

Review

Decarbonizing Insular Energy Systems: A Literature Review of Practical Strategies for Replacing Fossil Fuels with Renewable Energy Sources

Paul Arévalo ^{1,2,*} , Danny Ochoa-Correa ¹ , Edison Villa-Ávila ^{1,2} , Juan L. Espinoza ¹  and Esteban Alborno ¹

¹ Department of Electrical Engineering, Electronics and Telecommunications (DEET), Faculty of Engineering, University of Cuenca, Balzay Campus, Cuenca 010107, Ecuador; danny.ochoa@ucuenca.edu.ec (D.O.-C.); eava0001@red.ujaen.es (E.V.-Á.); juan.espinoza@ucuenca.edu.ec (J.L.E.); esteban.alborno@ucuenca.edu.ec (E.A.)

² Department of Electrical Engineering, University of Jaen, EPS Linares, 23700 Jaen, Spain

* Correspondence: warevalo@ujaen.es

Abstract: The reliance on fossil fuels for electricity production in insular regions creates critical environmental, economic, and logistical challenges, particularly for ecologically fragile islands. Transitioning to renewable energy is essential to mitigate these impacts, enhance energy security, and preserve unique ecosystems. This systematic review addresses key research questions: what practical strategies have proven effective in reducing fossil fuel dependency in island contexts, and what barriers hinder their widespread adoption? By applying the PRISMA methodology, this study examines a decade (2014–2024) of research on renewable energy systems, highlighting successful initiatives such as the integration of solar and wind systems in Hawaii, energy storage advancements in La Graciosa, hybrid renewable grids in the Galápagos Islands, and others. Specific barriers include high upfront costs, regulatory challenges, and technical limitations, such as grid instability due to renewable energy intermittency. This review contributes by synthesizing lessons from diverse case studies and identifying innovative approaches like hydrogen storage, predictive control systems, and community-driven renewable projects. The findings offer actionable insights for policymakers and researchers to accelerate the transition towards sustainable energy systems in island environments.

Keywords: renewable energy; insular power systems; fossil fuel dependency; literature review



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1. Introduction

The reliance on fossil fuels for electricity in insular regions poses significant environmental, economic, and logistical challenges, particularly for fragile ecosystems. High emissions and energy insecurity threaten these regions' viability [1]. Transitioning to renewable energy is critical for combating climate change, reducing its impacts, and enhancing energy sovereignty [2]. Studies emphasize the role of renewables in achieving sustainability, with the European Union leading efforts to prioritize low-carbon technologies and improve energy efficiency [1,3,4]. Renewables' adoption in industries by major fossil fuel consumers has been identified as a key strategy for substantial carbon reduction [2].

Islands heavily depend on imported fossil fuels, making them vulnerable to price fluctuations and supply disruptions [5]. Transitioning to renewable energy sources like solar, wind, and hybrid systems can improve energy security and reduce environmental impacts, but challenges such as intermittency and high costs of storage and infrastructure

remain significant [6–10]. Technologies like batteries and hydrogen storage are critical for stabilizing renewable supply and enhancing grid reliability [11–13]. Case studies in Europe and Asia show the technical and economic feasibility of integrating solar and wind systems with storage solutions [14]. These examples demonstrate the need for tailored strategies that consider local conditions and regulatory frameworks. Social aspects are equally vital. The concept of a “just transition”, as discussed in [15], emphasizes including socio-economic dimensions, such as community involvement and labor equity, to ensure displaced workers from fossil fuel sectors benefit from renewable energy projects. Advanced energy storage systems, including supercapacitors, also play a crucial role in addressing grid challenges, requiring flexible and collaborative solutions between operators and prosumers [16].

Historical studies on energy networks [17] and the growing potential of biofuels [18] highlight the need for innovation and sustainable resource management to achieve renewable energy goals. Governments and organizations support this transition through subsidies, tax incentives, and regulatory reforms [19,20]. The environmental and economic benefits of renewables’ adoption on islands include significant greenhouse gas reductions and lower long-term energy costs [21,22]. However, high initial investments and the need for technological innovation remain barriers [23–25]. Research stresses continued development to improve efficiency and cost-effectiveness in isolated regions [26,27]. Community engagement is essential for ensuring social acceptance and maximizing benefits, including local ownership, job creation, and equitable energy access [28–32]. The “just transition” framework seeks to protect vulnerable populations during the shift to a low-carbon economy [33–35]. Then, emerging technologies, such as advanced storage solutions, smart grids, artificial intelligence, and machine learning, offer promising tools to optimize renewable integration and enhance grid resilience [36–40]. Innovations in materials and energy conversion technologies are expected to play pivotal roles in supporting sustainable energy transitions [41,42].

Although the existing literature explores the potential of renewable energy systems and technologies in insular regions, several critical gaps persist. Many studies primarily focus on specific technologies, such as solar and wind, or highlight the economic and environmental benefits of renewable energy adoption in isolated settings [6–8]. However, comprehensive analyses that evaluate the integration of multiple renewable energy sources—such as hybrid systems coupled with advanced energy storage solutions—remain limited, despite their importance for ensuring reliable and sustainable energy supply on islands [10,11,13]. Furthermore, while successful case studies exist, they often lack a detailed exploration of the strategies and contextual factors that contributed to their success. This absence of standardized frameworks for replicating these initiatives in other insular regions limits their scalability and applicability [14,16,18]. In addition, the socio-economic and regulatory challenges of transitioning to renewable energy on islands are underexplored. Research frequently emphasizes technical and financial barriers but rarely investigates the intricacies of local governance, policy enforcement, and community engagement, all of which are vital for the long-term success of energy transitions [19,21,29]. Emerging technologies, such as smart grids, artificial intelligence (AI), and digital tools for energy management, are often mentioned as promising solutions but are seldom analyzed in depth concerning their applicability and potential impact in insular settings [37,39,40]. These gaps hinder the development of holistic and context-specific strategies needed for effective energy transitions on islands.

This paper addresses these gaps by conducting a systematic and transparent review using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. It catalogs existing initiatives and identifies key success factors, including technological integration, economic feasibility, and social acceptance. By focusing on

hybrid renewable energy systems and advanced energy storage solutions—areas often overlooked in previous studies—this research offers fresh perspectives on overcoming the unique challenges of energy transitions in insular regions. Additionally, it provides actionable recommendations for policymakers, practitioners, and researchers to advance sustainable energy solutions tailored to the distinctive contexts of islands. The remainder of this paper is structured as follows: Section 2 details the methodology for the systematic review. Section 3 presents the results and discussion on renewable energy integration in insular regions. Section 4 concludes with recommendations for advancing sustainable energy transitions on islands.

2. Research Methodology

This review follows the PRISMA 2020 guidelines [43], a rigorous and structured approach 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 socio-economic analyses.

The methodology in this review follows four essential phases: 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 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, relevant studies 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. Figure 1 presents a simplified diagram of this process.

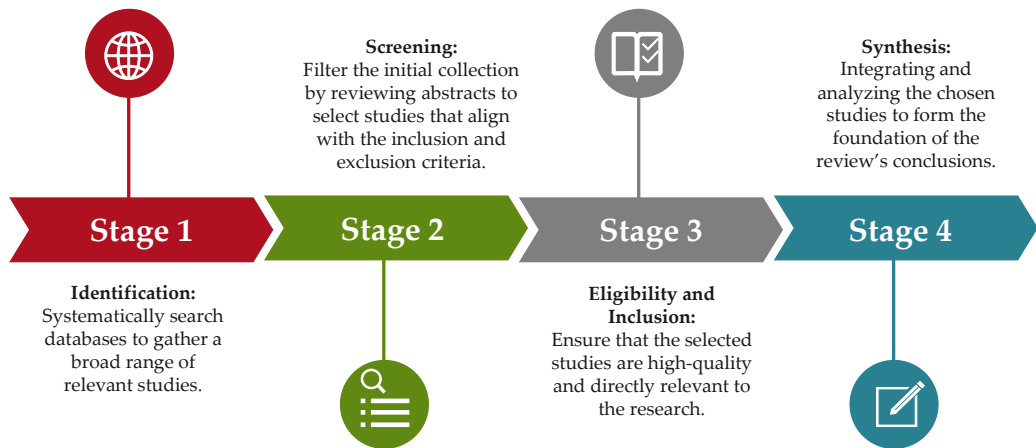


Figure 1. Simplified diagram of literature review methodology process.

2.1. Identification Phase: Databases, Search Terms’ Definitions, Duplicated Removal

In this systematic literature review, we extensively searched for relevant studies published between 2014 and 2024. The search targeted journal and conference articles with full-text access through institutional subscriptions or open access to ensure comprehensive coverage of current research trends. Publications that did not meet this study’s scope and objectives—such as editorials, review articles, book chapters, theses, white papers, and non-peer-reviewed materials—were excluded, as they often lacked the original research findings and methodologies essential for rigorous analysis.

The bibliographic resources were drawn from two leading databases: Scopus and Web of Science. With its wide-ranging multidisciplinary coverage, Scopus provides access to peer-reviewed journals, books, and conference proceedings and is known for its extensive indexing and citation data. Web of Science, similarly renowned for its selective and high-quality research articles, offers robust citation indexing, enabling comprehensive citation analysis and a broader assessment of research impact. These databases were selected for their expansive coverage and ability to support a transparent, objective, and holistic review process. By utilizing Scopus and Web of Science (WoS), we ensured that our search included works from reputable publishers such as IEEE, Elsevier, Springer, Taylor & Francis, Wiley, MDPI, and others, all recognized for their stringent peer-review standards. This approach guaranteed the inclusion of high-quality, relevant research, providing a thorough and reliable overview of advancements in decarbonizing insular energy systems.

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 WoS with a slightly different syntax.

Table 1. Literature search terms and summary of database search results.

Database	Query String	N° of Returned Documents	Removal of Duplicates	Final Sample for Screening Phase
Web of Science	(ALL = ("insular") OR ALL = ("island")) AND (ALL = ("power system") OR ALL = ("grid") OR ALL = ("microgrid")) AND ALL = ("renewable energy") 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	1044	11	1033
Scopus	TITLE-ABS-KEY (("island" OR "insular") AND ("power system" OR "grid" OR "microgrid") AND "renewable energy") AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")) AND (LIMIT-TO (LANGUAGE, "English"))	1999	827 *	1172
Total items		3043	838	2205

* WoS entries served as the reference point while identifying duplicates. As a result, whenever a Scopus item shared the same DOI as a WoS entry, the bibliographic management tool automatically removed the Scopus entry.

A 10-year timeframe was selected to capture the most recent advancements in renewable energy technologies, as innovations in this field have accelerated significantly over the past decade. By focusing on research published between 2014 and 2024, this review reflects technological developments and emerging trends in the decarbonization of insular energy systems. Limiting the search to peer-reviewed journal articles and conference papers ensured the inclusion of high-quality studies presenting original research, cutting-edge methodologies, and relevant case studies. Excluding non-peer-reviewed materials, such as editorials and book chapters, allowed this review to concentrate on publications that substantively contribute to the research objectives and offer valuable insights for future directions.

The initial search resulted in a total of 3043 items: 1044 from the WoS database and 1999 from Scopus. Given the overlap between these two extensive databases, which often share documents from the same publishers and conferences, duplicate items were common. Using bibliographic management tools, we identified and removed 838 duplicate entries. This left a final sample of 1033 items from WoS and 1172 from Scopus, resulting in a total of 2205 unique items, representing 72.5% of the original total. The 2205 unique items then proceeded to the screening phase for further evaluation. Table 1 summarizes these metrics.

