eligibility and inclusion phase, a detailed full-text review confirms that only high-quality studies that address the research objectives are selected for deeper analysis. Finally, the synthesis phase integrates and analyzes the selected literature to form the foundation of the review's findings and conclusions. The literature systematic review protocol designed for this study is registered in the Open Science Framework (OSF) and can be found at https://doi.org/10.17605/OSF.IO/N8XSU (accessed on 28 April 2025). The systematic methodology outlined in Sections 2.1–2.4 has been meticulously designed to address the following research questions (RQ):

- RQ1: What are the primary technical and operational challenges in achieving 100% renewable energy integration in island power systems?
  This question aims to identify the main obstacles that island systems encounter when transitioning to fully renewable energy, including aspects related to grid stability, frequency and voltage regulation, and the management of low-inertia systems.
- RQ2: How do energy storage technologies contribute to mitigating intermittency and enhancing grid stability in island microgrids?
  This question focuses on evaluating the potential of different energy storage solutions, such as battery energy storage systems, hydrogen storage, pumped hydro storage, and flywheels, in providing frequency and voltage support, optimizing storage capacity, and maintaining stability in isolated grid environments.
- RQ3: What advanced control strategies and smart grid technologies have proven effective in maintaining grid stability and efficiency in island microgrids?
  This question explores the role of advanced technologies, including grid-forming and grid-following inverters, decentralized control systems, and smart grid innovations, in enhancing the operational performance and resilience of island energy systems.
- RQ4: Which island case studies provide valuable insights into the successful implementation of 100% renewable energy systems, and what general lessons can be drawn regarding technology, strategy, and policy frameworks?
  This question seeks to analyze real-world examples to extract best practices and critical success factors, including the influence of technological approaches, strategic planning, and supportive policy frameworks in facilitating renewable energy transitions in island contexts.

2.1. Identification Phase—Systematic Database Exploration for Relevant Studies

The bibliographic resources for this literature review were sourced from two prestigious databases: Scopus and Web of Science. These databases were selected due to their extensive coverage of high-quality research articles, ensuring a comprehensive, transparent, and objective review. Scopus, managed by Elsevier, is one of the largest abstract and citation databases, covering a wide range of disciplines, including engineering, energy, and environmental sciences. Web of Science, maintained by Clarivate, provides access to a curated collection of journals and conference proceedings with a strong emphasis on impactful research. Both databases index publications from well-regarded publishers such as IEEE, Elsevier, Springer, Taylor & Francis, Wiley, and MDPI, ensuring a high level of academic rigor.

Based on the objectives outlined in the Introduction and the scope of this research, the following search terms were defined for each database to ensure a comprehensive and focused literature search. As indicated in Table 1, the search query for Scopus was designed

to identify studies related to renewable energy in island or insular contexts, explicitly focusing on power systems, grids, or microgrids. A similar search query was used for Web of Science (WoS) with slightly different syntax.

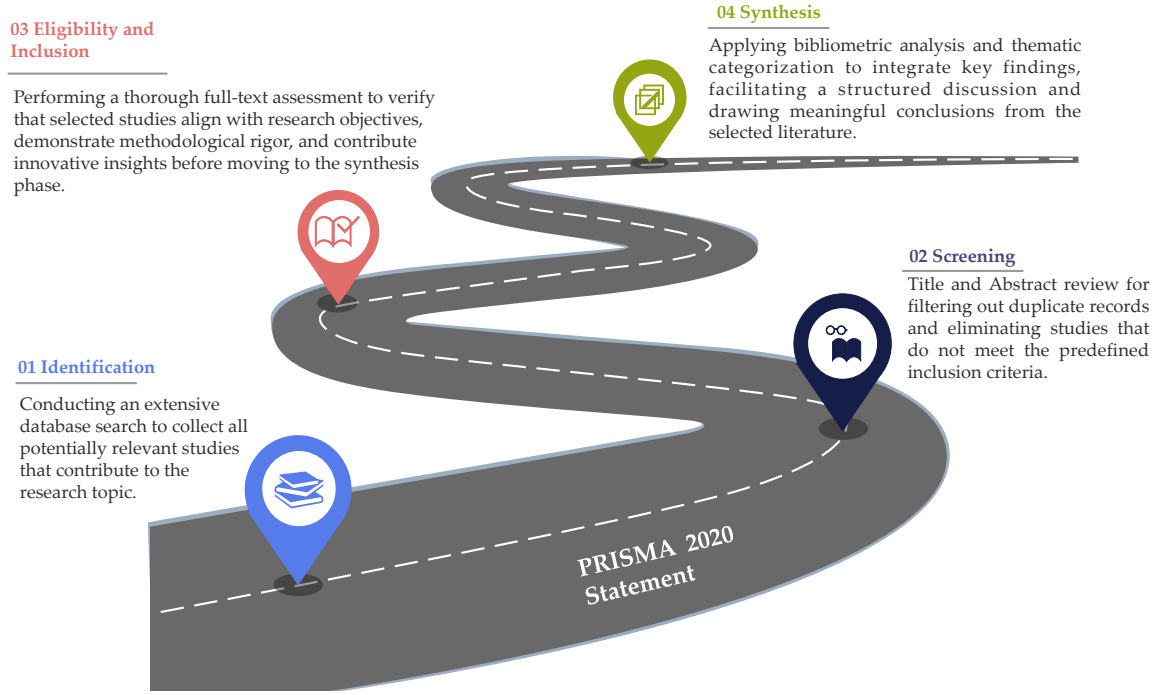


Figure 1. Phases of the systematic literature review process.

Table 1. Search terms and summary of database query results.

Database	Query String	N° of Returned Documents	Removal of Duplicates	Final Sample for Screening Phase
Scopus	TITLE-ABS-KEY (“renewable energy” AND “island” AND “power system”) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “cp”)) AND (LIMIT-TO (LANGUAGE, “English”))	904	39	865
Web of Science	(ALL = (“renewable energy”)) AND (ALL = (“island”)) AND (ALL = (“power system”)) Refined By: Publication Years: 2024 or 2023 or 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015 or 2014; Document Types: Article, Proceeding Paper or Article	354	228 *	126
Total items		1258	267	991

* Scopus entries were used as the primary reference for detecting duplicates. Consequently, if a WoS record shared the same DOI as a Scopus entry, the bibliographic management tool automatically excluded the WoS entry.

The initial search across Scopus and WoS retrieved a total of 1258 documents, with 904 from Scopus and 354 from WoS. Due to the overlap between these databases, which frequently index the same journals, conference proceedings, and publishers, duplicate entries were expected. Using bibliographic management tools, 267 duplicate items (21.2% of the total) were identified and removed, refining the dataset to 991 unique items for the screening phase. Specifically, 39 duplicates were found in Scopus, reducing its final count to 865, while WoS exhibited a higher redundancy, with 228 duplicates, leaving only 126 unique records. The substantial proportion of duplicates in WoS (64.4% of its initial records) suggests significant content overlap with Scopus, reinforcing the necessity of cross-checking sources in systematic reviews.

2.2. Screening Phase—Selecting Studies That Meet Inclusion Criteria

During the screening phase, predefined inclusion criteria were designed to evaluate the relevance and suitability of the 991 unique studies found in the identification phase. This process involved a meticulous review of each study's title, abstract, and relevant metadata to ensure alignment with the research objectives.

For this review, the following inclusion criteria were applied:

- Criteria 1—Publication Date: Studies published between 2014 and 2024.
- Criteria 2—Publication Type: Journal articles and conference papers, as these represent widely recognized contributions within the academic and technical communities.
- Criteria 3—Language: Only articles written in English were considered.
- Criteria 4—Full-Text Availability: Studies accessible via institutional subscriptions or open access repositories.
- Criteria 5—Focused on: The selected studies needed to broadly address topics related to the transition of island power systems to 100% renewable energy. This includes, but is not limited to, discussions on renewable energy integration strategies, grid stability challenges, energy storage solutions, policy implications, and real-world case studies.

Editorials, opinion pieces, book chapters, technical reports, patents, white papers, and preprints were not considered. While these sources can offer valuable insights and perspectives, the focus of this review was on primary studies with clearly defined methodologies and formal evaluation processes.

Of the 991 studies initially evaluated, only 962 successfully passed the screening phase. A binary assessment was conducted independently by the research team. Articles were approved only if they met all five predefined inclusion criteria. The historical evolution of studies in this field, presented in Figure 2, reveals a clear upward trend in research contributions over the past decade. From 2014 to 2016, publication numbers remained relatively low, with fewer than 60 studies per year. However, a notable increase was observed from 2017 onward, with a peak in 2023, where 142 studies were published. The consistent rise, particularly in the last five years, suggests growing academic and technical interest in the transition of island power systems to 100% renewable energy. The fluctuations in 2021 and 2024, with slight declines, could indicate variations in funding availability, shifting research priorities, or delays in publication cycles. The increasing engagement from prestigious databases such as Scopus and WoS highlights the expanding recognition of this field within the scientific community. This trend reveals the urgency and relevance of addressing renewable energy integration, grid stability, energy storage solutions, and policy frameworks in insular contexts. The growing volume of literature reflects both advancements in technology and a heightened policy focus on sustainable energy transitions. The 962 studies that passed the screening phase will now undergo a more in-depth analysis in the following stage to extract valuable insights and synthesize the main contributions to the field.

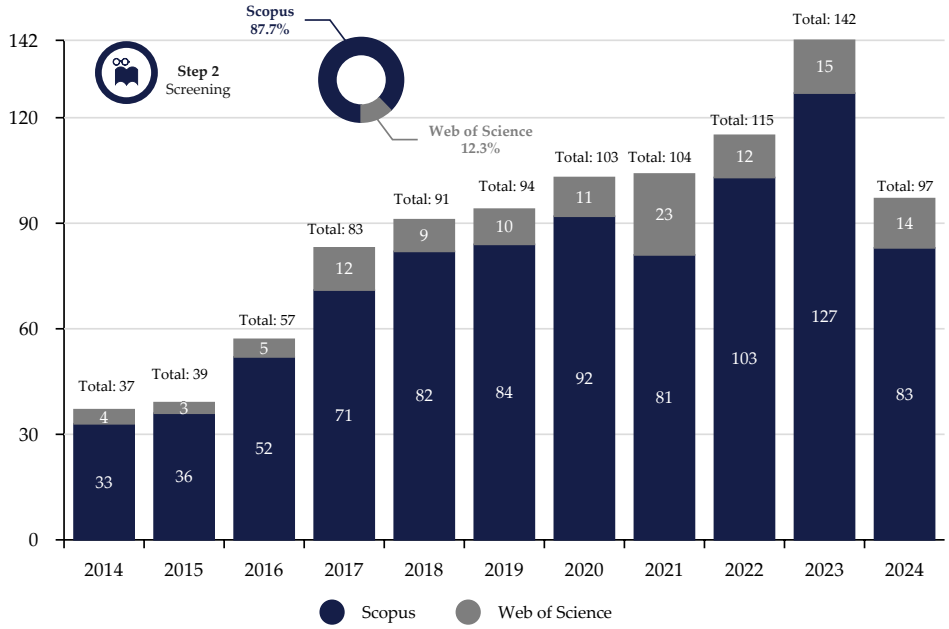


Figure 2. Historical distribution of the screened studies.

2.3. Eligibility and Inclusion—Selecting High-Quality and Relevant Studies

At this stage of the systematic review, a comprehensive full-text evaluation is conducted for all studies that successfully passed the screening phase to ensure their relevance, quality, and contribution to the research objectives. The purpose of this phase is to refine the dataset, including only studies that exhibit methodological rigor and direct alignment with the scope of transitioning island power systems to 100% renewable energy. To achieve this, five eligibility criteria have been established, each assessed on a three-level scale:

- Eligibility Criterion 1—Alignment with Research Objectives: This assesses how effectively the study addresses critical aspects of renewable energy integration in island systems, including grid stability, energy storage, and operational challenges in high-renewable penetration scenarios. (Scoring: 1: Peripheral, 2: Related, and 3: Highly Relevant).
- Eligibility Criterion 2—Methodological Rigor: This assesses the robustness and appropriateness of the study's methodology, including the reliability of data sources, modeling accuracy, and validation techniques to ensure scientifically sound conclusions. (Scoring: 1: Needs Improvement, 2: Acceptable, and 3: Strong).
- Eligibility Criterion 3—Originality and Innovation: This considers the novelty of the proposed solutions, technologies, or strategies for renewable energy integration, with particular emphasis on innovative grid-forming and grid-following inverter applications, energy storage advancements, and hybrid system configurations. (Scoring: 1: Minor, 2: Moderate, and 3: Major).
- Eligibility Criterion 4—Data Quality and Analysis: This measures the quality, reliability, and depth of data analysis, including transparency in methodology, statistical rigor, and replicability of results to ensure robust findings. (Scoring: 1: Satisfactory, 2: Good, and 3: Excellent).
- Eligibility Criterion 5—Scientific Contribution: This evaluates the study's impact within the research community, measured by the number of citations it has received, as a proxy for its influence in the field of renewable energy transitions in island systems. (Scoring: 1: low citation count, 2: moderate citation count, and 3: high citation count).