2.2. Screening Phase: Inclusion Criteria Assessment—Title and Abstract Review

In the screening phase, the predefined inclusion criteria, as shown in Table 2, were rigorously applied to assess the relevance and suitability of each study identified during the identification phase. This process involved thoroughly evaluating the titles, abstracts, and relevant metadata of all 2205 items. The primary goal was to ensure that only studies that directly aligned with the research objectives were selected for further analysis.

Table 2. Inclusion criteria designed for screening literature entries.

N°	Criterion	Inclusion
1	Publication Date	Articles published between 2014 and 2024. Studies published before 2014 were excluded to ensure up-to-date information.
2	Publication Type	Peer-reviewed journal articles and conference papers. Other types of publications, such as editorials, review articles, book chapters, theses, white papers, and non-peer-reviewed materials, were excluded to ensure an original research focus.
3	Language	Articles had to be in English to maintain consistency in language and accessibility. Non-English articles were excluded.
4	Access	Only studies with full-text access via institutional subscription or open access were included to allow comprehensive analysis. Articles without full-text access were excluded.
5	Focus	Studies had to focus on renewable energy solutions in island or insular power systems, grids, or microgrids specifically aimed at replacing conventional thermal generation. Articles not centered on these topics were excluded to align with the objectives of this review.

The inclusion criteria were explicitly designed for this research to capture studies that addressed the key focus of the review. Articles published between 2014 and 2024 were included to reflect the latest advancements in the field. Only peer-reviewed journal articles and conference papers were considered to ensure the inclusion of high-quality, original research. Publications in English were chosen to maintain consistency and accessibility. Additionally, only studies with full-text access via institutional subscriptions or open access were selected to allow for comprehensive analysis.

This review targeted studies focusing on renewable energy solutions in island or insular power systems, grids, or microgrids, particularly those aimed at replacing conventional thermal generation. Articles not meeting these topics were excluded to ensure alignment with the research objectives.

During this phase, a binary assessment was conducted to determine whether each study met all the inclusion criteria. This evaluation required careful consideration of each study's relevance, scope, and quality based on its title and abstract. Only articles that fully complied with all the criteria proceeded to the next review phase. This systematic approach ensured that the final selection of studies directly aligned with the goals of this research, focusing on the high-quality, relevant literature that enhances understanding of renewable energy solutions in insular energy systems.

Based on the inclusion criteria applied during the screening phase, 100% of the screened items met criteria 1 (publication date), 3 (language), and 4 (access), while 98% satisfied criterion 2 (publication type), and 92% fulfilled criterion 5 (focus). According to the defined methodology, each item was required to meet all the inclusion criteria to proceed to the next phase. As a result, 1982 items, representing 89.9% of the total screened items, were eligible for further analysis.

The bibliometric statistics in Figure 2 reveal a significant predominance of certain publishers among the items that passed this stage. IEEE led the sample, accounting for 35.27% of the 1982 items, followed by Elsevier with 27.55% and MDPI with 12.06%. Other publishers, such as the Institution of Engineering and Technology, Wiley, Taylor & Francis Inc., and Springer, held smaller shares, ranging from 0.81% to 2.02%. This distribution highlights the dominance of IEEE, Elsevier, and MDPI in publishing research on renewable energy solutions in insular contexts, reflecting their substantial contribution to this field.

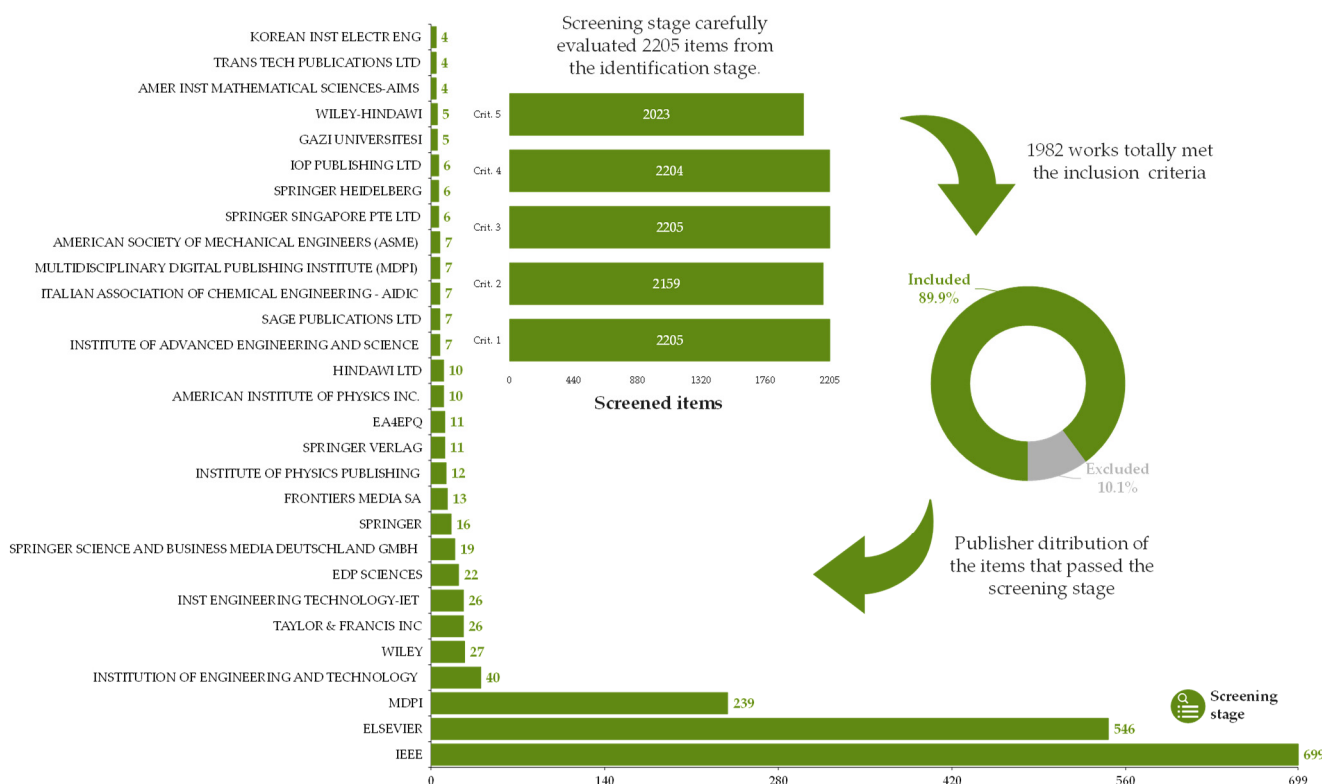


Figure 2. Overview of screening phase results.

As a preliminary measure of the relevance of the selected items, Figure 2 also shows the progression of the number of citations received by the items grouped by publication year. The figure illustrates a steady and consistent impact over the years, marking this topic as a prominent focus within the research community. Citations began at 2937 in 2014, fluctuating with peaks such as 3974 citations in 2019, and remained relatively high through to 2022. The drop in citations for 2023, with only 1022 citations, is likely due to the limited time these publications have had to accumulate citations. As of 2024, there are already 124 citations, indicating that the impact of these publications will likely increase over time. This sustained citation trend, excluding the most recent year, underscores the research's ongoing relevance and influence, further cementing its status as a key topic in the field.

While this screening phase facilitated the selection of high-quality works, a thorough review of each item's content was still necessary to confirm their relevance and value in enriching this literature review. This comprehensive evaluation was conducted in the next phase: eligibility and inclusion.

2.3. Eligibility and Inclusion Phase: Full-Text Review

The eligibility and inclusion phase was a critical step in this systematic review process, where each item that passed the screening phase underwent a comprehensive evaluation to ensure that it met the required standards of quality and relevance for inclusion in the final analysis. This phase involved a thorough examination of the full text of each study to verify its alignment with the research objectives and its contribution to the field of renewable energy solutions for insular power systems. The goal was to refine the selection further, ensuring that only the most relevant and high-quality studies were included in this review.

During this phase, each study was evaluated based on predefined eligibility criteria, with each criterion rated on a Likert scale from 1 to 3: 1 indicated moderate quality or relevance, 2 represented acceptable quality or relevance, and 3 indicated excellent quality or relevance.

The studies were assessed according to the following criteria:

1. **Relevance to Study Goals:** this assessed how well the study addressed renewable energy solutions for insular power systems, grids, or microgrids aimed at replacing conventional thermal generation.
(1: *Peripheral*; 2: *Related*; 3: *Highly Relevant*.)
2. **Methodological Soundness:** this evaluated the appropriateness and robustness of the research methodology, including the design, data collection, analysis techniques, and overall rigor.
(1: *Needs Improvement*; 2: *Acceptable*; 3: *Strong*.)
3. **Originality and Contribution:** This examined the originality of the study and its significance in advancing the field. It considered whether the study offered new insights or innovations in renewable energy for insular systems.
(1: *Minor*; 2: *Substantial*; 3: *Major*.)
4. **Data Quality and Reliability:** this assessed the accuracy, consistency, and validity of the data presented, along with transparency in data reporting.
(1: *Satisfactory*; 2: *Good*; 3: *Excellent*.)
5. **Practical Applicability:** this evaluated the potential for the study's findings to be implemented in real-world insular scenarios and whether they addressed practical challenges in the field.
(1: *Limited*; 2: *Useful*; 3: *Highly Applicable*.)
6. **Relevance to the Field:** this measured the impact of the manuscript on the scientific community, based on citation count and its potential influence on ongoing research.
(1: *Rarely cited*; 2: *Moderately cited*; 3: *Highly cited*.)

Figure 3 illustrates the verification matrix used to assess the eligibility of items in the full-text review process. Each item was evaluated against a set of predefined criteria, with scores assigned on a scale of 1 to 3 for each criterion. A score of 1 indicated moderate quality or relevance, while 3 represented excellent quality or relevance. This scoring system allowed for a thorough assessment of the studies' alignment with this review's objectives and their overall quality.

To ensure the inclusion of only the most pertinent and high-quality studies, the researchers set a minimum threshold of 14 out of 18 points. This threshold was chosen to guarantee that the selected studies strongly aligned with the research objectives and significant methodological rigor, originality, and data reliability. Studies scoring less than 14 points were excluded, as they did not meet the high standards required for this review.