Each article underwent a detailed full-text evaluation based on a structured three-level scoring system. Two independent reviewers assessed the studies thoroughly, applying predefined criteria to maintain objectivity and minimize bias. When discrepancies arose in their evaluations, they engaged in structured discussions to reach a consensus. Figure 3 presents the verification matrix used in this phase, where each study was evaluated according to specific criteria and assigned the mentioned score ranging from 1 to 3. To guarantee the inclusion of only the most relevant and methodologically sound studies, the researchers established a minimum threshold of 13 out of 15 points. This benchmark ensured that selected works demonstrated a strong connection to the research focus, robust methodology, originality, and reliable data analysis. Studies that did not meet this threshold were excluded, not due to a lack of scientific merit, but because they did not align closely enough with the specific objectives of this review as measured by the eligibility criteria. Following this selection process, the 81 studies shown in Figure 3—representing 8.4% of the 962 screened—were included in the final review.

N°	ID	Crit. 1	Crit. 2	Crit. 3	Crit. 4	Crit. 5	Total
1	S-736	3	3	3	3	3	15
2	S-775	3	3	3	3	3	15
3	WoS-033	3	3	3	3	3	15
4	S-202	3	3	3	3	3	15
5	WoS-108	3	3	3	3	3	15
6	S-860	3	3	3	3	3	15
7	S-253	3	3	3	3	3	15
8	S-381	3	3	3	2	3	14
9	S-404	3	3	3	2	3	14
10	S-406	3	3	3	2	3	14
11	S-433	3	3	3	2	3	14
12	S-485	3	3	3	2	3	14
13	S-502	3	3	3	2	3	14
14	S-520	3	3	3	2	3	14
15	S-552	3	3	3	2	3	14
16	S-585	3	3	3	2	3	14
17	S-613	3	3	3	2	3	14
18	S-636	3	3	3	2	3	14
19	S-723	3	3	3	2	3	14
20	S-724	3	3	3	2	3	14
21	S-730	3	3	3	2	3	14
22	S-757	3	3	3	2	3	14
23	S-773	3	3	3	2	3	14
24	S-785	3	3	3	3	2	14
25	S-793	3	3	3	2	3	14
26	S-816	3	3	3	2	3	14
27	S-880	3	3	3	2	3	14
28	S-899	3	3	3	2	3	14
29	WoS-100	3	3	3	2	3	14
30	WoS-125	3	3	3	2	3	14
31	WoS-150	3	3	3	2	3	14
32	WoS-270	3	3	3	2	3	14
33	S-417	3	3	3	2	3	14
34	WoS-168	3	3	3	3	2	14
35	S-247	3	3	3	3	2	14
36	S-764	3	2	3	2	3	13
37	S-048	3	3	3	3	1	13
38	S-100	3	3	3	2	2	13
39	S-171	3	3	3	3	1	13
40	S-186	3	3	3	3	1	13
41	S-189	3	3	3	3	1	13
42	S-218	3	3	3	2	2	13
43	S-239	3	3	3	2	2	13
44	S-279	3	3	3	2	2	13
45	S-325	3	3	3	2	2	13
46	S-335	3	3	3	2	2	13
47	S-343	3	3	3	2	2	13
48	S-395	3	3	3	2	2	13
49	S-423	3	3	3	2	2	13
50	S-448	3	3	3	2	2	13
51	S-467	3	3	3	2	2	13
52	S-525	3	3	3	1	3	13
53	S-548	3	3	3	1	3	13
54	S-553	3	3	1	3	3	13
55	S-567	3	3	3	2	2	13
56	S-658	3	3	3	1	3	13
57	S-676	3	3	3	3	1	13
58	S-763	3	3	3	2	2	13
59	S-778	3	2	3	2	3	13
60	S-813	3	3	3	1	3	13
61	S-819	3	3	3	1	3	13
62	S-820	3	3	3	2	2	13
63	S-829	3	3	3	1	3	13
64	S-830	3	3	3	1	3	13
65	S-886	3	3	3	1	3	13
66	S-896	3	3	3	1	3	13
67	WoS-132	3	3	3	1	3	13
68	S-195	3	3	3	3	1	13
69	S-297	3	3	3	3	1	13
70	WoS-276	3	3	3	1	3	13
71	S-483	3	3	3	3	1	13
72	S-435	3	3	3	2	2	13
73	S-619	3	3	3	1	3	13
74	S-124	3	3	3	3	1	13
75	S-078	3	3	3	3	1	13
76	S-173	3	3	3	3	1	13
77	S-302	3	3	3	3	1	13
78	S-321	3	3	3	3	1	13
79	S-704	3	3	3	3	1	13
80	S-015	3	3	3	3	1	13
81	S-063	3	3	1	3	3	13

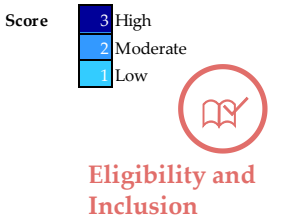


Figure 3. Eligibility matrix for full-text assessment.

In the interest of transparency and to support the reproducibility of this systematic review, the metadata of all selected studies have been made publicly available. The shared information includes the ID, title, abstract, authors, year of publication, journal or conference name, publisher, DOI, and citation count. This dataset can be accessed through the following GitHub repository: https://github.com/dannyochoa87/technologies-SLR/archive/refs/heads/main.zip (accessed on 28 April 2025).

2.4. Synthesis Phase—Applying Bibliometric Analysis to Guide the Discussion of Findings

This section presents an overview of the 81 studies selected during the eligibility and inclusion phase, offering insights into the current research landscape on the transition of island power systems to 100% renewable energy. The selected works cover a range of thematic areas and originate from various journals and conferences, highlighting the multidisciplinary nature of this research domain. Figure 4 illustrates the distribution of these publications, showing that journal articles make up 65 of the selected studies, while 16 come from conference proceedings. This prevalence of journal publications reflects the emphasis on peer-reviewed research, where studies undergo extensive evaluation and provide detailed analyses. Meanwhile, conference papers contribute to capturing recent advancements and emerging trends, demonstrating their value in presenting innovative solutions and evolving perspectives.

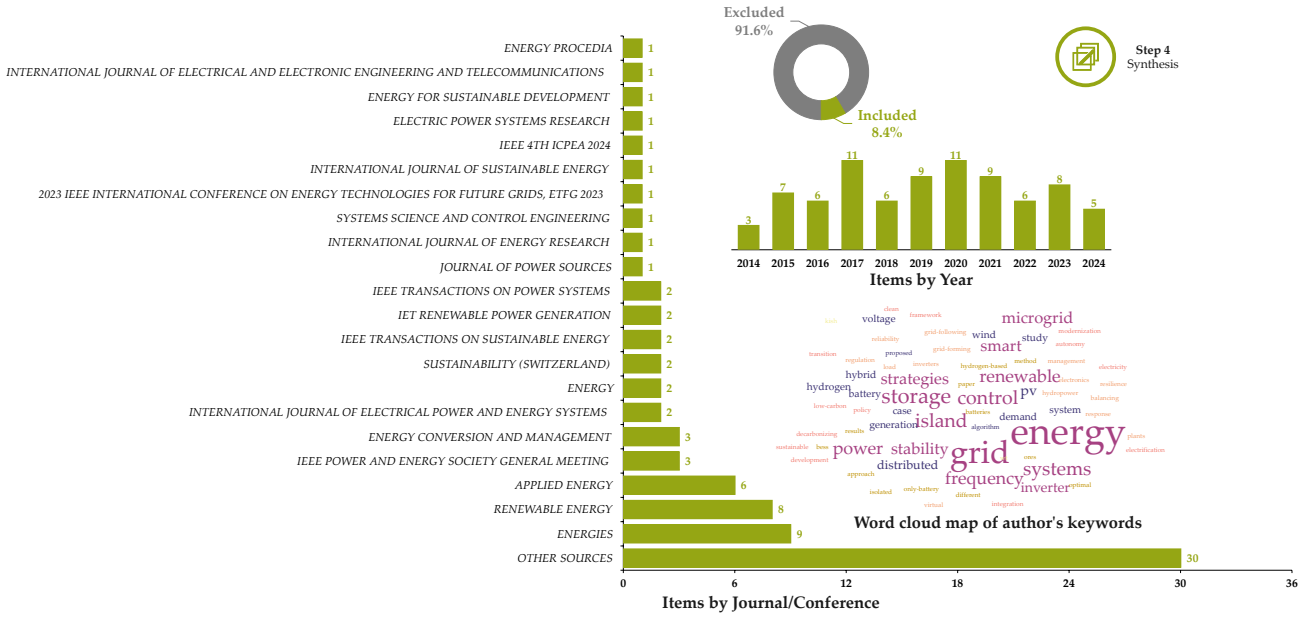


Figure 4. Distribution of selected articles by source, historical trend, and keyword analysis.

Among journal publications, *Energies* is the most frequently represented, with nine articles, followed by *Renewable Energy* with eight and *Applied Energy* with six. These journals are well established in the field of renewable energy, suggesting a strong focus on both technical innovations and policy implications related to sustainable energy transitions. Other journals, including *Energy Conversion and Management*, *International Journal of Electrical Power and Energy Systems*, and *Sustainability*, have at least two contributions each, indicating their role in discussions on grid stability, energy storage, and regulatory aspects.

Regarding conference publications, the *IEEE Power and Energy Society General Meeting* appears most frequently, contributing to three studies that demonstrate its importance as a venue for presenting developments in power system technologies and renewable integration. Additionally, the *2023 IEEE International Conference on Energy Technologies for Future Grids* contributed to the dataset, reflecting the growing research interest in advanced grid solutions and control strategies designed explicitly for island energy systems. The range of publication sources illustrates the broad scope of ongoing research, covering technical, economic, and policy-driven aspects of renewable energy adoption in island systems.

The analysis of publication trends over the years further shore up the scientific relevance of this topic. Despite the narrowing process inherent in systematic reviews, the

number of selected studies per year remains relatively stable, with peaks in 2017 and 2020, where 11 studies were included in each year. Even in the most recent years, the dataset retains a strong representation, with eight studies in 2023 and five in 2024, demonstrating that research interest in this area remains high. The presence of multiple studies across the past decade, even after applying strict eligibility criteria, highlights the sustained academic engagement in renewable energy transitions for island power systems.

Figure 4 also presents a word cloud map generated from the author's keywords of the reviewed studies, constructed based on the frequency of occurrence. Through a detailed analysis of this visualization, it has been possible to identify specific thematic areas that characterize the selected literature. To provide a structured synthesis of the main findings, the reviewed studies have been systematically categorized into the following four thematic units:

1. Renewable Energy Integration and Grid Stability in Island Systems.
   This thematic area examines the technical and operational challenges associated with incorporating renewable energy sources into island power grids. The literature emphasizes strategies for integrating solar, wind, hydro, and other renewable technologies while addressing the inherent constraints of isolated energy systems. A primary concern is grid stability, particularly regarding frequency and voltage regulation due to the low inertia of renewable-dominated grids. Several studies propose solutions such as enhanced power electronics, hybrid renewable energy systems, advanced forecasting techniques, and demand-side management to mitigate instability risks. Moreover, the increasing role of grid-forming inverters and virtual synchronous machines is highlighted as a crucial factor in improving system resilience and maintaining grid robustness.
2. Energy Storage Technologies and their Role in Island Energy Systems.
   Energy storage is widely acknowledged as a fundamental enabler of high renewableenergy penetration in island grids. This section explores various storage technologies, including battery energy storage systems, hydrogen storage, pumped hydro storage, and flywheels. The reviewed studies discuss how these technologies contribute to mitigating the intermittency of renewable generation, enhancing grid reliability, and supporting frequency and voltage regulation. Special attention is given to optimizing storage capacity, extending battery lifespan, and implementing hybrid storage solutions to achieve a balance between cost-effectiveness and performance. Additionally, emerging trends in long-duration storage solutions are analyzed for their potential to facilitate the transition to 100% renewable energy systems in island settings.
3. Control Strategies and Smart Grid Technologies for Island Microgrids.
   This thematic area delves into the implementation of advanced control strategies and smart grid technologies aimed at improving the reliability, resilience, and efficiency of island energy systems. The literature highlights the increasing adoption of decentralized control mechanisms, including grid-forming and grid-following inverters, multi-agent systems, and artificial intelligence-driven approaches for real-time energy management. Several studies examine microgrid architectures, peer-to-peer energy trading models, demand response programs, and adaptive protection schemes designed to handle the variability of renewable energy generation. Furthermore, advancements in digital twins and predictive analytics are explored as innovative tools for optimizing grid performance and preemptively addressing stability concerns.
4. Case Studies and Success Stories of 100% Renewable Island Systems.
   This topic presents real-world case studies of islands transitioning to fully renewable energy systems, offering valuable insights into the strategies, technologies, and policy frameworks that have facilitated successful implementations. The reviewed literature

covers a diverse range of islands with distinct geographic, economic, and technological contexts, analyzing factors such as the optimal renewable energy mix, storage integration, grid management practices, and socio-political challenges. Important lessons derived from these case studies include the significance of government incentives, regulatory frameworks, community engagement, and the deployment of hybrid renewable-storage solutions. Additionally, several studies discuss ongoing projects and future pathways for scaling up renewable energy adoption in island regions.

Finally, Figure 5 presents the standardized PRISMA 2020 flow diagram, outlining the systematic literature review process followed in this study.

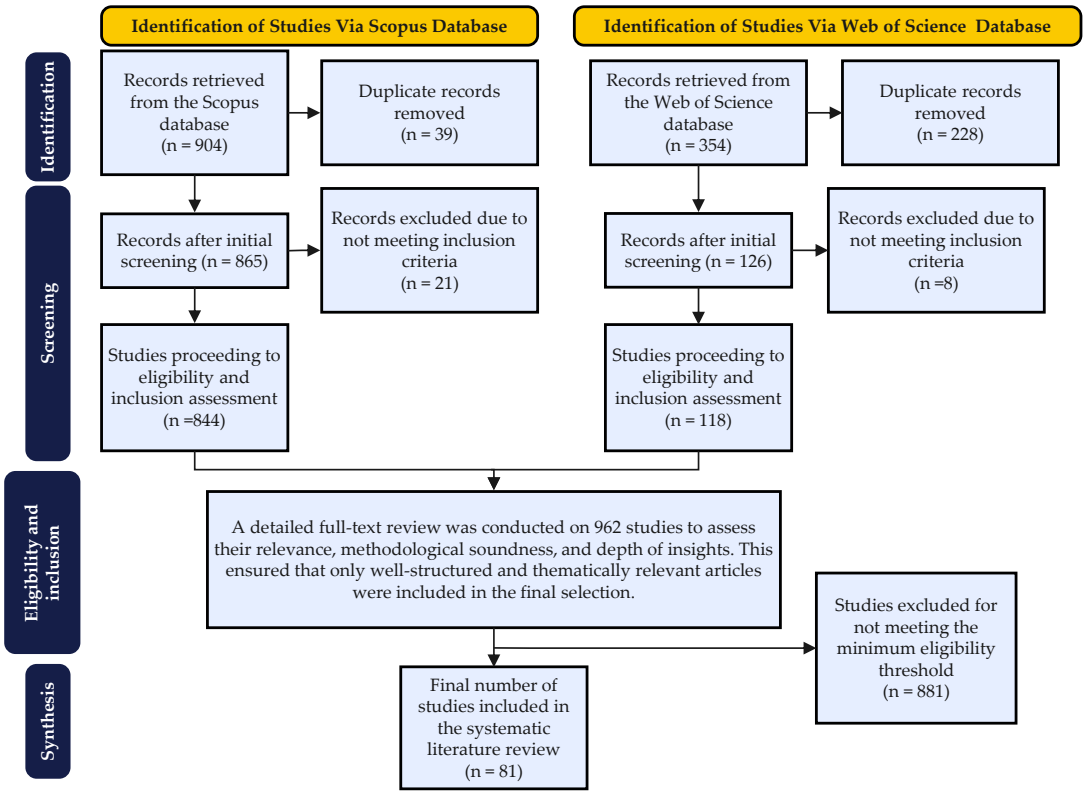


Figure 5. PRISMA 2020 flow diagram of the systematic literature review process.

3. Results and Discussions

3.1. Renewable Energy Integration and Grid Stability in Island Systems

The integration of renewable energy sources (RESs) into island power systems presents significant technical and operational challenges due to the isolated nature of these grids and the high penetration of variable energy sources. Islands often rely on expensive diesel generators with high operational costs, driving the transition to more sustainable and cost-effective systems through the use of renewables such as solar, wind, hydro, and, in some cases, energy storage in batteries and hydrogen systems [22,23]. The unique characteristics of island grids, such as their low inertia, limited interconnectivity, and susceptibility to external disruptions, necessitate tailored strategies for achieving grid stability while maximizing the use of renewable resources [24,25].

A primary concern in renewable energy integration for island power supply is grid stability, particularly regarding frequency and voltage regulation. The low inertia of renewable-dominated systems makes them vulnerable to rapid fluctuations and frequency drops during dynamic events [26,27]. Studies focusing on isolated systems, such as those conducted on the Canary Islands (e.g., El Hierro), emphasize the need for robust frequency control strategies that can maintain stability under varying renewable energy output [28,29].

Hybrid systems that combine different RESs with storage technologies, such as BESSs, have shown promising results in enhancing grid stability [30,31]. Various technologies and control strategies are being implemented to mitigate instability risks. The use of grid-forming and grid-following inverters has become increasingly important for managing power quality and ensuring seamless integration of renewables [32,33]. Virtual synchronous generators (VSGs) are innovative technologies that replicate the inertial response of traditional synchronous generators, thereby improving frequency stability [34,35]. Additionally, advanced forecasting techniques and demand-side management (DSM) strategies contribute to better balancing of supply and demand, which is critical for systems with high renewable penetration [36,37].

The deployment of ESSs, including both short-term (e.g., lithium-ion batteries) and long-term (e.g., hydrogen storage), offers another layer of stability. Hydrogen-based energy storage, in particular, provides a viable solution for seasonal storage needs and for addressing long-term fluctuations in renewable energy availability [38,39]. Case studies from the Faroe Islands and Cape Verde demonstrate that hydrogen storage, when combined with wind and solar energy systems, can significantly enhance grid stability while reducing reliance on fossil fuels [40,41]. In addition to technological solutions, strategic planning and optimization of microgrid designs are critical for maintaining grid stability. Research conducted on the Philippines and South Korean islands indicates that both centralized and decentralized approaches to grid management can offer distinct advantages depending on the specific geographical and operational constraints of the island system [24,42]. The choice of energy storage capacity, grid architecture, and control strategies must be tailored to local conditions to maximize the efficiency and reliability of the grid [43,44]. Furthermore, operational strategies such as demand response (DR) and virtual power plants (VPPs) play an essential role in enhancing grid flexibility. By coordinating the operation of distributed energy resources (DERs) and controllable loads, these strategies help stabilize the grid by modulating demand in response to supply fluctuations [36,37]. This approach has been successfully applied in islands like the Maldives and Lesbos, Greece, where DR strategies have reduced the need for costly energy imports and improved system resilience [45,46].

3.1.1. Technical and Operational Challenges in Renewable Integration

Integrating renewable energy into island power systems involves addressing multiple technical and operational challenges that arise from the inherent variability of renewable sources and the isolated nature of these grids. One of the primary technical challenges is maintaining frequency stability, as RESs, such as wind and solar energy, are often connected to the grid via inverters, which do not provide the same inertial response as conventional synchronous generators [26,35]. The implementation of advanced inverter technologies, such as grid-forming inverters and virtual synchronous generators, has been proposed to enhance system stability by simulating the inertial response of traditional power plants [32,34]. Another significant challenge is voltage regulation, particularly under high penetration of DERs. Voltage instability can lead to operational inefficiencies and, in severe cases, power outages. To address this, studies have recommended the use of advanced power electronics and control strategies, including dynamic reactive power support and voltage control through smart inverters [27,33]. The deployment of hybrid renewable systems that combine solar, wind, and energy storage has also proven effective in maintaining voltage stability while improving the reliability of power supply [31,47].

Operationally, the integration of renewables requires robust forecasting and management strategies to balance supply and demand effectively. DSM and DR programs play a crucial role in this context, as they provide the flexibility needed to adapt consumption patterns to the intermittent nature of renewable generation [36,37]. Additionally, VPPs have

been implemented to aggregate distributed generation and controllable loads, enabling more effective grid management and enhancing system resilience [36,37]. Energy storage technologies, such as batteries and hydrogen-based systems, are critical for smoothing out fluctuations in renewable energy supply. BESS can provide fast-response grid services, including frequency regulation and load shifting [30,31]. Hydrogen storage, while less efficient in short-term applications, offers significant advantages for seasonal energy storage and long-term grid stability [38,39]. Case studies in the Faroe Islands and Cape Verde highlight how these technologies can transform isolated systems into resilient and self-sufficient energy networks [40,41].

3.1.2. Solutions Based on Power Electronics and Advanced Control

Nowadays, power electronics and advanced control strategies are devoted to enhancing grid stability and facilitating the integration of RES in island power systems. These technologies tackle major challenges such as frequency and voltage stability, power quality, and system reliability, which are especially important in isolated grids with high renewable penetration [48]. One of the most effective solutions involves the use of grid-forming inverters, which emulate the behavior of traditional synchronous generators by providing synthetic inertia and frequency support. Studies have demonstrated that grid-forming inverters can significantly improve the stability of fully inverter-based systems, enabling island grids to operate reliably even under 100% renewable energy scenarios [32]. These inverters maintain grid stability by controlling voltage and frequency autonomously, allowing for seamless integration of RES and enhancing the resilience of island systems.

VSGs are another advanced method for providing inertia and frequency regulation. These devices replicate the mechanical inertia of traditional generators through advanced control algorithms, offering dynamic support during grid disturbances [22,49]. Research has shown that VSGs can effectively stabilize microgrids by providing a fast and adaptive response to frequency deviations, which is crucial for systems with a high share of renewables [34]. Additionally, combining VSGs with electric vehicle (EV) charging stations has been proposed as a novel approach to provide inertia to the system, utilizing the energy stored in EVs to support grid stability during fluctuations. Advanced control techniques, such as model predictive control and fuzzy logic controllers, offer dynamic and adaptive responses to grid disturbances, helping to smooth out frequency fluctuations and enhance voltage regulation [50]. These methods can optimize the operation of ESS and grid-connected inverters, providing both short-term frequency support and long-term grid stability. A study focusing on a hybrid power system for an island in the Mediterranean demonstrated that fuzzy logic controllers, combined with wind and battery storage systems, significantly improved the system's response to power imbalances [25].

The integration of ESS with power electronics is also critical for grid stability. BESSs, when combined with advanced inverters, provide fast response capabilities that are essential for managing the intermittent nature of renewable generation [51]. For example, on the island of Nusa Penida, the deployment of BESS alongside grid-forming inverters enabled a 100% renewable energy supply while maintaining grid stability under fluctuating load conditions. Similarly, ultra-capacitors have been tested in the Canary Islands to enhance frequency stability by providing rapid energy discharge during grid disturbances, demonstrating the effectiveness of storage-based solutions integrated with advanced control systems [52]. Hybrid control strategies that combine different technologies are also being explored. On El Hierro island, a hybrid control scheme utilizing wind turbines, flywheel energy storage, and power electronics helped optimize frequency control and reduce system inefficiencies [29]. Another study proposed the use of active voltage feedback control in hybrid multiterminal HVDC systems, which successfully managed power flow and

enhanced grid stability without requiring high-speed communication systems [53]. Additionally, novel approaches like the use of vehicle-to-grid (V2G) technologies are emerging as promising solutions. By allowing EVs to act as distributed energy storage, V2G systems can contribute to grid stability by injecting power back into the grid during peak demand or under-frequency events [54]. This strategy provides frequency regulation and enhances the flexibility and resilience of island power systems.

3.1.3. Hybrid Strategies and Renewable Hybrid Systems

Hybrid strategies and renewable hybrid systems are gaining significant attention as effective solutions for enhancing grid stability and achieving 100% renewable energy integration in island power systems [55]. These approaches combine multiple RESs with energy storage and advanced control mechanisms to optimize generation, improve reliability, and mitigate the intermittency of renewables [56]. One widely adopted strategy involves the integration of solar PV, wind turbines, and BESS. These hybrid systems can dynamically balance power supply and demand, offering a robust solution for isolated grids. A study on Miangas Island in Indonesia demonstrated that a hybrid system combining PV, wind, diesel, and batteries reduced operational costs and enhanced energy reliability [57]. Similarly, research on Prince Edward Island indicated that combining wind and solar resources with a high-capacity thermal storage system could achieve a fully renewable energy supply, demonstrating the flexibility of hybrid systems in adapting to local resource availability [58]. In addition to PV and wind combinations, hybrid systems also incorporate pumped hydro storage (PHS) to store excess energy and provide stability during low renewable generation periods. On Crete Island, a hybrid system utilizing wind energy and PHS proved effective in reducing energy curtailment and enhancing grid reliability [43].

The concept of multi-vector energy communities has also been proposed to enhance flexibility and resilience in island systems [27]. Multi-vector energy communities integrate various energy sources and technologies, including batteries, hydrogen storage, and demand-side management, to create a more adaptable energy ecosystem [59]. A study involving the islands of Ærø in Denmark and Vis in Croatia highlighted how multi-vector approaches could optimize local renewable energy use and reduce dependency on external energy imports [60]. A promising hybrid strategy involves the use of wave energy integrated with other renewables to diversify the energy mix. Research on El Hierro island explored the integration of wave farms with wind and solar systems, demonstrating that this approach could improve frequency stability and reduce wear and tear on conventional generation assets [61]. The hybridization of wave and solar power with advanced control techniques provided a balanced and resilient power supply, even under highly variable renewable energy generation conditions. Another innovative approach is the deployment of VPPs in microgrids. VPPs aggregate DERs, including PV systems and controllable loads, to create a virtualized and centrally managed power system [35]. In a study focusing on island microgrids, the coordinated control of VPPs enabled primary frequency regulation and enhanced the stability of the grid under high renewable penetration scenarios [36]. VPPs' ability to modulate power output and adapt to grid demands makes them particularly suitable for managing the challenges of isolated systems.

Hybrid systems also contribute to enhancing the resilience of microgrids against extreme weather events and grid disturbances [62]. On Orcas Island, a hybrid microgrid incorporating PV and BESS was developed using a bi-level optimization model to maximize critical load supply and minimize operational costs during grid isolation events [63]. The study showed that hybrid strategies could significantly improve the grid's resilience by ensuring that critical loads remain powered even during extended outages. A novel hybrid approach explored in the Canary Islands involved combining wind power, hydro-

gen storage, and conventional generation to manage frequency stability effectively. The hybrid system utilized hydrogen as a long-term energy storage medium, offering a cost-effective alternative to battery-based systems while enhancing the grid's ability to handle renewable energy fluctuations [39]. Lastly, hybrid systems that integrate V2G technologies offer additional flexibility. The island of Korčula implemented a V2G strategy as part of a fully renewable energy system, demonstrating that EVs could act as both loads and generators, contributing to grid stability and enhancing renewable energy integration [64]. By leveraging the energy stored in EVs, hybrid systems can provide valuable grid services, such as frequency regulation and peak load management.