N°	ID	Relevance to Study Goals	Methodological Soundness	Originality and Contribution	Data Quality and Reliability	Practical Applicability	Relevance to the Field	Total
1	WoS-0203	2	3	3	3	3	2	16
2	WoS-0097	2	3	3	1	3	3	15
3	WoS-0467	2	3	3	1	3	3	15
4	WoS-0083	3	3	3	1	3	2	15
5	WoS-0337	2	3	3	2	3	2	15
6	WoS-0384	2	3	3	2	3	2	15
7	WoS-0390	3	3	3	1	3	2	15
8	WoS-0489	3	3	3	1	3	2	15
9	WoS-0952	2	3	3	2	3	2	15
10	S-0891	3	3	3	1	3	2	15
11	S-1304	2	3	3	2	3	2	15
12	WoS-0359	2	3	3	3	3	1	15
13	WoS-0509	2	3	3	3	3	1	15
14	S-0359	3	3	3	2	3	1	15
15	S-1943	2	2	3	1	3	3	14
16	WoS-0036	3	2	3	1	3	2	14
17	WoS-0069	2	3	3	1	3	2	14
18	WoS-0160	2	3	3	1	3	2	14
19	WoS-0253	2	3	3	1	3	2	14
20	WoS-0578	2	3	3	1	3	2	14
21	WoS-0942	2	3	3	1	3	2	14
22	S-1167	2	3	3	1	3	2	14
23	S-1335	2	3	3	1	3	2	14
24	S-1665	2	3	3	1	3	2	14
25	S-1869	2	3	3	1	3	2	14
26	WoS-0283	2	2	3	2	3	2	14
27	WoS-0635	2	2	3	2	3	2	14
28	WoS-0832	2	2	3	2	3	2	14
29	WoS-0765	2	3	2	2	3	2	14
30	WoS-0010	2	3	3	2	3	1	14
31	WoS-0016	2	3	3	2	3	1	14
32	WoS-0031	3	3	3	1	3	1	14
33	WoS-0044	2	3	3	2	3	1	14
34	WoS-0126	2	3	3	2	3	1	14
35	WoS-0140	2	3	3	2	3	1	14
36	WoS-0181	2	3	3	2	3	1	14
37	WoS-0257	3	3	3	1	3	1	14
38	WoS-0263	2	3	3	2	3	1	14
39	WoS-0266	2	3	3	2	3	1	14
40	WoS-0303	2	3	3	2	3	1	14
41	WoS-0338	2	3	3	2	3	1	14
42	WoS-0358	3	3	3	1	3	1	14
43	WoS-0370	3	3	3	1	3	1	14
44	WoS-0496	2	3	3	2	3	1	14
45	WoS-0541	2	3	3	2	3	1	14
46	WoS-0579	2	3	3	2	3	1	14
47	WoS-0631	2	3	3	2	3	1	14
48	WoS-0646	2	3	3	2	3	1	14
49	WoS-0698	1	3	3	3	3	1	14
50	WoS-0745	3	3	3	1	3	1	14
51	WoS-0828	2	3	3	2	3	1	14
52	WoS-0897	2	3	3	2	3	1	14
53	WoS-0954	2	3	3	2	3	1	14
54	S-0009	3	3	3	1	3	1	14
55	S-0104	2	3	3	2	3	1	14
56	S-0177	2	3	3	2	3	1	14
57	S-0530	2	3	3	2	3	1	14
58	S-0531	1	3	3	3	3	1	14
59	S-0539	3	3	3	1	3	1	14
60	S-0596	2	3	3	2	3	1	14
61	S-0837	2	3	3	2	3	1	14
62	S-0936	2	3	3	2	3	1	14
63	S-1083	2	3	3	2	3	1	14
64	S-1092	2	3	3	2	3	1	14
65	S-1455	2	3	3	2	3	1	14
66	WoS-0015	2	3	3	2	3	1	14
67	WoS-0078	2	3	3	2	3	1	14
68	WoS-0250	3	2	3	2	3	1	14
69	WoS-0847	2	3	3	1	2	3	14
70	WoS-1018	2	2	3	3	2	2	14
71	WoS-0286	2	3	3	3	2	1	14
72	WoS-0785	2	3	3	3	2	1	14
73	S-0778	2	3	3	3	2	1	14
74	S-1941	2	3	3	3	2	1	14
75	WoS-0918	2	3	3	2	1	3	14
76	WoS-0613	3	3	3	3	1	1	14
77	WoS-0805	2	3	3	2	3	1	14
78	S-1491	2	3	3	2	3	1	14
79	WoS-0163	2	3	3	2	3	1	14
80	S-0048	2	3	3	2	3	1	14

Figure 3. Verification matrix used for assessing eligibility and inclusion criteria in full-text review.

Each study was expected to score at least 2 points per criterion, ensuring that it adequately addressed this study's focus on renewable energy solutions for insular power systems, used solid methodologies, and contributed meaningfully to advancing knowledge in the field. In addition, the selected studies needed high-quality data with appropriate transparency and accuracy, and their findings had to be practically applicable to real-world insular scenarios. The relevance of each study to the broader scientific community was also considered, as indicated by citation counts.

Through this rigorous process, 80 articles—representing 4% of the total 1982 items screened—were selected for inclusion in this systematic review. The narrowing of items achieved by this methodology was one of its primary strengths, ensuring a focused, high-impact review by filtering out less relevant studies and retaining only those that met the highest standards of quality and relevance.

2.4. Synthesis Phase: Bibliometrics and Clustering of Topics of Selected Studies

This section synthesizes the 80 articles selected during the eligibility and inclusion phase, providing a comprehensive overview of the current state of research on low-carbon thermal electricity generation in oil-rich developing countries. These articles represent a carefully curated subset of the broader literature, ensuring the inclusion of only the most relevant and high-quality studies. The selected works span various thematic areas and originate from various journals and conferences, reflecting the field's interdisciplinary nature.

As shown in Figure 4, most of the selected studies (70 out of 80) were published in journals, with the remaining 10 presented at conferences. Leading the journals' contributions was *Energy Conversion and Management*, which had 9 articles, followed by *Renewable Energy* (7 articles) and *Energy* (6 articles), indicating a strong focus on sustainability and energy management. Other significant contributions came from *Applied Energy* and *Energies* (5 and 4 articles, respectively), while journals like *IEEE Transactions on Power Systems* and the *International Journal of Hydrogen Energy* each contributed two articles, showcasing a blend of technological and environmental perspectives.

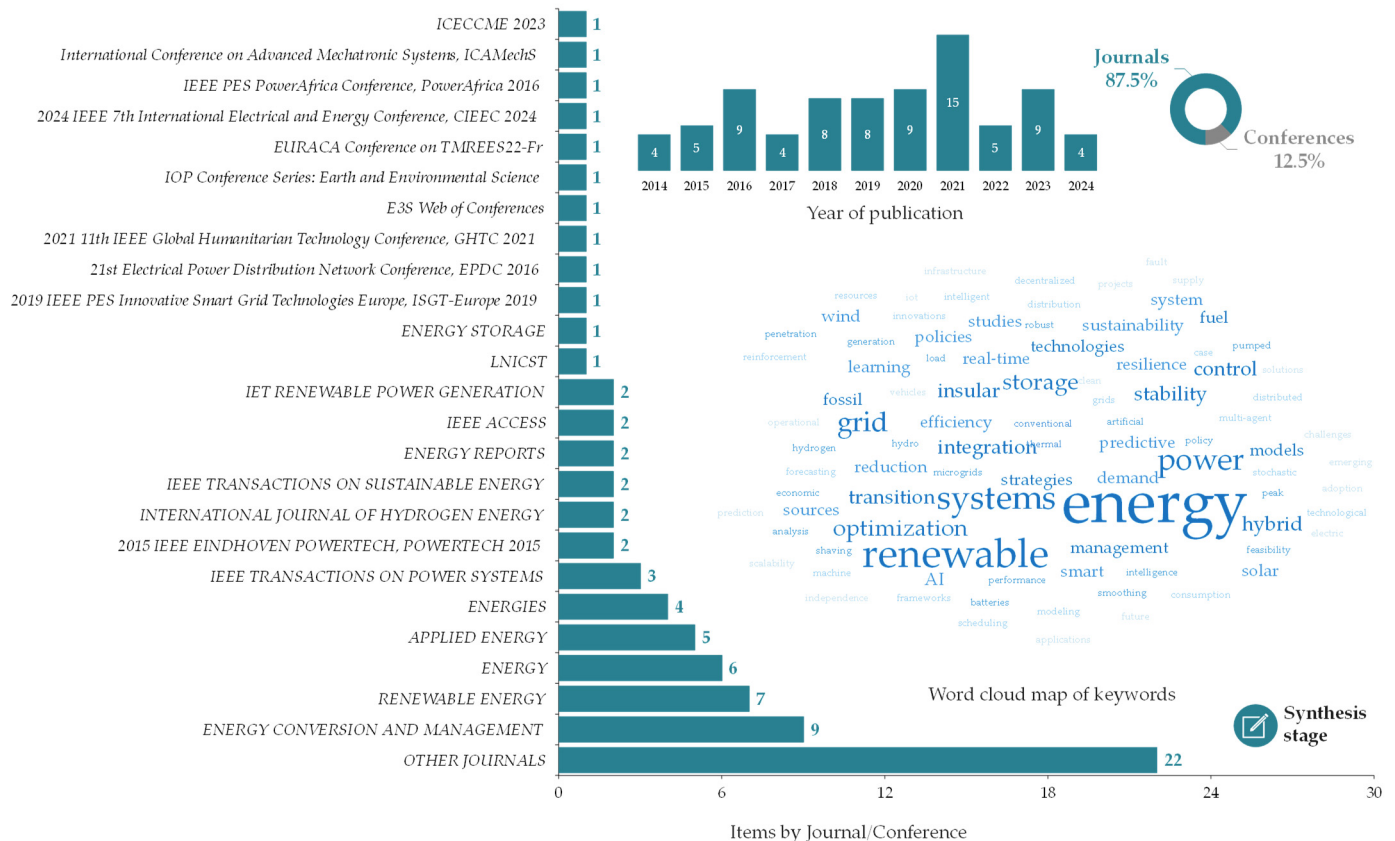


Figure 4. Bibliometrics of selected articles.

The conference proceedings emphasized the multidisciplinary approach of this research, with notable contributions from the 2021 11th IEEE Global Humanitarian Technology Conference (GHTC 2021) and the *Proceedings of the 2024 IEEE 7th International Electrical and Energy Conference (CIEEC 2024)*. Other relevant conferences included the E3S Web of Conferences and IOP Conference Series: Earth and Environmental Science, both focusing on environmental sustainability, alongside the EURACA Conference on Technologies and Materials for Renewable Energy, Environment, and Sustainability (TMREES22-Fr) and the International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME 2023), which highlighted technological advancements in renewable energy.

The distribution of selected studies over the years reflects the growing global interest in renewable energy solutions for insular power systems. Beginning with 4 studies in 2014, the number of publications gradually increased, peaking at 15 in 2020. While there was a brief decline to 5 studies in 2021, the number stabilized at 9 in 2022 and 2023. In 2024, although the year is still ongoing, four studies have already been published, indicating sustained research activity. This upward trend over the past decade underscores the increasing global emphasis on sustainable energy solutions for insular regions and the continued evolution of this important field.