3.1.4. Examples of Implementation in Specific Islands

Numerous island systems around the world have implemented renewable energy strategies, showcasing successful pathways to achieving significant or even 100% renewable energy integration [31]. These real-world examples provide valuable insights into effective technologies, strategies, and policy frameworks that can be replicated in other island contexts [65]. One of the most notable success stories is El Hierro, part of Spain's Canary Islands, which aims to become energy self-sufficient through a hybrid system combining wind energy with a PHS plant. The island's system includes variable-speed wind turbines, Pelton turbines, and a pump station, demonstrating how hybrid energy systems can maintain grid stability and reduce greenhouse gas emissions [29]. The innovative frequency control strategies used in El Hierro allow for high renewable penetration while minimizing reliance on diesel generators.

Another notable example is the Faroe Islands, which have explored integrating wind, hydro, and PHS systems to achieve over 90% renewable energy penetration [66,67]. The islands' strategy involves the development of wind and PV parks along with energy storage solutions to address the variability of renewable resources and maintain a stable power supply [40]. This approach highlights the importance of storage technologies in supporting grid stability in isolated systems. The Azores Archipelago has also demonstrated effective renewable energy integration by using a multi-year expansion-planning optimization model that includes DC submarine power cables to interconnect the islands. This strategy increases renewable energy penetration and, at the same time, enhances the overall economic and environmental sustainability of the islands [68]. The study suggests that interconnecting smaller island systems can provide significant benefits, including reduced energy costs and improved reliability. Reunion Island has set an ambitious goal to achieve 100% renewable energy by 2030, using a comprehensive approach that combines solar, wind, and advanced energy storage technologies. The island's strategy focuses on enhancing system reliability through flexibility solutions such as DR and storage, which help counterbalance the variability of renewable generation [69]. The deployment of kinetic energy-based transient reliability indicators is a novel method that supports system stability under high renewable penetration.

In the Cape Verde Islands, a reference model for 100% renewable deployment has been developed to evaluate the impact of different technologies and grid management strategies. This model incorporates power electronics, energy storage, and DR technologies, providing a benchmark for studies on grid stability and renewable integration in medium-to-large isolated power systems [41]. The insights gained from Cape Verde's approach are particularly relevant for islands aiming to integrate diverse renewable technologies. The Island of Nusa Penida in Indonesia serves as a case study for achieving grid stability through a 100% renewable energy supply using batteries as a backup system. The implementation of advanced grid controllers and defense backup systems has proven essential to maintaining grid stability under conditions of high renewable energy variability [51].

The island's approach underlines the critical role of advanced grid management tools and energy storage in supporting renewable energy systems. On Orcas Island in the United States, a hybrid microgrid incorporating solar PV and BESS was developed to enhance resilience during extreme weather events. This project used a bi-level optimization model to transform the island's power system into a flexible microgrid capable of maintaining critical load supply even during grid isolation [63]. This example showcases how hybrid systems can be tailored to improve resilience and stability in island grids. Moreover, Korčula Island in Croatia has pioneered the integration of transport and energy sectors using a 100% renewable energy system combined with V2G technology. This approach involves EVs acting as both loads and power generators, offering grid stability and facilitating the higher adoption of renewable energy [64]. Korčula's strategy demonstrates the potential of integrating transportation electrification with renewable energy systems to create a more robust and resilient grid.

Figure 6 provides a comprehensive summary of the preliminary findings on renewable energy integration and grid stability in island systems.

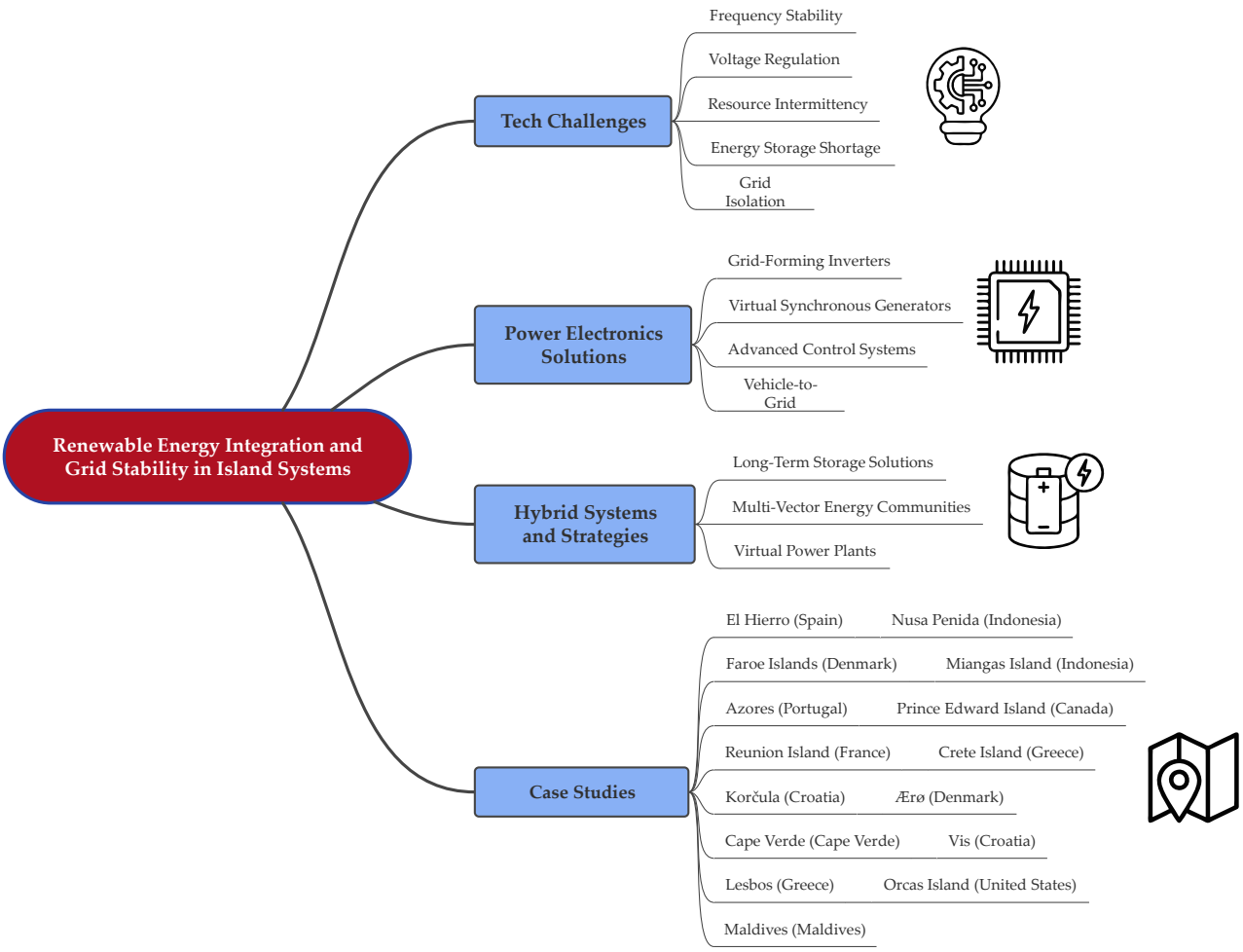


Figure 6. Preliminary findings on renewable energy integration and grid stability in island systems.

3.2. Energy Storage Technologies and Their Role in Island Energy Systems

Energy storage is widely recognized as a crucial facilitator of high renewable energy penetration in island systems [70,71]. This thematic area explores different storage solutions, including BESSs, hydrogen storage, PHS, and flywheels. The reviewed articles discuss how these technologies help mitigate the intermittency of renewable generation, improve grid reliability, and provide frequency and voltage support. Particular emphasis is placed on

optimizing storage capacity, extending battery lifespan, and implementing hybrid storage solutions to balance cost and performance [62]. Additionally, studies examine emerging trends in long-duration storage and their potential role in achieving 100% renewable energy systems in islands [44].

3.2.1. Types of Energy Storage Technologies: BESS, Hydrogen, Pumped Hydro Storage, and Flywheels

Energy storage are often present in island energy systems by providing operational flexibility and grid stability [72]. The primary storage technologies analyzed include BESS, hydrogen storage, PHS, and flywheels. BESSs are widely used due to their fast response and versatility. These systems perform critical functions such as load leveling and peak shaving, helping maintain system stability during renewable generation fluctuations [30]. In a study conducted in Hawaii, a BESS installed in an island power system demonstrated 90% availability over three years, delivering over 5000 equivalent full cycles. BESSs also contribute to enhancing transient stability in microgrids with high renewable penetration by supporting both on-grid and off-grid operations [73,74]. Additionally, integrating BESSs with intelligent energy management systems (iEMS) has proven effective in maintaining stability during significant disturbances, such as diesel generator or PV system trips [73]. Other studies highlight the role of BESSs in reducing fuel consumption and greenhouse gas emissions by maximizing renewable energy use and minimizing diesel generator reliance [51,75].

Hydrogen storage stands out for its ability to provide long-term energy storage. In a case study of a renewable system based on PV and floating offshore wind turbines, using a battery-only configuration was found to increase system costs by 155% compared to using hydrogen storage [38]. Hydrogen-based solutions are particularly effective in achieving cost-efficient energy self-sufficiency, especially in scenarios requiring seasonal storage [39]. For instance, on Yong Shu Island, integrating hydrogen storage with other technologies significantly improved system efficiency and reduced carbon emissions [76]. Moreover, studies on hybrid battery–hydrogen systems emphasize that hydrogen storage can complement batteries by offering a more economical and scalable long-duration storage option [77]. PHS is a mature and efficient technology for island systems. The hybrid wind-PHS system on El Hierro Island has achieved high renewable energy shares while enhancing frequency control [29].

Another study in Crete evaluated the technical and economic feasibility of a PHS system to utilize excess wind energy, demonstrating its effectiveness in stabilizing the grid and storing energy during low-demand periods [43]. Furthermore, integrating PHS with large-scale wind energy production on the island of Lesbos showed that PHS can effectively reduce renewable energy curtailment and replace energy imports from the mainland [46]. The synergy between PHS and renewable resources is also highlighted in studies where PHS helps maintain grid stability without curtailing PV output [78]. Flywheels provide an ultra-fast response for frequency support, particularly in low-inertia systems. These devices offer synthetic inertia, which is critical for maintaining stability in grids with high renewable penetration [79]. On El Hierro Island, combining flywheels with wind and hydro turbines effectively reduced frequency fluctuations and improved power supply quality [28]. Flywheels also show potential to reduce mechanical wear and extend the lifespan of critical components in hybrid systems [76]. Additionally, integrating flywheels into hybrid storage systems with hydrogen and batteries can optimize the overall energy storage strategy, providing both short-term stability and long-term energy security [50,80].

3.2.2. Optimization of Storage Capacity and Durability

Optimizing the capacity and durability of ESSs is critical for enhancing the reliability and economic performance of island energy systems [81]. The reviewed studies emphasize strategies to maximize storage efficiency, extend lifespan, and reduce costs while maintaining grid stability [82,83]. One practical approach to optimizing storage capacity involves using hybrid systems that combine batteries and hydrogen storage. For instance, a study conducted on a Mediterranean island demonstrated that a hybrid PV–wind–battery system significantly reduced the net present cost and improved energy reliability [25]. Another study showed that using hydrogen storage alongside batteries reduced overall system costs compared to battery-only configurations, highlighting the economic benefits of hybrid storage solutions [38]. BESSs have shown considerable promise in enhancing storage durability. An analysis of a lithium titanate BESS in Hawaii revealed that the system operated at 90% availability over three years, completing over 5000 equivalent full cycles, indicating robust long-term performance [30]. Additionally, implementing intelligent energy management systems (iEMSs) with BESSs helps maintain stability during large disturbances, further enhancing the lifespan of the battery systems [73].

PHS is also essential in optimizing storage capacity for island grids. On El Hierro Island, the integration of a wind–PHS hybrid system allowed for higher renewable energy penetration while maintaining grid stability through advanced frequency control strategies [29]. In Crete, the optimal sizing and implementation of a PHS system to utilize excess wind energy demonstrated the technology's potential to store significant amounts of energy during periods of low demand [43]. Emerging technologies like flywheels contribute to enhancing the durability of storage systems by reducing mechanical wear and extending the lifespan of critical components. Studies show that integrating flywheels with other storage technologies, such as hydrogen and batteries, can provide both short-term stability and long-term energy security [76,80].

3.2.3. Long-Term Storage and Intermittency Mitigation

Long-term energy storage acts as a cornerstone for addressing the intermittency of RES in island systems [84]. The reviewed studies emphasize the importance of integrating storage technologies capable of maintaining energy reserves over extended periods, thereby enhancing grid stability and reliability [37]. These technologies include hydrogen storage, PHS, and hybrid systems combining different storage modalities. Hydrogen storage has emerged as a viable solution for long-term energy storage, particularly for balancing seasonal variations in renewable energy generation. A study on island energy systems with high renewable penetration highlighted that hydrogen-based storage systems could significantly reduce the need for oversizing BESSs and help maintain energy self-sufficiency in a cost-effective manner [38]. This approach was further validated by research in the South China Sea, where combining hydrogen storage with flywheels led to reduced energy costs while ensuring a stable and dependable long-term storage solution [76]. Additionally, the integration of hydrogen storage with other technologies, such as flywheels and BESS, demonstrated the potential for optimizing both the cost and performance of storage solutions [85].

PHS is another proven technology for long-duration storage. On Crete Island, a PHS system effectively stored excess wind energy by converting it to hydraulic energy, maintaining a reliable energy reserve during periods of low renewable generation [43]. The El Hierro Island project showcased how a hybrid wind-PHS system enhanced renewable energy penetration while providing sophisticated frequency control, which is essential for a low-inertia grid [29]. This combination of PHS with other technologies provided an effective method for managing both short-term fluctuations and long-term energy storage needs.