Figure 4 also presents a word cloud map constructed from the keywords of the selected articles. The most frequently occurring terms prominently highlight key research themes, including “renewable energy”, “insular power systems”, and “hybrid energy systems”. Notably, terms such as “energy storage”, “grid stability”, and “optimization models” also stand out, reflecting the critical role of advanced control strategies and optimization models in managing the high penetration of renewable energy in these isolated systems. Furthermore, the word cloud underscores the importance of “transition” and “fossil fuel reduction”, indicating a significant focus on real-world examples of reducing dependence

on conventional thermal generation. Other prominent terms include “solar”, “wind”, and “AI”, suggesting that the research places considerable emphasis on integrating multiple renewable sources and leveraging artificial intelligence for enhanced system performance. These recurring themes correspond to the subthemes identified in this review, covering the current state of insular energy systems, hybrid renewable solutions, energy storage innovations, and successful case studies of fossil fuel reduction in electricity generation. This word cloud visually reinforces the core topics driving research in renewable energy for insular regions and allows for the classification of the selected articles into the following thematic subgroups:

1. **Current State of Electrical Systems in Insular Regions:** this subgroup addresses the existing infrastructure and energy mix in insular areas, focusing on challenges related to conventional thermal generation and the pathways for transitioning to renewable energy.
2. **Hybrid and Standalone Renewable Energy Systems:** research in this subgroup explores systems combining multiple renewable sources like solar, wind, and hydro, evaluating their technical feasibility, performance, and suitability for insular or off-grid contexts.
3. **Energy Storage for Integrating Renewable Energy and Reducing Thermal Generation:** this subgroup focuses on various energy storage technologies, such as batteries and pumped hydro, essential for balancing load demands, stabilizing renewable energy supply, and reducing reliance on fossil fuels.
4. **Advanced Control Strategies and Optimization Models:** articles in this subgroup examine control strategies and optimization models, including using artificial intelligence and machine learning, to manage the high penetration of renewable energy while maintaining system stability and efficiency.
5. **Impact of Renewable Energy Penetration on Grid Stability:** research here explores the challenges posed by integrating renewable energy into power grids, focusing on strategies to enhance grid stability and resilience in response to the variable nature of renewable sources.
6. **Successful Cases of Reducing Fossil Fuel Dependence:** this subgroup highlights case studies where insular regions have effectively reduced their reliance on fossil fuels, providing real-world examples and strategies that can be replicated in other regions.

The entire details of this systematic literature review process are summarized in the flow diagram shown in Appendix A.

3. Results and Discussion

Based on this literature review, several case studies were identified focusing on insular energy systems across a wide range of islands globally, as shown in Figure 5. These studies reveal significant diversity in the geographic distribution and the number of articles dedicated to each island. Notably, Greece stands out, with Crete [44,45] being the subject of four studies, and Milos [46] is also featured in one. Jeju Island [47] has also been the subject of four studies in Korea [48], exploring its renewable energy challenges and solutions.

Ecuador has two islands, Baltra–Santa Cruz (two separate islands electrically interconnected) [49,50] and San Cristobal Island [51,52], each with two articles, reflecting the country’s focus on sustainable energy for the Galápagos. Spain is represented by La Graciosa [53,54] (two articles) and Tenerife [55] and Gran Canaria [56], with one article each, showing a broad interest in the Canary Islands’ energy transitions [57]. In France, La Réunion [58,59] and Ushant Island [60] each have two articles and one article, respectively, focusing on renewable energy integration. Other regions, like Iran with Kish Island [61,62] (two articles), the Philippines with the Talaud Islands [63,64] (two articles), and Indonesia

with Bali [65] and Java [66] (one article each), highlight the widespread research into renewable energy solutions across Southeast Asia. Australia is represented by Bruny [67] and Flinders [68] Islands, with one article for each. In Italy, Sardinia [69], Sicily [70], and Favignana Island [71] each feature in studies focusing on energy system innovations. Additionally, Portugal is represented by Porto Santo [72] and Terceira [73] Island, while Croatia features Korcula [74] and Vis [75], each with one article. Smaller and more remote islands, such as Fernando de Noronha in Brazil [76], Ometepe Island in Nicaragua [77], and Rakiura/Stewart Island in New Zealand [78], also appear in the literature, highlighting the global interest in transitioning these isolated systems to more sustainable energy models. Similarly, a case study [79] on K Island in the Taiwan Strait optimized a wind-PHS hybrid system, significantly reducing diesel consumption and demonstrating the potential of PHS to support renewable energy in remote locations. Thailand: Research [80] has examined the lifecycle assessment (LCA) of vertical- and horizontal-axis wind turbines in Thailand, finding that installations in Chiangmai are more reliable than those in Phuket and Surat Thani. Moreover, Koh Samui, Thailand: Hybrid renewable systems combining solar PV, wind, fuel cells, and battery storage achieved 89% energy from solar PV while meeting a 104 MW peak load [81].

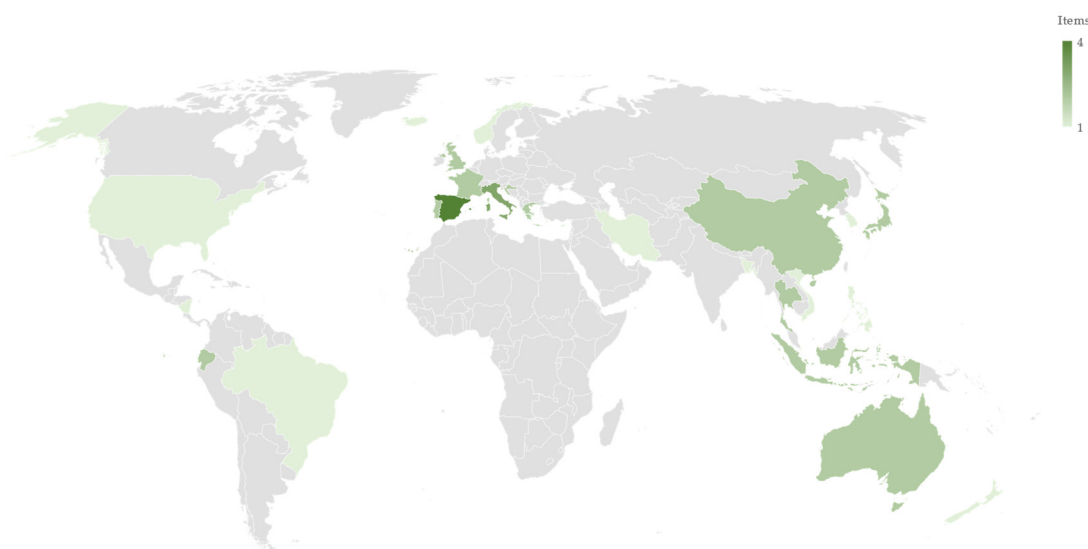


Figure 5. Geographic distribution of insular energy systems featured in selected studies.

3.1. Current State of Electrical Systems in Insular Regions

Here, we present a concise categorization of various insular electricity systems, highlighting their installed capacities, levels of renewable integration, infrastructure sophistication, and the nature of local demand. This overview provides a framework to understand each island's unique context and progress toward reducing fossil fuel reliance.

3.1.1. Large Islands with Developed Infrastructure and/or Interconnection to Larger Grids

These islands have substantial installed capacity, higher electricity demand, advanced infrastructure, and, often, submarine cable interconnections. This setup eases the integration of renewables and reduces exclusive reliance on diesel.

- Crete (Greece): wind, ~200 MW; solar, ~90 MW; historically diesel/HFO-based, now adding renewables and planning mainland interconnection. Demand: residential, tourism, and commercial.
- Sicily (Italy): wind and solar > 5000 MW combined; connected to the mainland grid, transitioning from oil/gas to renewables. Demand: residential, tourism, and industry.

- Sardinia (Italy): wind and solar > 2000 MW combined; connected via HVDC to the mainland, reducing coal use. Demand: residential, tourism, and industry.
- Cyprus (Cyprus): wind, ~175 MW; solar, ~476 MW; originally oil-fired, now integrating solar/wind and exploring gas/battery storage. Demand: residential, tourism, and commercial.
- Hawaii (USA): solar, 1808 MW; wind, 236 MW; reducing oil imports, aiming for 100% renewables by 2045. Demand: residential, tourism, and commercial.
- Bali (Indonesia): solar/wind/micro-hydro, ~50–100 MW; part of the Java–Bali grid, shifting from coal/gas to more renewables. Demand: residential, tourism, and commercial.
- Canary Islands (Spain): wind, 645 MW; solar, 234 MW; diesel/gas turbines, 2395 MW; an archipelago with isolated grids improving storage and renewables. Demand: residential, tourism, and commercial.
 - Gran Canaria: wind, 228 MW; solar, 114 MW; a mix of diesel/gas. Demand: residential, tourism, and commercial.
 - Tenerife: wind and solar in hundreds of MW; diesel/gas backup. Demand: residential, tourism, and commercial.
- La Réunion (France): a mix of diesel/coal and ~40% renewables (solar, wind, hydro, biomass); increasing renewables. Demand: residential, tourism, and agriculture.
- Hokkaido (Japan): wind, >2000 MW; solar, ~337,471 MW (prefecture-wide); connected to the main grid, adding renewables. Demand: residential, commercial, and industrial.
- Barry Island (Wales, UK): fully connected to the UK grid, with no standalone system. Demand: residential, tourism, and commercial.
- Java (Indonesia): large multi-GW coal/gas-based system, with a growing but still small renewable share. Demand: residential, commercial, and industrial.

3.1.2. Medium-Sized Islands with Hybrid Systems Undergoing Energy Transition

These islands have moderate demand and rely on hybrid setups. They mix diesel with renewables and often employ storage to stabilize supply.

- Jeju Island (South Korea): wind, ~295 MW; solar, ~525 MW; integrating battery storage and smart grids. Demand: residential, tourism, and commercial.
- Porto Santo Island (Portugal, Madeira): wind, 0.66 MW; solar, 1 MW; diesel, 32 MW; reducing fossil fuels via storage. Demand: residential and tourism.
- San Cristobal Island (Ecuador, Galápagos): wind, 2.4 MW; solar, 1.04 MW; diesel, 5.97 MW; a hybrid system protecting a fragile ecosystem. Demand: residential, tourism, and local services.
- Fernando de Noronha (Brazil): solar, ~400 kW+; reducing diesel use with PV and storage. Demand: residential and tourism.
- Flinders Island (Australia): wind, ~0.9 MW; solar, ~0.2 MW + battery storage; pioneering in diesel reduction. Demand: residential and local services.
- Ushant Island (France): tidal, 250 kW; solar, 480 kW; wind, ~1 MW; pilot projects to cut diesel. Demand: residential and tourism.
- Milos (Greece): wind, 2650 kW; MW-scale solar; transitioning from diesel. Demand: residential and tourism.
- Favignana Island (Italy): small-scale solar PV; shifting from diesel to renewables with storage. Demand: residential and tourism.
- Ometepe Island (Nicaragua): kW-scale solar/wind; diesel backup; community-driven diesel reduction. Demand: residential and local services.
- Terceira Island (Portugal, Azores): wind, several MW; diesel and some geothermal; adding storage to reduce fossil fuels. Demand: residential and tourism.

3.1.3. Small Islands with Limited Electrical Infrastructure and Pilot Projects

These islands have lower demand and rely heavily on diesel. Renewable integration is in an early, pilot stage, often with small-scale solar/wind power and with limited storage.

- Baltra–Santa Cruz (Ecuador, Galápagos): wind, ~2.25 MW; solar, ~1.5 MW; diesel, 5.68 MW; hybrid but small-scale. Demand: residential, tourism, and local services.
- La Graciosa (Spain): solar PV pilot projects; relies on cables from Lanzarote, aiming for partial self-sufficiency. Demand: mainly residential and tourism.
- Talaud Island (Philippines): diesel-based; small solar PV pilot projects are reducing dependency. Demand: residential and local services.
- Kish Island (Iran): diesel/natural gas, limited solar PV pilot projects. Demand: tourism, residential, and commercial.
- Bruny Island (Australia): diesel backup with community solar and battery trials. Demand: residential and tourism.
- Con Dao Island (Vietnam): diesel-based; pilot solar/wind integration. Demand: residential, tourism, and local services.
- Hengsha Island (China): pilot microgrids (solar, wind, diesel, and some storage). Demand: residential and local services.
- K Island (Kinmen, Taiwan): diesel-based; a small amount of solar/wind; storage trials. Demand: residential and tourism.
- Koh Samui (Thailand): a tourism island with mainland cables and some solar. Demand: residential and tourism.
- Korcula (Croatia): mainland cables with some solar; historically diesel. Demand: residential and tourism.
- Kutubdia Island (Bangladesh): historically diesel; solar mini-grids are improving access. Demand: residential and local services.
- Phuket and Surat Thani Island (Thailand): mainland connections; a small amount of solar. Demand: residential, tourism, and commercial.
- Rakiura/Stewart Island (New Zealand): diesel-based; exploring solar/wind. Demand: residential, tourism, and small services.
- Teuri and Yagishiri (Japan): diesel with pilot solar/wind/battery projects. Demand: residential and local fishing communities.
- Vis (Croatia): diesel-based; 3.5 MW solar PV is integrated. Demand: residential and tourism.

3.1.4. Islands Fully Integrated into Larger Grids or Almost 100% Internally Renewable

These cases are either fully interconnected to a larger grid, minimizing isolation constraints, or have nearly eliminated fossil fuels through abundant renewables.

- Iceland: hydro, 2.11 GW; geothermal, 755 MW; nearly 100% renewable. Demand: residential, commercial, and industry.
- Orkney Islands (Scotland, UK): wind, 50.62 MW; solar, 1.4 MW; tidal/wave > 100 MW; grid-connected with surplus renewables. Demand: residential, tourism, and commercial.

3.1.5. Key Technical Aspects of the Identified Island Systems

- Hawaii, USA: Studies [82,83] highlight Hawaii's dependency on imported fossil fuels to meet energy demands, resulting in some of the highest electricity costs in the United States. The state's grid instability and aging infrastructure pose significant challenges to integrating renewable energy sources like solar and wind. Efforts to transition to renewables are hampered by the need for substantial infrastructure upgrades and the intermittency of renewable energy sources.

- Hong Kong, China: Research [84,85] indicates that Hong Kong faces similar difficulties. Despite initiatives to integrate solar and wind power, the region remains heavily reliant on fossil fuels due to outdated grid systems and the logistical difficulties of supporting renewable energy in a densely populated urban setting. Studies [62] further emphasize the city's energy system vulnerabilities due to its heavy reliance on external fuel supplies.
- Sicily, Italy: Sicily's reliance on fossil fuels, particularly diesel, for electricity generation remains strong, especially in off-grid areas. Studies [70,74] demonstrate that while the island has potential for solar and wind energy, infrastructural and financial barriers have slowed the transition. Renewable energy projects remain in pilot stages, and the high costs of importing renewable energy technologies add to the challenges.
- La Graciosa, Spain: On La Graciosa, efforts to transition to renewable energy are still in their infancy. Research [53,68] shows that solar energy has been integrated into the island's energy mix, but progress is limited by an outdated electrical grid and the high costs of implementing renewable energy projects. Diesel generators continue to play a critical role in meeting energy demand during periods of low solar output.
- Jeju Island, Korea: Jeju Island has made progress toward integrating wind and solar power into its energy system. However, studies [76,86,87] reveal that grid instability remains a major challenge due to the lack of modern energy storage solutions and smart grid infrastructure. Despite these challenges, Jeju is seen as a model for renewable energy adoption in insular regions.
- **Crete, Greece:** Crete has emerged as a significant study location for assessing the potential of innovative renewable energy strategies. Research [88] highlighted the benefits of integrating load shifting (LS) to reduce generation costs and optimize the energy mix in large insular power systems. By using real-world data from Crete, the study demonstrates how LS can enhance system flexibility and reduce the cycling of power generation units, particularly in systems with high shares of renewable energy sources (RES). Additionally, Crete's focus on smart campus microgrids is explored in [44], which examines the Hellenic Mediterranean University's (HMU) implementation of a microgrid system. This system, featuring PV arrays, wind turbines, battery storage, and EV chargers, not only reduces the load on the main grid but also acts as an RES producer, improving grid adequacy and promoting the island's decarbonization efforts. The study underscores Crete's potential as a model for sustainable energy transitions in regions with high RES capacities and research-focused communities.
- Thailand: Research [80] has examined the lifecycle assessment (LCA) of vertical- and horizontal-axis wind turbines in Thailand, finding that installations in Chiangmai are more reliable than those in Phuket and Surat Thani. Vertical-axis turbines are more energy- and emission-intensive, but strategies like material reuse or using fiberglass can reduce embodied energy and environmental impacts by over 50%. These findings underscore the potential for localized solutions to improve wind energy sustainability in developing regions.
- Portugal—Porto Santo Island: Research [72] highlights the role of battery electric vehicles (EVs) in integrating renewable energy into isolated microgrids. A case study on Porto Santo Island analyzed real-world charging data from 20 EVs, revealing a preference for home charging and flexible overnight charging patterns. Using linear optimization models, the study found that smart charging could increase the share of renewable energy used for EV charging to 33%, reducing CO₂ emissions and enhancing grid efficiency. This showcases the potential of EVs and smart charging as tools for sustainable energy transitions in island communities.

- Rakiura/Stewart Island, Aotearoa/New Zealand: Research [78] explored the design of a standalone multi-carrier energy microgrid (MECM) tailored to the electricity, heating, and transportation fuel needs of Rakiura/Stewart Island. The proposed system integrates solar PV, wind turbines, hydrogen storage, a hybrid supercapacitor/battery system, and other components to optimize off-grid energy delivery. Using a meta-heuristic optimization algorithm, the study found that this innovative MECM could reduce electricity costs by 54% compared to the current diesel-based system. The solution also provides a cost-effective, resilient platform to support heating and transportation needs, demonstrating the viability of decentralized energy systems for remote communities.
- Sardinia, Italy: Research [69] examined the impact of electric mobility on regional infrastructure using Sardinia as a case study. By modeling the mobility patterns of 700,000 vehicles and the charging behavior of electric vehicle owners, the study found that Sardinia's current renewable energy production could sustain commuter mobility even with a complete transition to electric vehicles. Network theory identified key mobility hubs, revealing imbalances caused by the spatial segregation of energy production and consumption areas. The findings highlight the need for strategic planning to install renewable energy plants near high-demand regions, ensuring a balanced and efficient energy system to support the island's transition to electric mobility.
- **Cyprus:** The case of Cyprus provides a significant example of achieving grid parity in insular energy systems. Research [82] highlighted how the rapid decline in solar photovoltaic (PV) costs has accelerated the timeline for achieving grid parity. This study examined variations in manufacturing costs, energy selling prices, and solar panel performance, concluding that achieving grid parity in insular systems is more feasible due to the typically higher cost of primary energy. The findings suggest that solar energy can already compete with traditional grid-supplied electricity on islands like Cyprus, presenting a strong case for scaling renewable energy projects in similar contexts.
- **Fernando de Noronha, Brazil:** Fernando de Noronha demonstrates significant photovoltaic potential through innovative assessment methods. Research [76] using aerial photogrammetry and solar irradiation modeling found that 83.3% of rooftops were viable for PV installations, with 80% and 60% receiving irradiation levels above 1600 kWh/m² and 2000 kWh/m², respectively. Decentralized PV systems could supply 66% to 199% of the island's projected 31 GWh annual energy consumption by 2031, offering a sustainable alternative to its diesel-based power plant. This cost-efficient approach highlights the role of geospatial tools and UAVs in advancing renewable energy in remote islands.
- **Froan Islands, Norway:** The Froan Islands exemplify the potential of renewable hydrogen-based energy storage systems in off-grid applications. Research [89] conducted a lifecycle environmental analysis comparing a hydrogen-based system under the European REMOTE project to diesel-based and submarine cable scenarios. The hydrogen system resulted in significantly lower emissions (148.2 kgCO₂eq/MWh) compared to diesel (1090.9 kgCO₂eq/MWh) and proved to be the most cost-effective solution for providing electricity to the remote community. Sensitivity analysis demonstrated that local conditions, such as the CO₂ intensity of the electricity and cable length, strongly impact outcomes, highlighting the adaptability and sustainability of hydrogen systems for insular microgrids.
- Tenerife, Spain: Research [55] examined wave energy integration into Tenerife's power system, using simulations to assess frequency impacts over a year. The findings showed that wave energy's oscillatory nature can cause over-frequency events, es-

pecially at high penetration levels. Energy storage systems are proposed as effective solutions to mitigate frequency deviations and ensure grid stability, highlighting their importance for renewable integration in isolated grids.

- Terceira Island, Azores (Portugal): Research [73] evaluated short-term frequency control in isolated power grids with increasing renewable energy penetration. Using an analytical model incorporating synthetic inertia and primary frequency control for wind power plants, the study estimated frequency responses in future insular scenarios. Verified with real data from Terceira Island, the findings highlighted the effectiveness of these control schemes in maintaining grid stability as renewable energy integration grows.
- Ushant, France: Research [60] introduced a methodology for assessing reliability and power flow in island power networks with limited data, aimed at supporting energy transitions from fossil fuels to renewables. Applied to Ushant, the study evaluated the current grid performance and compared diesel-based operations to renewable scenarios. Results highlighted improved system reliability and network planning benefits when integrating renewable energy, offering actionable recommendations for sustainable island energy systems.
- Aero, Denmark, and Vis, Croatia: Research [75] evaluated multi-vector energy communities (MECs) for decarbonizing energy islands using mixed-integer linear programming. Results showed that electric heat pumps and battery storage enhance self-sufficiency but are limited by high costs. Hydrogen storage offers potential for seasonal energy needs but remains expensive, while natural gas provides a low-cost transitional option without meeting environmental goals. Geographic factors favor wind energy in Aero and solar energy in Vis, highlighting the importance of tailored solutions for energy transitions.

3.1.6. Key Findings on the Challenges and Opportunities of Insular Electrical Systems

Island energy systems present diverse challenges and opportunities for renewable energy integration. In Hawaii, USA [82,83], heavy reliance on imported fossil fuels results in high energy costs and grid instability, with outdated infrastructure hampering renewables' adoption. Similarly, Hong Kong, China [84,85], struggles with fossil fuel dependency due to aging grids and urban density, leaving it vulnerable to external energy supply risks. Sicily, Italy [70,74], and La Graciosa, Spain [53,68], showcase the potential of solar and wind energy, but financial and infrastructural barriers limit progress, with diesel generators still playing a significant role. Innovative solutions are emerging in locations like Fernando de Noronha, Brazil [76], where PV installations could supply up to 199% of the island's projected energy needs by 2031. In Crete, Greece [44,88], load-shifting strategies and smart microgrids reduce costs and improve energy mix flexibility, promoting decarbonization. Porto Santo, Portugal [72], highlights the role of electric vehicles (EVs) in renewable integration, with smart charging increasing renewable usage for EVs by up to 33%.

Emerging technologies like hydrogen-based systems are gaining traction on islands such as Froan, Norway, and Aero, Denmark [75], offering sustainable and adaptable storage solutions. Similarly, Tenerife, Spain [55], explores wave energy integration, proposing energy storage to mitigate grid frequency challenges. Terceira Island, Azores [73], demonstrates the effectiveness of synthetic inertia and primary frequency control for wind power plants in maintaining grid stability. Strategic planning for renewable deployment is emphasized in Sardinia, Italy [69], where mobility hubs are identified to balance production and consumption. Tailored microgrid designs on Rakiura/Stewart Island, New Zealand [78], and Ushant, France ([60]), showcase the potential of decentralized systems to improve

reliability, reduce costs, and meet diverse energy demands. These findings underscore the importance of localized strategies and advanced technologies in achieving sustainable energy transitions in island communities.