Hybrid systems that integrate BESSs, hydrogen, and flywheels offer a balanced approach to managing renewable energy variability. For instance, on Prince Edward Island, a study compared BESSs with high-temperature thermal-turbine storage, showing that while BESSs offer rapid response times ideal for short-term balancing, thermal-turbine systems provide extended storage durations at a lower cost [58]. This hybrid approach underlined the benefits of combining technologies to achieve both economic and operational efficiencies in storage systems.

Innovative control strategies, such as V2G technology, have also proven effective in managing intermittency. On Brittany Island, EVs acted as dispersed energy storage units, contributing to grid stability by absorbing excess energy during peak production and supplying power back to the grid during demand surges [50]. This strategy established a flexible energy reserve while simultaneously improving the economic viability of storage systems by utilizing existing infrastructure. Similarly, microgrid studies in Porto Santo and Hawaii highlighted the role of smart energy management systems in optimizing BESS usage to smooth load curves and stabilize the grid [54]. These systems used predictive algorithms to effectively manage storage and energy dispatch, demonstrating the potential of integrating digital technologies with physical storage solutions. Overall, long-term storage technologies, particularly hydrogen and PHS, along with hybrid systems and advanced control mechanisms, are critical for mitigating the intermittency of renewable energy in island systems. These solutions enhance energy reliability while also contributing to the objective of achieving fully renewable energy systems in isolated regions. Through a combination of technology integration, economic optimization, and strategic control systems, island microgrids can enhance resilience and reduce dependency on fossil fuels, setting a strong example for broader renewable energy transitions [29,43,50,54,58,76,86].

3.2.4. Energy Storage Applications in Specific Case Studies

Numerous specific case studies have demonstrated how ESSs can be successfully applied in island systems to facilitate renewable energy integration and enhance grid stability. These studies highlight the use of diverse storage technologies, such as BESSs, hydrogen, PHS, and flywheels, in different island contexts, providing practical examples of their benefits and challenges. In El Hierro, a hybrid PHS and wind generation system enabled the island to achieve high levels of renewable penetration, significantly reducing the use of diesel generators and improving frequency stability [29]. This project has become a benchmark for other island systems seeking to maximize renewable energy use through strategic ESS deployment. Additionally, various frequency control schemes were evaluated, demonstrating that using flywheels and advanced pump control improves system efficiency.

In Porto Santo, integrating EVs as part of the storage and demand management strategy showed how existing infrastructure can be utilized to improve the flexibility of the energy system. EVs operated both as load and power resources, contributing to balancing energy supply and demand [54]. This practical application underscores the potential of V2G-based solutions to act as distributed storage in island microgrids. The Greek island of Astypalaia implemented a hybrid system combining BESS with wind turbines, boosting renewable energy penetration and delivering a quick response to grid disturbances [75]. Simulation results indicated that using ESS significantly enhanced system stability during critical events, demonstrating the importance of agile and efficient storage in island grids. In a similar context, the island of Maui in Hawaii used BESSs for peak shaving and load curve smoothing in a distribution circuit with high solar energy penetration [86]. This study showed how battery storage can be optimized through predictive control algorithms to reduce fluctuations and improve grid stability. Additionally, on the island of Kythnos,

using virtual synchronous generators combined with EV charging stations provided critical inertia support to the grid, stabilizing both frequency and voltage [34].

On the island of Crete, a PHS system was implemented to capture excess wind energy, showing how this technology mitigates intermittency and maximizes renewable resource utilization by converting surplus energy into a valuable asset during low-generation periods [43]. This case study highlights PHS's capacity to act as long-duration storage that supports energy self-sufficiency in isolated systems. Each successful application emphasizes the importance of selecting the appropriate storage technology based on demand characteristics, renewable generation profiles, and the economic and technical constraints of each island environment [29,34,43,54,75,86].

3.3. Control Strategies and Smart Grid Technologies for Island Microgrids

As has already been seen so far, the deployment of advanced control strategies and smart grid technologies is essential to enhance the reliability, resilience, and efficiency of island energy systems. The literature highlights the increasing adoption of decentralized control strategies, including grid-forming (GFM) and grid-following (GFL) inverters, multi-agent systems, and artificial intelligence (AI)-based approaches for real-time energy management. Studies also investigate microgrid architectures, peer-to-peer energy trading, DR programs, and adaptive protection schemes to handle fluctuating renewable generation. Additionally, advancements in digital twins and predictive analytics are being explored to optimize grid performance and preemptively address stability issues [87].

3.3.1. Implementation of Grid-Forming and Grid-Following Inverters

The implementation of GFM and GFL inverters in island microgrids is a critical aspect of modern control strategies, providing enhanced stability and flexibility. A unified distributed cooperative voltage control approach to GFL- and GFM-distributed generators has been proposed to improve voltage regulation and system stability through a range-consensus-based distributed control algorithm [88]. This approach harmonizes the control structures of different distributed generators, demonstrating their effectiveness through simulation and hardware-in-the-loop tests. The challenges of operating fully non-synchronous electrical grids with 100% converter-interfaced generation have been addressed, focusing on the necessary amount of GFM power, optimal unit sizing, and strategic placement of GFM converters to ensure synchronization and grid stability [26]. In this context, dynamic characteristics and frequency stability are critical areas where GFM inverters make a substantial contribution to grid performance.

Studies have also highlighted the economic and technical benefits of integrating GFM and GFL inverters into multi-vector energy communities. These systems enhance self-sufficiency and resilience by optimizing the interaction between local energy generation and consumption, especially under diverse geographical and operational scenarios [60]. Economic assessments show that the adoption of advanced inverter technologies within PV and battery storage systems enhances resilience and operational efficiency during grid outages. Simulation-based optimization methods reveal how GFM inverters can contribute to balancing costs and improving system islanding resilience [89]. The lifecycle cost–benefit analysis of smart grid technologies, including GFM and GFL inverters, underscores their role in supporting off-grid and urban decentralized energy systems, offering insights into economic performance and potential government support requirements [85].

Innovative control strategies, such as load frequency control using EVs as distributed energy storage, have been proposed to improve frequency stability in islanded microgrids. The V2G approach is particularly effective in enhancing load frequency control capacity and maintaining stability under island operation modes [50]. Additional advancements

include the development of hybrid multiterminal HVDC systems with active voltage feedback control, integrating synchronverter technologies that emulate synchronous machine behavior, and contributing to both GFM and GFL control applications [53].

3.3.2. Decentralized Control Systems and Artificial Intelligence

Decentralized control systems and AI are emerging as powerful tools to enhance the resilience, efficiency, and adaptability of island microgrids. The shift towards decentralized control is driven by the need for more flexible and autonomous energy management systems that can respond in real time to fluctuations in renewable energy generation and varying load demands. Unlike traditional centralized control systems, decentralized strategies distribute control tasks among multiple local controllers, reducing the risk of single points of failure and enhancing the robustness of the system [26,60,88]. AI-based approaches, such as machine learning and multi-agent systems, are being integrated with decentralized control systems to optimize the performance of island microgrids. These technologies enable predictive maintenance, fault detection, and adaptive control, allowing systems to anticipate and mitigate potential issues before they affect grid stability. Studies highlight the potential of AI algorithms to analyze large datasets from grid sensors, weather forecasts, and historical performance data to improve decision-making processes [50,53,85].

Advanced control strategies using AI include reinforcement learning for dynamic grid optimization and neural networks for load forecasting and energy management. These methods enhance the ability of microgrids to operate independently from the main grid, which is particularly valuable during extreme weather events or grid outages. Moreover, decentralized control combined with AI facilitates the integration of emerging technologies, such as V2G systems and DR programs, which contribute to load balancing and energy efficiency [63,80,90]. In this sense, the integration of decentralized control systems and AI in island microgrids represents a significant step forward in achieving reliable and sustainable 100% renewable energy systems, offering scalable solutions that can be adapted to diverse island environments and energy demands [29,73,79].

3.3.3. Digital Twins and Predictive Analytics

Digital twins (DTs) and predictive analytics (PA) have gained significant attention in enhancing the resilience and operational efficiency of island microgrids [91]. DTs provide a real-time virtual representation of physical assets, enabling the simulation, monitoring, and optimization of grid components under varying operational scenarios [88]. By integrating data from sensors, historical records, and advanced models, DTs can replicate the dynamic behavior of power systems, providing a platform for predictive maintenance and optimization of grid performance [92]. For example, a study on grid-forming converters combined with a resilience-monitoring application demonstrated improved stability in microgrids during extreme weather events. Predictive analytics leverage machine learning (ML) and advanced statistical methods to forecast grid behavior and identify potential issues before they manifest in real-world systems [33]. In particular, PA can anticipate load variations, optimize energy storage utilization, and improve DR strategies. A notable application of PA is in the development of wave-to-wire models for integrating wave energy converters in grid-forming applications, enabling continuous power supply to remote islands.

Furthermore, DTs and PA contribute to enhancing grid stability by offering predictive insights into frequency and voltage control. These technologies enable adaptive control mechanisms that respond proactively to disturbances, thus maintaining grid stability and reducing the risks of blackouts [79]. The use of virtual synchronous generators, for example, enhances system inertia and dynamic response, proving effective in mitigating frequency and voltage fluctuations in isolated island microgrids. Advanced implementations of DTs

include multi-agent systems that simulate different grid scenarios, evaluate the impact of renewable energy fluctuations, and optimize control strategies in real time [26]. Such systems are particularly effective in fully non-synchronous grids where traditional control methods are less effective. By creating a virtual environment where control strategies are tested and refined, DTs minimize the risk of real-world failures and improve the reliability of power supply in island systems. In addition, the integration of digital twins and predictive analytics into island microgrids represents a transformative approach to achieving grid resilience and efficiency. These technologies improve operational foresight while also facilitating the implementation of advanced grid-forming and grid-following control strategies, contributing to a stable and resilient power supply in renewable-driven island systems [26,33,79,88,92].

Figure 7 illustrates the main findings related to the implementation of DT in island microgrids discussed above.

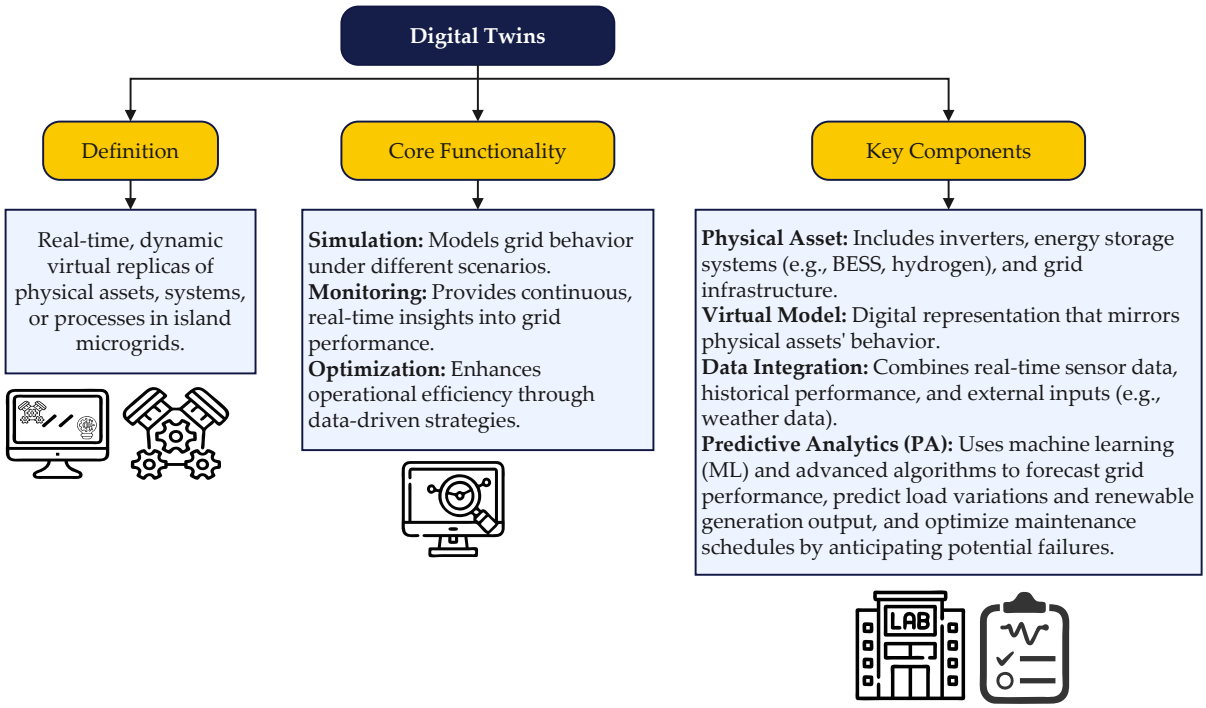


Figure 7. Key applications and benefits of digital twins in enhancing grid stability and operational efficiency in island microgrids.

3.3.4. Notable Island Microgrid Projects

Island microgrid projects provide invaluable insights into the practical application of renewable energy integration, storage technologies, and advanced control strategies. These real-world implementations highlight the potential and challenges of achieving energy resilience and sustainability in isolated systems. A range of projects around the world demonstrate diverse approaches to overcoming technical, economic, and operational barriers, showcasing both successes and areas for improvement. One of the most prominent examples is El Hierro Island in Spain, which aims to achieve 100% renewable energy through a hybrid wind–pump storage hydropower system (W-PSHP) combined with advanced frequency control strategies [29]. The project includes wind turbines, Pelton turbines, and a pump station with fixed and variable-speed pumps. The frequency control strategies implemented, including a hydraulic short-circuit operation mode, allow the system to regulate frequency deviations even when diesel units are offline, demonstrating significant potential for increasing renewable energy penetration [29].