The long-term sustainability and scalability of these solutions require careful consideration. Battery storage systems, critical for islands like La Graciosa [53,68], Sardinia [69], and Porto Santo [72], face challenges such as material scarcity, environmental impact, and disposal. Reliance on lithium may cause supply chain issues, while improper disposal risks contamination. Recycling and reuse strategies, like those in Crete's microgrid systems [44], could mitigate these issues.

Hydrogen-based systems in the Froan Islands and Aero [75] offer potential for seasonal storage but require advancements in production efficiency and cost reduction. Wave energy in Tenerife [55] and synthetic inertia on Terceira Island [73] must overcome economic and technical barriers for broader adoption. Modular expansions, as demonstrated in Crete [88] and Fernando de Noronha [76], could support scalable, sustainable renewable systems in insular regions.

3.1.7. Case-Specific Insights into Insular Electricity Generation and Grid Infrastructure

- Hawaii, USA: Reliance on imported fossil fuels and outdated infrastructure pose significant challenges to Hawaii's renewable energy transition. High electricity costs and grid instability highlight the need for substantial infrastructure upgrades and energy storage solutions to support solar and wind integration [82,83].
- Hong Kong, China: Despite initiatives to incorporate solar and wind energy, Hong Kong remains dependent on fossil fuels due to aging grid systems and logistical difficulties in densely populated areas. The region's energy vulnerabilities stem from reliance on external fuel supplies [62,84,85].
- Sicily, Italy: While Sicily has strong potential for solar and wind energy, high costs and infrastructural limitations have delayed the transition. Diesel generators still dominate off-grid areas, and renewable projects remain in pilot phases [70,74].
- La Graciosa, Spain: Renewable energy efforts are nascent, with solar power integrated into the energy mix. However, outdated electrical grids and high implementation costs continue to hinder progress, leaving diesel generators critical for meeting demand during low solar output [53,68].
- Fernando de Noronha, Brazil: with 83.3% of rooftops viable for PV installations, decentralized photovoltaic systems could provide up to 199% of the island's annual energy needs by 2031, significantly reducing reliance on diesel and promoting sustainability [76].
- Crete, Greece: Innovative strategies like load-shifting and smart microgrids improve flexibility and reduce costs in Crete's energy systems. These efforts, including microgrid implementations at the Hellenic Mediterranean University, position Crete as a model for decarbonization in regions with high renewable energy capacity [44,88].
- Porto Santo, Portugal: The smart charging of electric vehicles demonstrates significant potential for renewable integration. By optimizing charging behavior, renewable energy use for EVs increases to 33%, reducing emissions and improving grid efficiency [72].
- Rakiura/Stewart Island, Aotearoa/New Zealand: a multi-carrier microgrid integrating solar PV, wind turbines, and hydrogen storage reduced electricity costs by 54%, demonstrating the feasibility of decentralized systems for meeting diverse energy needs in remote communities [78].

- Sardinia, Italy: Modeling commuter mobility revealed that Sardinia's renewable energy capacity could sustain a full transition to electric vehicles. Strategic renewable plant placement is critical to balance production and consumption [69].
- Tenerife, Spain: Wave energy integration offers potential benefits but poses challenges for grid stability. Energy storage systems are recommended to mitigate frequency deviations caused by wave energy's oscillatory nature [55].
- Terceira Island, Azores (Portugal): Synthetic inertia and primary frequency control in wind power plants effectively stabilize grids with high renewable penetration. These control schemes are crucial for future renewable scenarios [73].
- Ushant, France: Reliability and power flow assessments of Ushant's grid underline the advantages of renewable energy over diesel-based systems. Renewable scenarios improve system reliability and offer actionable recommendations for transitioning to sustainable energy [60].
- Aero, Denmark, and Vis, Croatia: Multi-vector energy communities highlight diverse solutions, with wind energy favored in Aero and solar energy in Vis. Hydrogen storage shows promise for seasonal needs, while electric heat pumps and battery storage enhance self-sufficiency despite high costs [75].

3.1.8. Policy Frameworks, Governance, and Social Considerations

The transition to renewable energy in insular regions hinges on effective policies, governance, and community involvement. In Hawaii, the Renewable Portfolio Standard (RPS) mandating 100% renewable energy by 2045 has driven investments in solar, wind, and energy storage technologies while ensuring grid reliability [82,83]. Similarly, European Union directives have supported renewable initiatives in Sicily and Crete, enabling innovative solutions like smart microgrids and load-shifting strategies [70,88]. Addressing social resistance is also crucial. For example, Jeju Island overcame opposition to offshore wind projects through transparent communication and stakeholder involvement, setting a precedent for balancing ecological concerns with renewable goals [76,87]. In Porto Santo, community engagement in electric vehicle projects has optimized renewable energy adoption and increased public acceptance [72].

3.2. Hybrid and Standalone Renewable Energy Systems

3.2.1. Overview of Hybrid and Standalone Renewable Energy Systems in Insular Contexts

Hybrid and standalone renewable energy systems have emerged as practical solutions for insular regions aiming to reduce their dependence on fossil fuels [90]. Hybrid systems typically combine multiple renewable energy sources, such as solar, wind, and bioenergy, with energy storage solutions like batteries or hydrogen storage. These systems are precious on islands, where energy security is a concern due to their geographic isolation and reliance on imported fossil fuels [91,92]. The hybrid approach helps mitigate the intermittency of individual renewable energy sources, making energy supply more reliable and sustainable [93,94].

3.2.2. Study Locations: Examining Hybrid and Standalone Energy Systems Across Islands

- Hong Kong, China: Studies [84,85] highlight the implementation of hybrid solar and wind energy systems in Hong Kong. While Hong Kong's dense urban environment challenges renewable energy integration, hybrid systems provide a more stable energy supply by utilizing complementary renewable sources. Despite this, grid instability and outdated infrastructure remain significant hurdles in achieving widespread renewable energy adoption.
- Flinders Island, Australia: Flinders Island has successfully implemented hybrid renewable energy systems integrating solar, wind, and energy storage technologies.

Research [68] shows that the hybrid system has significantly reduced the island's reliance on diesel generators, lowering fuel consumption and carbon emissions. Flinders Island is a leading example of how hybrid renewable systems can be effectively deployed in insular regions.

- **Java, Indonesia:** In Java, Indonesia, hybrid systems combining solar, wind, and biogas have been deployed in rural areas to provide off-grid solutions. Studies [66] demonstrate that these hybrid systems have helped increase energy access in remote communities while reducing dependency on fossil fuels. Integrating biogas offers an additional layer of reliability, particularly in agricultural regions.
- **Ometepe Island, Nicaragua:** Ometepe Island is another example of the successful deployment of hybrid renewable energy systems. The island's system, combining solar and wind energy with battery storage, has improved energy reliability and reduced reliance on diesel [77]. This approach has lowered emissions and reduced energy costs for the island's inhabitants.
- **Con Dao Island, Vietnam:** Con Dao Island in Vietnam illustrates the potential of isolated microgrids in remote areas. Research [95] highlighted a hybrid system design integrating PV systems, batteries, and diesel generators to meet a 60 kW peak load demand. Using HOMER (v5.1) software, the study demonstrated how hybrid systems can provide a reliable and economically practical power source for areas where grid extension is infeasible due to geographical constraints. Sensitivity analyses further validated the design's adaptability to local conditions, emphasizing its feasibility for electrifying isolated regions with sustainable energy solutions.

3.2.3. Key Findings on the Performance and Viability of Hybrid and Standalone Systems

Hybrid renewable energy systems demonstrate significant potential for improving energy reliability and reducing fossil fuel dependency in diverse settings. In Hong Kong, hybrid solar and wind systems offer a more stable energy supply in the dense urban environment, though outdated infrastructure and grid instability remain barriers to widespread adoption [84,85]. Flinders Island, Australia, serves as a model for hybrid renewable systems, with the integration of solar, wind, and storage technologies dramatically reducing diesel reliance, fuel consumption, and carbon emissions [68]. Similarly, Ometepe Island, Nicaragua, has achieved greater energy reliability and cost reductions by combining solar and wind energy with battery storage, minimizing the use of diesel generators [77]. In Java, Indonesia, hybrid systems incorporating biogas alongside solar and wind have increased energy access in rural areas, particularly in agricultural regions, where biogas enhances system reliability [66]. On Con Dao Island, Vietnam, hybrid microgrids with PV systems, batteries, and diesel generators effectively address the energy needs of remote regions, demonstrating adaptability and cost-effectiveness through sensitivity analyses [95].

Hybrid renewable energy systems hold promise for long-term sustainability, but challenges remain regarding scalability and environmental impacts. For instance, battery storage systems, as seen on Flinders Island [68] and Ometepe Island [77], must address issues such as the availability of raw materials like lithium, disposal challenges, and recycling inefficiencies. Incorporating circular economy practices, such as enhanced recycling and reuse technologies, could mitigate these impacts. Biogas integration, as demonstrated in Java [66], offers a renewable and scalable solution by utilizing local agricultural waste. However, ensuring consistent feedstock availability and minimizing methane emissions will be critical for its long-term viability. On Con Dao Island, Vietnam [95], hybrid systems' adaptability and scalability depend on reducing the high initial costs of components such as PV systems and diesel generators. Modular hybrid system designs could enhance economic feasibility and facilitate incremental expansions in similar remote regions.

3.2.4. Case-Specific Insights from Islands Utilizing Hybrid and Standalone Renewable Technologies

- Hong Kong, China: Hybrid solar and wind systems provide a stable energy supply despite the challenges of dense urban environments. However, outdated infrastructure and grid instability remain significant barriers to broader renewable adoption [84,85].
- Flinders Island, Australia: A successful implementation of hybrid systems integrating solar, wind, and storage technologies has drastically reduced diesel dependency, fuel consumption, and emissions. Flinders Island serves as a replicable model for other insular regions [68].
- Ometepe Island, Nicaragua: By combining solar and wind energy with battery storage, Ometepe Island has improved energy reliability, reduced emissions, and lowered energy costs for its inhabitants [77].
- Java, Indonesia: Hybrid systems incorporating solar, wind, and biogas provide off-grid solutions for rural areas, enhancing energy access and reliability, particularly in agricultural regions where biogas is readily available [66].
- Con Dao Island, Vietnam: A hybrid microgrid with PV systems, batteries, and diesel generators effectively meets energy demands in remote areas. Sensitivity analyses have highlighted the system's adaptability and feasibility for electrifying isolated regions with sustainable energy solutions [95].

3.2.5. Policy Frameworks, Governance, and Community Engagement in Renewable Energy Transitions

The success of hybrid renewable systems depends on supportive policies and community involvement. Flinders Island, Australia, has benefited from government incentives and local collaboration, reducing diesel dependency [68]. Java, Indonesia, has aligned biogas systems with agricultural needs, fostering community support [66]. Ometepe Island, Nicaragua, has leveraged participatory planning to enhance project acceptance and sustainability [77]. On Con Dao Island, Vietnam, subsidies and cost-sharing have mitigated high initial costs [95]. Transparent communication and policies encouraging local ownership are vital for overcoming resistance and ensuring the lasting adoption of renewable energy systems.

3.3. Energy Storage for Integrating Renewable Energy and Reducing Thermal Generation

3.3.1. The Role of Energy Storage in Enabling Renewable Integration and Reducing Fossil Fuel Dependence

Energy storage systems are essential for supporting the integration of renewable energy sources in insular regions, where the variability of solar and wind power presents significant challenges [96–98]. These storage solutions, such as batteries, pumped hydro, and hydrogen storage, play a crucial role in stabilizing the energy grid, particularly during periods of low renewable generation. In addition, energy storage systems reduce reliance on traditional thermal generation, which often depends on imported fossil fuels like diesel. The deployment of energy storage systems on islands has been shown to improve energy security, reduce carbon emissions, and facilitate the transition toward a more sustainable energy system [99].

3.3.2. Global Examples of Energy Storage Deployment in Insular Energy Systems

- Hawaii, USA: Hawaii has been a leader in adopting energy storage technologies to support its ambitious renewable energy targets. Studies [84,100] indicate that Hawaii has deployed large-scale battery systems to store excess solar and wind energy, reducing the island's reliance on fossil fuels. These systems provide essential grid stability and help mitigate the intermittency of renewable energy. Hawaii's energy storage

initiatives have contributed significantly to reducing fuel imports and improving the overall resilience of its energy system.

- **Sicily, Italy:** In Sicily, energy storage has been critical in supporting off-grid renewable energy systems. Research [70] shows that battery storage has been implemented to stabilize the island's energy grid, particularly in rural areas where renewable energy penetration is high. These systems have reduced reliance on diesel generators, leading to a reduction in carbon emissions and improved energy reliability.
- **La Graciosa, Spain:** La Graciosa has incorporated energy storage systems to complement its solar energy projects. Studies [53,68] indicate that battery storage on the island has significantly enhanced energy security by providing backup power during periods of low solar output. This has reduced the island's dependence on diesel, ensuring more reliable and sustainable energy supply for its residents.
- **Java, Indonesia:** Java has integrated energy storage systems with its renewable energy projects to improve grid stability and reduce reliance on thermal generation. Research [101] highlights the island's use of batteries and other storage technologies to store excess energy produced during peak solar and wind generation periods, ensuring continuous power supply during demand surges.
- **Kish Island, Iran:** Kish Island has employed innovative energy storage solutions as part of its hybrid renewable energy systems. Research [62] introduced a freshwater pinch analysis and genetic algorithm (FWaPA-GA) to optimize a photovoltaic-powered reverse osmosis desalination system with water storage tanks, eliminating the need for batteries. The system efficiently provides 10 m³/day of freshwater on demand while minimizing annual costs and outsourced freshwater needs. Another study [61] focused on the optimal design of a hybrid system incorporating photovoltaic panels, wind turbines, and ocean renewable energy storage (ORES). Using a Gravitational Search Algorithm (GSA), the study determined the optimal size of these components to ensure energy reliability and efficiency. The results emphasized the potential of hybrid systems with storage solutions to address the stochastic nature of renewable resources while ensuring sustainable energy and water supply for the island.
- **Barry Island, United Kingdom:** Barry Island demonstrates the potential of integrated energy storage within combined power and district heating networks. Research [101] proposed a distributionally robust co-optimization approach for energy and reserves, utilizing smart buildings as cost-effective storage devices to enhance operational flexibility. By modeling uncertainties in renewable energy production and ambient temperatures, the study generated reliable solutions to optimize system operations. Numerical results revealed the approach's ability to reduce risks and enhance economic benefits, showcasing the advantages of integrating energy and reserve management in smart city infrastructure.
- **Bruny Island, Australia:** Bruny Island explores the synergistic integration of desalination, electric vehicle loads, and hybrid microgrid systems. Research [67] examined the feasibility of combining photovoltaic panels, wind turbines, diesel generators, and battery storage to create a resilient microgrid. The study introduced a mixed-integer linear programming model to optimize interactions between a desalination plant, vehicle-to-grid (V2G)-enabled electric vehicles, and residential loads. By integrating diverse energy end-uses such as water filtration and transportation, the system achieved better scheduling and management for renewable energy resources. The results highlighted the economic advantages of decentralized storage solutions, such as leveraging EVs and desalination, over traditional grid-connected batteries.
- **Optimization of Renewable Integration:** Optimization models play a vital role in increasing renewable energy penetration in insular systems. Research [102] high-

lighted a design algorithm that uses a genetic approach to optimize renewable energy installations and heat pumps on the island of Hokkaido, Japan. By balancing electricity demand, heat load, and meteorological data, the study achieved an increase in renewable energy shares from 11% to 33.8% and improved the transmission network utilization factor from 14.5% to 41%. This demonstrated the potential of advanced optimization techniques to enhance the efficiency and reliability of renewable energy systems while reducing reliance on fossil fuels.

- **Hydrogen Energy Storage:** Hydrogen-based storage systems show great potential for reducing reliance on diesel in remote locations. A feasibility study [103] on Grimsey Island, Iceland, evaluated a wind-to-hydrogen system using HOMER software to optimize system components and energy balance. The proposed system demonstrated economic viability, with a payback period of less than four years, while significantly reducing transportation costs and emissions associated with diesel fuel. This highlighted the role of hydrogen storage as a complementary solution for insular energy systems facing high fuel and transport costs.
- Pumped hydro storage (PHS) stands out as a scalable and cost-effective solution for integrating renewable energy in insular systems. Studies [77,84,85] highlight its ability to address renewable energy intermittency, offering reliable and continuous power supply in remote communities. A feasibility study [84] on a remote island in Hong Kong compared PHS with battery systems, finding that standalone PHS presented the lowest lifecycle costs (29–48% of advanced battery-only systems), making it highly cost-competitive. Another study [85] demonstrated the technical feasibility of a standalone hybrid solar–wind–PHS system in Hong Kong, showing that PHS effectively compensated for the variability of solar and wind energy to achieve 100% energy autonomy.
- On Ometepe Island, Nicaragua, research [77] evaluated a hybrid PHS and battery system, leveraging a natural crater lake as an upper reservoir to reduce system costs while ensuring reliable renewable energy integration. Similarly, a case study [79] on K Island in the Taiwan Strait optimized a wind–PHS hybrid system, significantly reducing diesel consumption and demonstrating the potential of PHS to support renewable energy in remote locations. These findings underscore the role of PHS as a vital storage technology for enhancing grid stability, minimizing costs, and promoting sustainable energy transitions in isolated regions.

3.3.3. Key Lessons on Storage Technologies, Grid Stability, and Renewable Energy Optimization

Energy storage technologies are essential for stabilizing grids and enhancing renewable energy integration in island systems. Hawaii, Sicily, and La Graciosa demonstrate how battery storage reduces fossil fuel dependency and improves energy reliability, particularly in rural and off-grid areas [53,68,70,84,100]. Innovative approaches on Kish Island use water storage in hybrid systems, while Barry Island integrates smart buildings as storage, optimizing energy and reserve management [61,62,101]. On Bruny Island, decentralized solutions like EVs and desalination highlight alternatives to traditional batteries [67]. Optimization models, such as in Hokkaido, Japan, have increased renewable energy shares and improved grid efficiency, while Grimsey Island, Iceland, demonstrates that hydrogen storage is a viable, cost-effective alternative to diesel with significant emission reductions [102,103]. These solutions underline the importance of diverse and adaptable storage strategies for sustainable energy transitions in island communities.

Energy storage systems are crucial for renewable energy integration but face long-term challenges. Battery storage, as seen in Hawaii [84,100], Sicily [70], and La Graciosa [53,68], requires solutions for material scarcity, limited lifespan, and disposal impacts. Recycling ini-

tiatives and alternative chemistries can address these issues. Hydrogen storage, studied in Grimsey [103] and Kish Island [61,62], shows promise for seasonal storage but depends on cost and infrastructure advancements. Pumped hydro storage (PHS), effective on Ometepe Island [77] and in Hong Kong [84], is scalable but geographically constrained, requiring innovative designs. Decentralized systems like those on Bruny Island [67] illustrate adaptable alternatives, combining EVs and desalination to enhance flexibility. Long-term planning and innovation are essential for sustainable deployment.

3.3.4. Case Studies of Islands Utilizing Energy Storage to Transition Away from Fossil Fuels

- Hawaii, USA: large-scale battery storage systems have improved grid resilience, reduced reliance on fossil fuels, and supported Hawaii's renewable energy goals, decreasing fuel imports and stabilizing renewable intermittency [84,100].
- Sicily, Italy: battery storage has stabilized grids in rural areas with high renewable penetration, reducing emissions and reliance on diesel generators while improving energy reliability [70].
- La Graciosa, Spain: energy storage complements solar projects by providing backup power during low solar output, reducing diesel dependence and enhancing energy security [53,68].
- Java, Indonesia: integrated energy storage systems ensure grid stability by storing excess renewable energy during peak production, reducing reliance on thermal generation [101].
- Kish Island, Iran: hybrid systems utilizing water storage for desalination and ocean renewable energy storage optimize resource use, offering innovative solutions to reduce battery dependency [61,62].
- Barry Island, United Kingdom: smart buildings, as energy storage devices within combined power and heating networks, enhance flexibility, reliability, and cost-efficiency [101].
- Bruny Island, Australia: a hybrid microgrid combining desalination, EV integration, and renewable energy resources demonstrates economic advantages and better energy management with decentralized storage solutions [67].
- Hokkaido, Japan: advanced optimization models have increased renewable energy shares and improved transmission efficiency, demonstrating the importance of strategic planning [102].
- Grimsey Island, Iceland: hydrogen storage systems have shown economic viability, significantly reducing diesel reliance and emissions, offering sustainable solutions for remote energy systems [103].
- Koh Samui, Thailand: Hybrid renewable systems combining solar PV, wind, fuel cells, and battery storage achieved 89% energy from solar PV while meeting a 104 MW peak load. With an LCOE of 0.309 USD/kWh and a 9-year payback period, the system presents a sustainable and feasible alternative to Thailand's carbon-intensive power grid [81].

3.3.5. Policy Strategies, Regulatory Challenges, and Community Participation in Energy Storage Implementation

Effective policy frameworks and community engagement are critical to the deployment of energy storage solutions in insular regions. Hawaii has demonstrated leadership through progressive energy policies and community-driven initiatives that support large-scale battery storage and renewable integration [84,100]. In La Graciosa, public-private partnerships have facilitated solar and storage projects, addressing local energy demands and increasing system reliability [53,68]. Barry Island, UK, illustrates the benefits of in-

tegrating smart city strategies, engaging communities in innovative energy and heating solutions [101]. Bruny Island highlights the role of participatory planning in adopting decentralized systems, such as V2G-enabled EVs and desalination technologies, which improve local resource management [67]. However, overcoming resistance to infrastructure changes remains a challenge. For instance, introducing large-scale hydrogen or pumped hydro storage requires transparent communication to address concerns about land use, environmental impacts, and costs.

3.4. Advanced Control Strategies and Optimization Models for High Penetration of Renewable Energy Systems

3.4.1. The Importance of Advanced Control Strategies and Optimization Models in Insular Renewable Energy Systems

The increasing penetration of renewable energy sources, such as solar and wind, in insular regions poses significant challenges to grid stability and energy management [104]. Advanced control strategies and optimization models are essential for managing the variability of renewable energy and ensuring grid stability in these regions [105–107]. These strategies use techniques like real-time optimization, predictive modeling, and intelligent control systems to balance energy supply and demand, reduce curtailment, and enhance the reliability of energy systems [108]. This section explores how islands are adopting advanced control systems to manage high levels of renewable energy integration while reducing reliance on fossil-fuel-based backup generation.