Similarly, the Hawai'i Island system offers an exemplary model of dynamic security optimization in a 100% inverter-based resource system. The project employs grid-forming inverters as a critical component to maintain grid stability under N-1 contingency conditions. The operator support system implemented in this project combines dynamic security assessment with control parameter optimization, showing robust performance in high-fidelity simulations [32]. The Orcas Power & Light Cooperative project in the United States adopts a bi-level mixed-integer linear programming model to enhance resilience through optimized BESS sizing. This project enhances critical load supply during isolated operations while simultaneously reducing operational costs. The alignment of the PV profile with load demand has been shown to significantly impact BESS sizing, offering valuable lessons in balancing renewable generation with storage capacity [63]. Other notable projects include the Samsø and Orkney islands, which leverage heat pump district heating with heat storage, hydrogen production via electrolysis, and EVs to enhance self-resilience and minimize grid dependence [90]. These islands demonstrate how integrated approaches combining storage, demand-side management, and innovative technologies can lead to substantial reductions in energy imports and curtailment [90]. The Iconic Island of Nusa Penida in Indonesia further illustrates the critical role of BESSs in maintaining grid stability when operating under 100% renewable energy scenarios. The simulation results demonstrate how BESSs act as effective backup solutions, helping to manage the variability and uncertainty of renewable energy supply while improving overall grid resilience [51].

3.3.5. Emerging Renewable Energy Solutions for Island Systems

In addition to the established smart grid and control strategies previously discussed, a range of emerging technologies hold significant promise for enhancing the sustainability and resilience of island energy systems. Among these, Ocean Thermal Energy Conversion (OTEC) represents a largely untapped resource, which is particularly suitable for tropical island states. OTEC exploits the thermal gradient between warm surface seawater and cold deep seawater to generate continuous baseload power. Its applicability is highest in regions located near the equator, where the temperature differential exceeds 20 °C. Pilot projects such as the one implemented in South Tarawa, Kiribati, have demonstrated the viability of small-scale land-based OTEC plants for Small Island Developing States (SIDSs), providing a stable alternative to intermittent solar and wind resources [93].

Simultaneously, next-generation geothermal energy systems are gaining attention for their potential to deliver dispatchable and carbon-neutral electricity on geologically favorable islands. These systems go beyond conventional hydrothermal technologies by incorporating enhanced geothermal systems (EGSs) and closed-loop geothermal configurations, which enable heat extraction in areas with limited natural permeability or fluid availability. Such approaches could unlock geothermal potential in islands previously deemed unsuitable for development. Research indicates that EGSs may be particularly advantageous on volcanic islands where high subsurface temperatures exist but conventional hydrothermal reservoirs are absent [94]. Complementing these physical generation technologies, AI-based predictive maintenance is being investigated as a tool for ensuring operational continuity in island microgrids. By leveraging machine learning algorithms and real-time data analytics, predictive maintenance frameworks can anticipate equipment degradation, optimize scheduling of maintenance tasks, and reduce system downtime, especially in remote or logistically constrained islands. Applications of AI for fault prediction in inverters, battery health monitoring, and early detection of component anomalies have shown measurable benefits in improving reliability and reducing costs in isolated energy systems [95]. Although the commercial deployment of these advanced technologies remains limited in island settings, ongoing pilot projects and feasibility studies indicate

their growing relevance. The integration of OTEC, advanced geothermal systems, and AI-driven asset management may soon redefine the technological landscape of renewable island microgrids. Their inclusion in strategic planning, supported by further research and policy incentives, is essential to expand the portfolio of viable solutions for achieving secure and autonomous energy systems in SIDSs.

3.4. Case Studies and Success Stories of 100% Renewable Island Systems

In this subsection, real-world examples of islands transitioning to fully renewable energy systems documented in the selected literature are presented. The reviewed literature provides insights into the strategies, technologies, and policy frameworks that have enabled successful transitions. Case studies cover a range of islands with varying geographic, economic, and technological conditions, analyzing factors such as renewable energy mix, storage deployment, grid management practices, and socio-political challenges. Valuable lessons include the importance of government incentives, regulatory frameworks, community involvement, and the integration of hybrid renewable storage solutions. Several articles also explore ongoing projects and future strategies for achieving full renewable energy transitions in island settings [96,97].

3.4.1. Analysis of Islands with Advanced Transition to Renewables

Successful transitions to high-penetrated renewable energy systems have been documented in diverse island settings [74]. The case of Kish Island in Iran illustrates the effectiveness of hybrid renewable systems combining PV, wind turbines, and ocean renewable energy storage (ORES) through an optimized Gravitational Search Algorithm, achieving operational efficiency and energy reliability [98]. Similarly, a Mediterranean island community has benefited from a PV–wind–battery hybrid system, showcasing the economic and technical feasibility of such microgrid solutions [25]. El Hierro in the Canary Islands, Spain, stands out for its hybrid hydro–wind–flywheel frequency control strategy that ensures grid stability and enhances renewable energy penetration [28]. The South China Sea island's approach to nearly 90% renewable energy integration demonstrates the synergy between power supply and demand management, emphasizing hydrogen and traditional battery storage [76]. The Maldives' Fenfushi Island utilized Voluntary Demand Participation (VDP) strategies to lower costs and integrate renewables in its hybrid microgrid [45].

Further examples include the study of hydrogen-based energy storage in the Aegean island grid, demonstrating how fuel cells and hydrogen storage can effectively support large-scale wind energy integration [39]. Yeongjong Island in South Korea achieved a fully renewable energy supply by adopting an optimal hybrid power system that balanced economic viability and technological feasibility [42]. A notable project in Nusa Penida Island showcased how BESSs can stabilize grids under 100% variable renewable energy scenarios, contributing to grid resilience and operational stability [51]. Additionally, La Réunion Island has developed a robust multi-timescale approach to achieve a fully renewable power generation system by 2030, using dynamic models to ensure system stability and reliability [99]. Puerto Rico's transition to 100% inverter-based resources highlights the challenges of reducing system strength while maintaining grid protection and stability. The study provided valuable insights into the necessary system modifications to support a renewable-driven energy transition [100].

3.4.2. Evaluation of Effective Technologies and Strategies

The transition to 100% renewable energy systems in island settings relies not only on ambitious goals and policy frameworks but also on deploying effective technologies and strategies that promote stability, efficiency, and resilience. The reviewed literature presents

a broad spectrum of solutions, from energy storage technologies and grid management practices to innovative energy generation methods and hybrid systems, all of which contribute to successful renewable transitions in islands. ESSs play a critical role in stabilizing island grids characterized by high renewable energy penetration. For example, a study on Nusa Penida Island highlights how the integration of BESSs can significantly enhance grid stability, providing a backup system to address the challenges posed by distributed and fluctuating RESs [51]. Similar results were noted in Maui, Hawaii, where BESSs were employed to smooth load curves and shave peak loads in a highly renewable energy environment [86]. Additionally, hydrogen-based energy storage presents a viable alternative to traditional battery systems. Research conducted in the South China Sea demonstrated that hybrid systems combining hydrogen storage with flywheels could reduce energy costs by up to 5.6%, showcasing hydrogen's potential as a long-term storage solution [76].

In addition to storage solutions, advanced control strategies are essential for maintaining grid stability. The implementation of grid-forming converters and real-time monitoring systems, as demonstrated in an island medium-voltage grid under extreme weather conditions, has been proven to enhance power system resilience [92]. The integration of EVs as part of the energy management system also offers significant advantages, with studies on Porto Santo Island showing how EVs can act as both load and power resources, contributing to grid flexibility and increased renewable energy integration [54]. Hybrid systems that combine multiple renewable sources with storage solutions are becoming the preferred approach in island settings. The Mediterranean island study that implemented a PV–wind–battery hybrid system achieved a levelized cost of electricity of 0.15 USD/kWh, demonstrating the economic viability of hybrid renewable systems [25].

Furthermore, projects like the one on El Hierro in the Canary Islands illustrate the success of hybrid frequency control strategies based on hydropower, wind, and ESSs in achieving 100% renewable energy generation [28]. Advanced grid management practices and infrastructure improvements are also important for successful renewable transitions. The use of pumped-hydro storage (PHS) in interconnected island grids, such as in Lesbos, Greece, supports large-scale wind energy integration while also boosting economic viability by reducing the need for energy imports [46]. Moreover, innovative approaches like VDP in the Maldives enable local communities to adapt their energy consumption based on supply availability, thereby reducing reliance on fossil fuels and enhancing grid stability [45].

3.4.3. Critical Success Factors: Policies, Incentives, and Community Engagement

The successful transition of island energy systems to 100% renewable energy heavily depends on well-designed policies, financial incentives, and active community participation [100,101]. Various studies emphasize the critical role of government initiatives and regulatory frameworks in enabling renewable energy adoption and ensuring long-term sustainability. Effective policies, including feed-in tariffs, renewable portfolio standards, and net metering, have been mandatory in encouraging investment in renewable energy infrastructure on islands [45]. As mentioned in the previous subsection, the Maldives' government initiative to promote VDP effectively reduced reliance on diesel generation by allowing end-users to adjust their consumption during periods of renewable energy surplus. Similarly, South Korea's policies in Yeongjong Island facilitated the integration of a 100% renewable energy-oriented hybrid system, demonstrating the positive impact of well-structured energy policies [42]. Financial incentives, such as subsidies, grants, and tax incentives, play a significant role in reducing the financial risks associated with renewable energy projects. Studies on Mediterranean islands highlighted how hybrid systems combining PV, wind, and battery technologies could achieve a lower Levelized Cost of Electricity compared to conventional energy sources, with financial incentives

further enhancing economic feasibility [25]. Additionally, the case of La Réunion Island showed how strategic investments and economic policies supported the island's goal of achieving 100% renewable energy by 2030 [99].

Community involvement is a decisive factor in the success of renewable energy projects. The El Hierro island project, for example, demonstrated how local support and involvement in renewable energy initiatives could enhance the adoption and operational success of hybrid energy systems [28]. A study on Porto Santo Island demonstrated that EVs used as distributed storage systems contributed to grid stability and engaged the community in energy transition efforts, promoting broader participation and support [54]. Furthermore, the project in Astypalaia emphasized that community acceptance of renewable technologies and the involvement of local stakeholders are essential for overcoming challenges related to grid stability and the integration of intermittent renewable sources [75].

Demand-side management programs, combined with community incentives, can significantly optimize energy use patterns. The Maldives' VDP model, which included a feedback system for end-users to manage their load based on fuel availability, is an example of how aligning consumer behavior with renewable energy availability can lead to improved system efficiency [45]. The concept of hybrid systems utilizing V2G technology, as studied in Korčula, showed that financial incentives for EV adoption and grid integration could increase renewable energy penetration while maintaining grid stability [64]. Across different island case studies, common success factors include the integration of smart grid technologies, adaptive regulatory frameworks, and active communication with the community to build trust and acceptance. The Puerto Rico transition study highlighted how a robust policy framework and targeted incentives could facilitate the transition to a fully renewable grid while addressing technical challenges such as system strength reduction and grid stability [100].

Table 2 provides a concise summary of the main research opportunities identified in the thematic areas of grid stability, energy storage, control strategies, and successful island case studies, highlighting innovative technologies, effective strategies, and potential research lines for advancing 100% renewable energy systems in island grids.

Table 2. Key research opportunities and innovative strategies for achieving 100% renewable energy systems in island grids.

Ref.	Topic	Novel Aspects (Current Advances)	Research Gaps (Unresolved Needs)
[25,38,98]	Hybrid Renewable Systems in Island Grids	Deployment of hybrid PV–wind–ORES systems with energy management algorithms for stability optimization	Design and validation of control architectures for large-scale deployment under high variability scenarios
[26,28,29]	Frequency Control in 100% Renewable Systems	Implementation of hydro–wind–flywheel hybrid strategies for frequency regulation in isolated grids	Comparative evaluation of frequency control schemes under different inertia and penetration levels
[42,51,76]	Energy Storage Technologies: Hydrogen and BESSs	Integration of hydrogen and BESSs to buffer intermittent supply and provide ancillary services	Lifecycle optimization and techno-economic modeling of multi-timescale storage integration

Table 2. *Cont.*

Ref.	Topic	Novel Aspects (Current Advances)	Research Gaps (Unresolved Needs)
[45,46,54]	Demand Response (DR) and Community Engagement	Use of Voluntary Demand Participation (VDP) and Electric Vehicles (EVs) as controllable demand-side assets	Development of adaptive DR models that incorporate community behavior and variable renewables
[39,43,92]	Grid-Forming and Grid-Following Technologies	Application of grid-forming inverters and hydrogen-based energy buffers for stable island grid operation	Stability analysis of inverter-based systems under fault and recovery conditions in island contexts
[31,75,86]	Microgrid Design and Optimization	Use of intelligent energy management systems (iEMSs) for optimal sizing and dispatch	Co-optimization of microgrid topologies, control layers, and market participation mechanisms
[34,64,99]	V2G and Hybrid Solutions	Integration of V2G technology with hybrid microgrids for bidirectional energy exchange	Quantitative assessment of V2G impacts on grid frequency, reserve margins, and infrastructure wear
[100]	System Strength and Protection in 100% Inverter-Based Grids	Initial frameworks addressing protection coordination and synthetic inertia requirements	Design of protection schemes and system hardening measures for low-inertia, fully inverter-based systems

3.5. Additional Case Studies from Small Island Developing States in the Caribbean, Pacific, and Indian Ocean

The energy transition in SIDSs is of paramount importance due to their acute vulnerability to climate change and heavy dependence on imported fossil fuels. Despite the increasing global focus on renewable energy integration, these regions are often underrepresented in academic literature. This section addresses that gap by highlighting representative cases from the Caribbean, Pacific, and Indian Ocean regions based on peer-reviewed journal articles. In the Caribbean, Barbados has demonstrated early leadership in solar energy adoption. The country built on its historical use of solar thermal systems by expanding its PV capacity to approximately 200 kWp as early as 2010, reflecting strong institutional and technical readiness for further PV development [102]. Jamaica has also made significant progress by setting a national target to generate 50% of its electricity from renewable sources by 2030. This has led to the deployment of solar and wind power projects supported by evolving policy frameworks [103]. Meanwhile, Dominica is actively exploring geothermal energy as a principal alternative to reduce greenhouse gas emissions by 99.5% and electricity costs by 70% by 2030 [104]. Grenada has participated in regional initiatives to build energy-resilient infrastructure, focusing on both public and private sector engagement in renewable energy development [105].

In the Pacific, Fiji increased its renewable electricity generation from 59% in 2013 to 65% in 2016 and aims to achieve a further increase up to 81% using a combination of hydropower, biomass, solar, and wind. The country continues to face institutional and infrastructural challenges in implementing these strategies [106]. Samoa has implemented integrated renewable energy systems combining solar, hydro, and storage technologies, aiming to achieve 90% renewable electricity, which underscores the feasibility of energy independence in Pacific island contexts [107]. Notably, Vanuatu has doubled its renewable capacity between 2013 and 2016, with particular emphasis on solar PV deployment in rural areas, reflecting energy justice principles and localized development needs [108,109]. Kiribati has also made incremental gains in renewable energy deployment, raising the

share of electricity from renewables through solar installations targeted at both household and commercial users [110]. In the Indian Ocean region, Mauritius has committed to sourcing 60% of its electricity from renewable sources by 2030. While the country has a clear strategic roadmap, challenges related to policy implementation and infrastructure upgrades persist [111]. Seychelles is progressing toward a 15% renewable energy target by 2030 through investments in solar and wind energy projects, though technical and institutional capacity development remains critical [112]. Comoros aims to achieve 55% renewable electricity generation by 2033, leveraging solar and biomass as primary sources, supported by external partnerships and national planning efforts [113]. Lastly, Madagascar plans to achieve 85% renewable electricity generation by 2030 by scaling up solar and hydroelectric projects. The country's significant untapped renewable potential could serve as a foundation for broad-based electrification strategies [114].

3.5.1. Distinctions Between Large-Scale and Very Small Island Systems

It is necessary to distinguish between large island systems, such as Hawai'i, Azores, and Reunion Island, and very small island systems—typically those with fewer than 10,000 inhabitants—such as Tuvalu, Kiribati, Vanuatu, and Dominica. The scale of the energy system significantly influences the technological, economic, and operational strategies available for transitioning to renewable energy. Large islands often benefit from meshed transmission networks, diversified generation portfolios, and access to financing mechanisms that allow for high-penetration renewable energy deployment supported by utility-scale storage and grid-forming inverters. In contrast, very small islands generally operate with isolated, fragile, and low-inertia microgrids dominated by diesel generators. These systems face acute challenges, including constrained logistics for component delivery, limited technical staff, and minimal redundancy in energy supply. Under these conditions, feasible solutions emphasize modular and scalable technologies such as solar PV combined with lithium-ion or lead-acid battery storage, often integrated into solar–diesel hybrid systems. Moreover, simplicity and ease of maintenance are critical design criteria. Case studies from Tuvalu and Kiribati [106,107] illustrate incremental solar deployment as a strategy for reducing diesel dependency while avoiding major grid upgrades. In Vanuatu, the use of solar for lighting transitions has been implemented through community-led initiatives that align with local energy governance practices [105,106]. Tailored strategies are required, particularly for very small islands, where centralized, high-capacity grid solutions are neither technically nor economically viable.

3.6. Future Research Directions for 100% Renewable Island Systems

Despite notable progress in the deployment of renewable energy solutions in island systems, several key research areas remain open and demand in-depth investigation. These future research directions stem from the technological, operational, and systemic challenges identified throughout this review. First, the optimal design and dynamic control of hybrid renewable energy systems—combining PV, wind, storage (e.g., BESSs, hydrogen), and dispatchable renewables—require further modeling and experimental validation, particularly under high renewable penetration and limited inertia conditions [25,38,98]. Advanced energy management strategies that co-optimize reliability, economic efficiency, and emissions remain a priority.

Second, while grid-forming inverters and synthetic inertia technologies have emerged as critical enablers of stability in inverter-dominated island grids, their real-world behavior under grid faults, black-start conditions, and cyber-physical disturbances is still not well understood [39,43,92]. Research is needed to develop protection and control schemes that are robust to multi-event scenarios and to evaluate the system-wide impact of integrating

these technologies at scale. Third, the role of AI in predictive control, fault detection, and maintenance scheduling in island environments must be further developed. As discussed in Section 3.3.2, AI-driven methods have shown promise in optimizing system resilience and reducing downtime. However, their applicability in data-sparse, low-connectivity contexts common to SIDSs remains limited [95]. Fourth, energy-storage integration strategies, particularly those involving multi-timescale and multi-vector solutions (e.g., combining BESSs, hydrogen, and thermal storage), demand systematic exploration. Few studies have addressed the long-term performance, degradation modeling, and coordinated dispatch of such systems in insular contexts [42,51,76].

Fifth, very small island systems (<10,000 inhabitants) pose unique constraints that require dedicated investigation. As highlighted in Section 3.5.1, there is a need to develop low-complexity modular control and planning tools that can function with minimal technical supervision, limited economies of scale, and constrained logistics [105–107]. Sixth, emerging renewable technologies—such as OTEC and enhanced geothermal systems—offer promising pathways for baseload renewable generation. However, feasibility studies, techno-economic assessments, and policy readiness analyses are still scarce for SIDS applications [93,94]. Finally, beyond technical aspects, interdisciplinary frameworks integrating engineering, climate adaptation, socioeconomics, and governance are crucial to guide just and inclusive energy transitions. Research should explore co-creation methodologies, resilience indicators, and the role of community-based planning in decentralized renewable energy adoption [45,54].

3.7. Synthesis of Existing Solutions in Relation to the Research Questions

The analysis conducted throughout this review has been guided by four key research questions (RQ1–RQ4), which reflect the critical dimensions of transitioning to 100% renewable energy systems in island contexts. A synthesis of the reviewed literature reveals a broad array of technological strategies and policy frameworks that have been proposed or implemented to address the multifaceted challenges these systems face. In response to RQ1, which explores the technical and operational barriers to high-penetration renewable energy in insular environments, numerous studies have addressed the limitations imposed by low-inertia systems and highly variable generation. Hybrid renewable configurations that combine PV, wind, and diesel generators with BESS have emerged as baseline architectures to stabilize frequency and voltage while ensuring reliability [25,38,98]. In particular, the deployment of grid-forming inverters and synthetic inertia mechanisms has been proposed as a core solution to overcome stability issues in inverter-dominated microgrids [39,43,92]. Nevertheless, current implementations remain largely limited to simulation environments or pilot-scale projects. There is still a lack of comprehensive validation under fault scenarios, sequential disturbances, and prolonged islanding conditions.

Regarding RQ2, which investigates the role of energy storage in mitigating renewable intermittency and enhancing grid stability, the integration of multiple storage technologies—including BESSs, hydrogen-based systems, and flywheels—has shown promising results. These solutions allow for both short-term balancing and long-term energy arbitrage, particularly in hybrid systems designed for autonomous operation [42,51,76]. Despite technical progress, challenges persist in the coordinated operation of heterogeneous storage units, particularly in terms of optimal dispatch, degradation modeling, and lifecycle cost analysis. Further research is required to define scalable strategies that are technically sound and economically viable within the resource constraints of SIDSs. In the case of RQ3, which addresses advanced control mechanisms and smart grid technologies, the literature highlights a shift from centralized supervisory control to decentralized and intelligent frameworks. Predictive analytics, multi-agent systems, and AI techniques are now more commonly

employed for dynamic forecasting, adaptive load management, and fault diagnosis [95]. Moreover, the integration of digital twins facilitates virtual testing and scenario planning without compromising real-world operations. However, the implementation of these systems in remote islands remains constrained by limited data availability, communication infrastructure, and cyber-resilience capacity. As such, research should focus on simplifying algorithmic complexity, increasing robustness under uncertainty, and tailoring architectures to low-bandwidth environments.

Moreover, RQ4 pertains to the extraction of lessons learned from successful case studies. Notable projects in El Hierro, Nusa Penida, and Hawai'i demonstrate that 100% renewable operation is achievable through integrated planning, diversified generation, and policy alignment (Sections 3.4 and 3.5). Furthermore, more recent inclusion of very small island systems—such as Tuvalu, Kiribati, and Dominica—has highlighted the importance of simplicity, modularity, and community engagement in solution design [93–95,105–107]. While these cases offer valuable insights, comparative meta-analysis across projects remains limited, and long-term monitoring data are scarce. This underscores the need for standardized performance metrics, multi-year evaluations, and policy impact assessments that capture technical indicators and socioeconomic outcomes.

4. Discussion

4.1. Vulnerabilities in Smart Grid Technologies for Isolated Systems

While the adoption of smart grid technologies in island energy systems has provided notable advances in terms of control flexibility, real-time monitoring, and renewable energy integration, these same technologies introduce a series of critical vulnerabilities that must be carefully considered. Unlike mainland power networks, island grids typically lack redundancy, operate with limited technical infrastructure, and are more susceptible to systemic disruptions, making the potential impact of these vulnerabilities significantly more pronounced.

A primary area of concern is cybersecurity. As island microgrids become increasingly reliant on interconnected digital platforms—such as intelligent energy management systems, remote control units, and cloud-based analytics—any compromise in these layers can propagate quickly across the network. Cyberattacks targeting supervisory control and data acquisition (SCADA) systems, sensor data manipulation, or denial-of-service (DoS) incidents could disable essential services, destabilize grid operations, or result in unsafe operational conditions. In isolated systems, where technical support and response capabilities may be delayed due to geographic remoteness, recovering from such breaches is also more challenging.

Another vulnerability lies in interoperability limitations among smart grid components. Many island deployments consist of a heterogeneous mix of legacy equipment, third-party renewable energy inverters, and modern communication protocols. Incompatibilities between devices or software updates that disrupt communication standards can lead to a loss of synchronization, inaccurate data reporting, or even cascading failures. This is particularly relevant when different energy sources—such as PV arrays, BESSs, and EV charging stations—must coordinate under decentralized control strategies.

Data dependency and communication infrastructure fragility also emerge as key weaknesses. Many smart grid functions, including predictive analytics, load forecasting, and autonomous dispatching, rely on uninterrupted data streams from sensors and smart meters. In island contexts, data links may depend on low-bandwidth or unstable communication channels, making them vulnerable to interruptions caused by weather events, hardware degradation, or satellite signal loss. Without real-time data, intelligent

controllers may misjudge system states, triggering inappropriate corrective actions or system instabilities.

Over-reliance on automation represents an additional challenge. The automation of critical decision-making processes through AI-based algorithms or multi-agent systems, while advantageous in normal operation, can reduce human situational awareness and preparedness in the face of unexpected failures. In systems where human operators may not have extensive experience with digital tools, or where operational procedures are not regularly updated, the potential for misinterpretation or delayed manual intervention increases.

Finally, the issue of resilience under extreme conditions must be highlighted. Natural disasters such as hurricanes, earthquakes, or volcanic events—which are disproportionately relevant to many island geographies—can simultaneously disrupt power generation, communications, and physical access. If smart grid infrastructure is not designed with sufficient physical hardening, redundancy, and contingency planning, such events can lead to prolonged blackouts and compromise recovery efforts.

In light of these vulnerabilities, it is essential that smart grid deployment in island systems be accompanied by robust cybersecurity frameworks, standardized communication protocols, resilience-focused design criteria, and human-in-the-loop architectures that enable safe fallback modes during failures. Future research and implementation efforts must focus on the functional capabilities of smart technologies and, at the same time, rigorously assess their risk profiles and failure modes, particularly in the context of geographically constrained, resource-limited island environments.

4.2. Operational Trade-Offs in Hybrid and Multi-Vector Control Architectures

The growing complexity of island microgrids has driven the adoption of hybrid and multi-vector control architectures that combine inverter-based control, demand response mechanisms, and distributed storage coordination. While these solutions have demonstrably enhanced system reliability and flexibility, they also introduce operational trade-offs that merit further attention. For instance, the coordination of grid-forming and grid-following inverters requires precise parameter tuning and real-time synchronization, especially under rapidly changing load or generation conditions. Imbalances in such coordination can lead to control loop interactions, reduced stability margins, or suboptimal power-sharing.

Furthermore, the integration of multiple vectors—such as batteries, hydrogen, and EV-based storage—demands a sophisticated energy dispatch algorithm capable of optimizing energy balance and system economics and asset lifespan. These trade-offs are particularly evident in systems where renewable penetration exceeds 80%, as control strategies must constantly arbitrate between maximizing renewable utilization and preserving system inertia or reserve capacity. Although multi-agent control systems have been proposed to mitigate these issues, their practical deployment is still constrained by communication latency, standardization gaps, and computational overheads. Thus, a key research direction involves developing scalable and robust control frameworks that ensure optimal performance across a wide range of operating conditions without compromising the integrity of the system.

4.3. Digitalization and Predictive Analytics: Limits and Opportunities

The integration of digital twins and predictive analytics (PA) in island microgrids has opened promising avenues for proactive grid management, enabling real-time simulation, fault anticipation, and asset optimization. Nevertheless, the effective deployment of these technologies is subject to several limitations that must be acknowledged. One of the main challenges lies in data quality and granularity. Many island systems lack the dense

sensor infrastructure or high-frequency data acquisition required to train reliable predictive models. Inadequate or noisy datasets can lead to model overfitting, reduced forecasting accuracy, and misleading optimization outputs.

Moreover, the implementation of digital twins entails a significant initial investment in both hardware and computational infrastructure. For small island utilities operating under budget constraints, these costs may outweigh the perceived benefits, particularly if the return on investment is not immediate. However, as cloud-based platforms and edge computing technologies mature, there is growing potential for cost-effective deployment of lightweight digital twin applications tailored to specific functions—such as predictive maintenance of inverters or storage degradation tracking.

In parallel, the synergy between digitalization and human-in-the-loop systems represents a valuable direction. Integrating operator feedback into machine learning pipelines or using PA for decision support, rather than automation alone, can increase operator confidence and enhance situational awareness. This approach balances innovation with operational safety and highlights the importance of maintaining a human-centric perspective in future digital transition strategies for island microgrids.

4.4. Timeline-Based Synthesis of Technological Evolution in Island Energy Systems

To complement the structured results derived from the systematic review and address the dynamic evolution of technologies in island energy systems, this subsection introduces a set of three timeline-based tables that organize key developments in a chronological format. While the systematic core of this review focuses on studies published between 2014 and 2024, aligned with PRISMA 2020 guidelines, the following synthesis offers a more comprehensive temporal perspective. It includes both recent high-impact contributions and a selection of earlier foundational milestones that have shaped the trajectory of innovation in renewable integration, storage, and intelligent control systems in island contexts.

The first timeline (Figure 8) synthesizes technological advancements in renewable energy integration and storage. It highlights critical milestones such as the early adoption of ultra-capacitors in microgrids, the integration of CSP with desalination in island systems, and the growing deployment of hybrid energy storage architectures—including BESS and supercapacitors—over the past decade.

The second timeline, presented in Table 3, shifts focus to control strategies and smart grid technologies, tracing the progression from centralized control schemes to advanced implementations of distributed intelligence, digital twins, and real-time grid-forming inverter coordination. These developments have played a pivotal role in enabling flexible and resilient energy systems under conditions of high renewable variability.

Table 3. Timeline of innovations in control strategies and smart grid technologies for island microgrids.

Year	Technological Milestone
2021	Implementation of BESSs in PV-rich island grids with advanced dispatch coordination (Ku et al., [73]).
2022	Frequency control strategies using hydro–wind storage configurations in 100% RE systems (Sarasúa et al., [28]).
2022	Frequency dynamics analysis in non-synchronous island grids (Ippolito et al., [26]).
2022	Mixed centralized/distributed control architectures in Cape Verde (Pombo et al., [17]).
2023	Grid-forming converter control with real-time monitoring for resilience (Ungerland et al., [92]).
2024	Review of GFC vulnerabilities in low-inertia island systems (Aljarrah et al., [14]).
2024	Vision of resilient future grids combining renewables, storage, and power electronics (Peng et al., [8]).

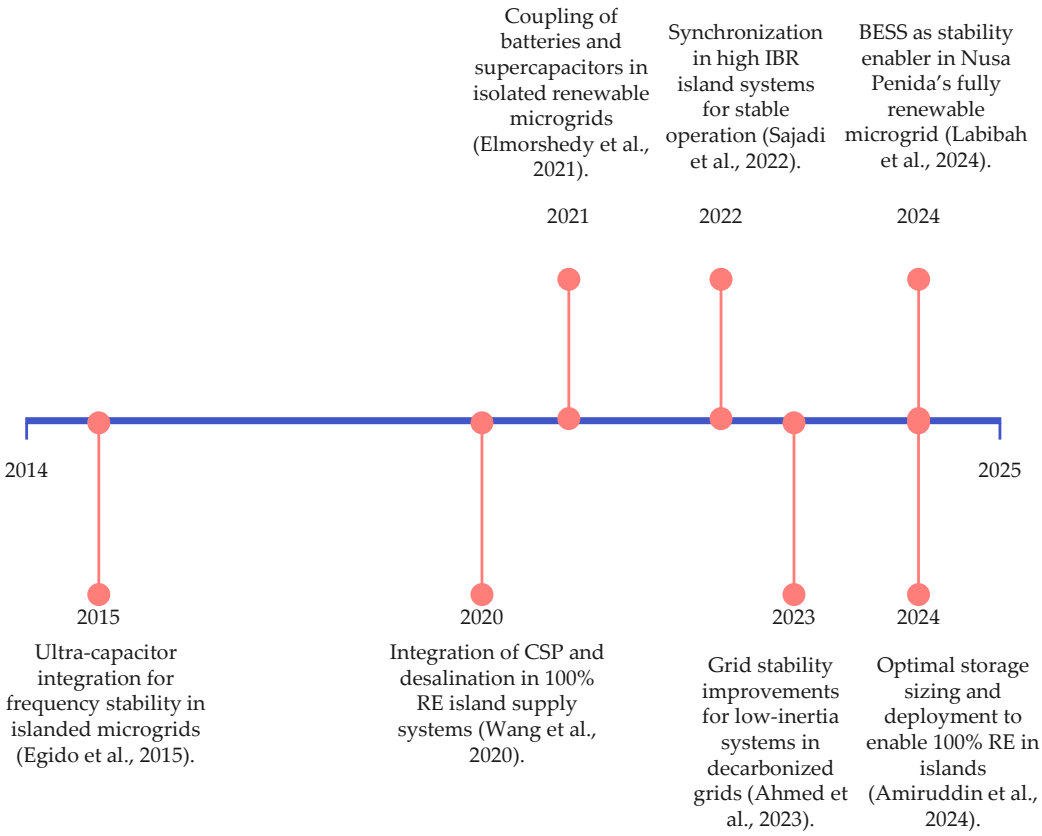


Figure 8. Timeline of technological developments in renewable energy integration and energy storage solutions in island systems.

To situate these advancements within a broader historical framework, Table 4 presents a timeline of foundational and transitional milestones spanning from 2008 to 2023. Although these references fall outside the formal inclusion criteria of the systematic review, they offer valuable context on how early pilot projects, hydrogen integration studies, and storage simulations paved the way for today's mature implementations.

Table 4. Historical and transitional milestones in the development of island energy systems.

Year	Historical or Transitional Milestone
2012	PV deployment initiatives under SIDSs programs (Rogers et al., [102]).
2013	Early hydrogen storage studies supporting wind integration in islands (Kaldellis et al., [39]).
2014	Simulation of pumped hydro energy storage feasibility in island contexts (Papaefthymiou et al., [97]).
2015	Centralized storage for frequency regulation using ultra-capacitors (Egido et al., [52]).
2017	VSG-based frequency control in microgrids for isolated applications (Wu et al., [49]).
2019	Planning models for centralized vs. decentralized energy systems in Southeast Asian islands (Bertheau et al., [24]).
2020	AI-assisted energy dispatch and EV integration in hybrid island microgrids (Dong et al., [77]).
2022	Coordinated control and predictive analytics in 100% RE microgrids (Sarasúa et al., [28]).
2023	Digital twin modeling and GFM inverter deployment for resilient island operations (Ungerland et al., [92]).

Together, these three timelines enhance the longitudinal dimension of the review by linking recent, systematically selected contributions with pivotal early-stage efforts. This layered representation underscores the cumulative and interdisciplinary nature of progress in island energy transitions, while reinforcing the relevance of technological maturity, and empirical validation in shaping sustainable off-grid systems.

5. Conclusions

This systematic review thoroughly examined the transition of island power systems to 100% renewable energy, employing the PRISMA 2020 methodology to maintain a high level of rigor and transparency throughout the selection and analysis of relevant literature. The review process started with the identification of 991 studies, followed by a systematic screening, eligibility, and inclusion process that refined this pool to 81 high-quality studies directly aligned with the research objectives. The methodological approach ensured that the included studies provided robust evidence and insights into the main challenges, strategies, and success factors associated with achieving fully renewable energy systems in island contexts.

The review identified several primary technical and operational challenges in transitioning island power systems to 100% renewable energy, mainly focusing on grid stability issues related to low inertia and the management of frequency and voltage fluctuations. The isolated nature of island grids, combined with their limited interconnectivity and high reliance on variable renewable energy sources such as wind, solar, and hydro, exacerbates these stability challenges. Studies highlighted the vulnerability of these systems to rapid fluctuations in supply and demand, with specific concerns around the capacity to maintain grid stability during dynamic events. These findings reinforced the critical need for advanced control strategies and energy management solutions tailored to the unique constraints of island power systems.

Energy storage technologies emerged as a crucial component in addressing these challenges, contributing significantly to mitigating the intermittency of renewable generation and enhancing grid reliability. BESSs, hydrogen storage, PHS, and flywheels each offer distinct advantages. BESS are widely adopted due to their fast response times and versatility in applications such as load leveling, peak shaving, and frequency regulation. Studies in Hawaii demonstrated that BESS could maintain high availability over extended periods, completing thousands of equivalent full cycles while enhancing the transient stability of microgrids. Hydrogen storage stood out for its ability to provide long-term energy storage, offering a scalable and economically viable alternative to batteries in scenarios requiring seasonal storage. The integration of hydrogen storage with renewable energy systems, as seen in the Faroe Islands and El Hierro, significantly improved system efficiency and reduced carbon emissions. PHS proved highly effective in mature island systems, offering an additional layer of stability by storing excess renewable energy and contributing to advanced frequency control. Flywheels, while primarily offering ultra-fast response for frequency support, were shown to be valuable when combined with other storage solutions, providing a holistic approach to both short-term and long-term energy stability.

Advanced control strategies and smart grid technologies were crucial in boosting the reliability, resilience, and efficiency of island microgrids. The deployment of grid-forming and grid-following inverters, decentralized control systems, and AI-based approaches were particularly notable. GFM inverters, for instance, emulate the behavior of traditional synchronous generators by providing synthetic inertia and frequency support, allowing island grids to maintain stability even under fully renewable scenarios. The integration of decentralized control systems, often enhanced by AI and machine learning algorithms, offered predictive maintenance, fault detection, and adaptive control capabilities, allowing

systems to anticipate and mitigate potential issues proactively. The review also explored the use of digital twins and predictive analytics, which provided real-time virtual representations of physical assets and enabled advanced simulations and optimizations. These technologies supported grid stability by enabling adaptive control mechanisms that preemptively addressed disturbances, thereby reducing the risks of blackouts and improving overall operational efficiency.

The analysis of real-world island case studies provided concrete evidence of how these technologies and strategies translate into practice. Successful examples included El Hierro, Hawai'i, Orcas Island, Nusa Penida, and other notable projects that showcased diverse approaches to achieving 100% renewable energy integration. These islands utilized innovative hybrid systems, advanced energy storage solutions, and strategic grid management practices, demonstrating how technology, supportive policy frameworks, and community engagement contribute to building resilient and sustainable energy systems. The practical application of these solutions underscored the potential to replicate success in other island contexts, highlighting the importance of adaptability and tailored strategies.

The research questions guiding this systematic review were effectively addressed through the synthesis of these findings. The primary technical and operational challenges were thoroughly identified, with grid stability, frequency, and voltage regulation, and energy management emerging as critical focus areas. The role of energy storage technologies in mitigating intermittency and enhancing grid stability was clearly demonstrated, mainly through the benefits of hybrid systems combining batteries, hydrogen, and PHS. Advanced control strategies and smart grid technologies were shown to offer viable solutions for maintaining system efficiency and resilience, enabling microgrids to adapt to renewable variability in real time. The review of island case studies provided practical insights into successful implementation strategies, highlighting how technology, policy, and community engagement converge to facilitate the transition to 100% renewable energy systems.

While the findings of this review demonstrate that achieving fully renewable island power systems is both technically and economically feasible, significant barriers remain. Legislative and regulatory challenges include outdated grid codes, limited financial incentives for energy storage deployment, and insufficient support for demand-side management initiatives. Economically, high initial investment costs and a lack of consistent funding mechanisms can deter the adoption of advanced technologies and the development of resilient infrastructure. Overcoming these barriers will require coordinated efforts from policymakers, industry stakeholders, and local communities to create supportive regulatory environments, develop innovative financing models, and promote broader acceptance of renewable technologies.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence.
BESS	Battery Energy Storage System.
CSP	Concentrated Solar Power.
DC	Direct Current.
DR	Demand response.
DT	Digital twins.
DERs	Distributed energy resources.
EV	Electric Vehicle.
GFM	Grid-forming.
GFL	Grid-following.
HVDC	High-Voltage Direct Current.
iEMS	Intelligent energy management system.
IBR	Inverter-based resources.
ORES	Ocean renewable energy storage.
PA	Predictive analytics.
PHS	Pumped hydro storage.
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses.
PV	Photovoltaic.
RES	Renewable energy sources.
RQ	Research question.
SIDS	Small Island Developing State.
SC	Supercapacitor.
V2G	Vehicle-to-Grid.
VDP	Voluntary Demand Participation.
VPP	Virtual Power Plant.
VSG	Virtual Synchronous Generator.

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