3.4.2. Case Studies of Islands Implementing Intelligent Energy Management and Grid Optimization

- **Hawaii, USA:** Research [100] highlights Hawaii's efforts to implement advanced control strategies for managing its high penetration of solar and wind energy. The state has developed predictive optimization models to balance energy supply and demand in real time, reducing the need for backup diesel generation. Hawaii's use of intelligent control systems has significantly improved grid stability, particularly during periods of high renewable energy generation.
- **Sicily, Italy:** In Sicily, studies [70] indicate that diesel generators still play a significant role in off-grid areas despite the increasing penetration of solar and wind power. Advanced control models have been deployed to manage the intermittency of renewable energy, ensuring reliable energy supply while minimizing diesel consumption. The integration of control systems has been crucial in reducing emissions and improving the efficiency of energy systems in remote areas.
- **La Graciosa, Spain:** La Graciosa has implemented advanced control strategies to manage its high penetration of solar energy. Research [53,54] shows that predictive models and intelligent control systems have been key to stabilizing the island's energy supply, particularly during periods of low solar generation. These systems have reduced the need for diesel backup power, improving both the sustainability and reliability of the island's energy system [109].
- **Baltra–Santa Cruz, Ecuador:** The Galápagos Islands are addressing their heavy reliance on diesel-based energy systems by transitioning to hybrid renewable microgrids. Research [49] focused on the Baltra–Santa Cruz mini-grid, which supplies 62% of the archipelago's electricity. Using HOMER Pro for techno-economic assessments, the study demonstrated that installing 18.25 MWp of photovoltaic systems and 20.68 MWh of battery storage could increase the renewable energy share from 18% to 39%, reducing the Levelized Cost of Electricity (LCOE) from 32.06 to 0.1895 USD/kWh. Energy efficiency measures could further reduce the LCOE to 0.1710 USD/kWh, promoting distributed energy systems as a way to involve the local community in the energy

transition process. Another study [50] addressed the integration of electric vehicles and induction stoves into the island's microgrid, revealing significant economic and environmental benefits. By reducing diesel dependency, these initiatives align with the Galápagos Zero Fossil Fuel Initiative and contribute to the sustainable development goals of the archipelago.

- **San Cristobal Island, Galápagos:** San Cristobal Island is also working towards increasing its renewable energy share. Research [52] highlighted the potential of decentralized demand-side response strategies for primary frequency control, which can complement generation-side solutions in addressing challenges arising from reduced inertia in renewable-dominated systems. The study evaluated how different response strategies impact frequency behavior and battery usage, providing insights into demand-side participation in grid stabilization. Another study [51] investigated the current power system on San Cristobal Island, where 84% of electricity is generated using diesel. The study developed a two-step renewable energy implementation plan, incorporating solar, wind, and biofuels, with the aim of achieving 100% renewable energy generation. Using MATLAB/Simulink, the research addressed infrastructure and microgrid stabilization challenges while emphasizing environmental protection and reliability improvements.
- **Las Palmas Port, Gran Canaria (Canary Islands, Spain):** Renewable energy communities (RECs) and collective self-consumption initiatives are being explored in Las Palmas Port. Research [57] introduced a platform that uses geographic information systems (GISs) and satellite solar radiation data to assess PV potential automatically. A case study at Las Palmas Port identified 342,020 m² of suitable surfaces for PV panels, with the capacity to generate 70.81 MWp and produce 113.351 GWh annually. These findings demonstrate the feasibility of integrating distributed energy resources (DERs) into urban and industrial zones, contributing to energy sustainability and planning.
- **Korcula Island, Croatia:** Korcula Island has been used as a case study for achieving carbon neutrality with intermittent renewable energy sources. Research [74] explored an integrated energy model that combines solar, wind, and V2G technologies using EnergyPLAN simulations. Two scenarios for 2030 suggested optimal configurations: 40 MW of wind and 6 MW of solar for cost efficiency and 22 MW of wind and 30 MW of solar for minimal electricity imports and exports. By integrating transport, heating, cooling, and power sectors, the model emphasizes the potential for self-sufficient energy systems on islands while maintaining CO₂ neutrality.

3.4.3. Key Insights into Predictive Control, Smart Grids, and System Optimization for Renewable Integration

Islands are leveraging advanced renewable energy strategies to address grid stability and reduce fossil fuel dependency. Hawaii and Sicily utilize intelligent control systems to manage the intermittency of solar and wind energy, ensuring reliable supply while minimizing diesel use and emissions [70,100]. Hybrid renewable microgrids, such as those in the Galápagos Islands, demonstrate how integrating solar, wind, battery storage, and biofuels can increase renewable energy shares, reduce costs, and support sustainability goals [49,50,52]. Innovative initiatives like renewable energy communities in Las Palmas Port use GISs and satellite data to plan photovoltaic systems, promoting energy sustainability in urban and industrial zones [57]. On Korcula Island, integrated energy models combining solar, wind, and V2G technologies showcase the potential for self-sufficient, carbon-neutral systems through sector integration [74]. These examples highlight the critical role of localized strategies and advanced technologies in enabling energy transitions, reducing emissions, and enhancing energy security for insular regions.

Advanced control strategies and optimization models are crucial for enabling the high penetration of renewable energy in island systems, but their long-term scalability and sustainability require attention. For instance, predictive optimization models used in Hawaii [100] and on San Cristobal Island [52] depend heavily on continuous data availability and computational resources, raising concerns about their adaptability to technological and infrastructural changes over decades. Investments in modular and flexible software architectures are essential to ensure their relevance. Decentralized systems, such as those in La Graciosa [53,54] and Baltra–Santa Cruz [49,50], demonstrate the feasibility of integrating renewable energy, but their reliance on advanced control solutions necessitates durable and low-maintenance hardware. Similarly, renewable energy communities in Las Palmas Port [57] and multi-sector integration models on Korcula Island [74] require ongoing updates to maintain efficiency and cost-effectiveness. Incorporating lifecycle assessments and robust maintenance plans into these solutions will be critical to sustain their performance and scalability in the long term.

3.4.4. Practical Applications of Optimization Models in Managing High Renewable Penetration on Islands

- Hawaii, USA: advanced control systems allow Hawaii to balance high levels of solar and wind energy generation in real time, reducing reliance on diesel backup systems and improving grid stability [100].
- Sicily, Italy: in off-grid and rural areas, advanced control models have reduced diesel usage, stabilized the grid, and lowered emissions, making renewable energy systems more efficient [70].
- La Graciosa, Spain: predictive and intelligent control systems have enhanced solar energy utilization and minimized diesel dependency, ensuring a more reliable and sustainable energy supply [53,54].
- Baltra–Santa Cruz, Ecuador: hybrid microgrids integrating solar PV, batteries, and energy-efficient technologies have increased renewable energy shares, reduced the Levelized Cost of Electricity (LCOE), and supported the Galápagos Zero Fossil Fuel Initiative [49,50].
- San Cristobal Island, Ecuador: hybrid systems combining solar, wind, and biofuels, along with decentralized demand-side response strategies, have improved grid stabilization and supported the transition to 100% renewable energy generation [51,52].
- Las Palmas Port, Spain: renewable energy communities and GIS-based tools for PV potential assessments have proven effective for integrating distributed energy resources in urban and industrial areas, advancing energy sustainability [57].
- Korcula Island, Croatia: integrated models combining solar, wind, and V2G technologies demonstrate the potential for self-sufficient, carbon-neutral energy systems through strategic sector integration [74].
- Gran Canaria, Spain: Gran Canaria illustrates the challenges of maintaining frequency stability with high wind generation penetration. A dynamic model accurately simulated grid conditions, providing insights into the control measures needed to manage frequency dynamics and ensure grid reliability as renewable energy shares increase [56].

3.4.5. Policy Considerations, Regulatory Challenges, and Community Involvement in Energy Management

Advanced control strategies for high renewable penetration depend on supportive policies and community involvement. Hawaii has leveraged state policies and local initiatives to drive grid modernization and reduce fossil fuel reliance [100]. La Graciosa and the Galápagos Islands illustrate how public–private partnerships and stakeholder engagement align

technology deployment with regional priorities, ensuring social acceptance [49,50,53,54]. Efforts in Las Palmas Port and on Korcula Island emphasize collaborative planning and transparent communication to address social resistance, demonstrating the importance of aligning renewable energy projects with local economic and environmental goals [57,74]. Robust policies fostering local participation, incentives, and lifecycle planning are vital for sustaining these advanced systems over time.

3.5. Impact of Renewable Energy Penetration on Grid Stability

3.5.1. Understanding the Effects of High Renewable Energy Penetration on Insular Grid Stability

The integration of renewable energy sources such as solar and wind into island power systems presents significant challenges for grid stability [103]. The intermittent nature of these energy sources can cause fluctuations in supply, leading to voltage and frequency imbalances that threaten the stability of the grid [89]. As the penetration of renewable energy increases, insular regions must adopt advanced strategies to manage these fluctuations and ensure a reliable energy supply [110]. This section examines how different islands are managing the impact of renewable energy penetration on grid stability and the strategies they are implementing to mitigate these challenges.

3.5.2. Case Studies of Islands Managing Grid Stability Amid Growing Renewable Energy Integration

- Sicily, Italy: Research [70] shows that in off-grid areas of Sicily, diesel engines continue to provide a stable energy supply, but the increasing penetration of solar and wind power is creating challenges for grid stability. Advanced control systems and energy storage solutions have been deployed to mitigate the impact of renewable energy on the grid, helping to ensure a consistent energy supply while reducing reliance on fossil fuels.
- Kutubdia Island, Bangladesh: Studies [86] highlight the challenges faced by Kutubdia Island as it transitions to a renewable energy-based system. The island has implemented energy system modeling to predict and manage the fluctuations caused by solar and wind energy, ensuring grid stability during periods of high renewable energy penetration. This has allowed the island to reduce its dependence on diesel generators while maintaining a reliable power supply.
- Teuri and Yagishiri Islands, Japan: In Japan, microgrids on Teuri and Yagishiri Islands have successfully integrated renewable energy into their power systems. Research [83] reveals that while the islands have seen significant improvements in energy sustainability, the intermittency of wind and solar energy has created challenges for grid stability. To address this, the islands have adopted advanced control strategies and energy storage solutions to balance energy supply and demand.
- Favignana Island, Italy: Favignana Island's shift toward renewable energy has raised concerns about the stability of its power grid. One study [71] showed that the increased penetration of solar power has led to voltage fluctuations and frequency imbalances. The island is exploring the use of energy storage and grid reinforcement technologies to stabilize the grid and support its renewable energy goals.
- La Réunion, France: In La Réunion, the high penetration of solar energy has posed significant challenges to grid stability. Research [59] highlights how the island has implemented grid management strategies and energy storage technologies to manage fluctuations in solar energy generation, ensuring a reliable energy supply during periods of low sunlight.

3.5.3. Key Findings on Voltage Regulation, Frequency Control, and System Reliability

The integration of renewable energy on islands presents both opportunities and challenges for grid stability and reliability. Sicily, Italy, and Favignana Island, Italy, demonstrate how increased solar and wind penetration can lead to grid instability issues, such as voltage fluctuations and frequency imbalances. Advanced control systems and energy storage technologies have proven effective in mitigating these challenges and reducing reliance on fossil fuels [70,71]. Kutubdia Island, Bangladesh, and Teuri and Yagishiri Islands, Japan, highlight the importance of energy system modeling and microgrids in managing renewable energy intermittency. By adopting advanced strategies, these islands have maintained reliable power supplies while transitioning away from diesel generators [83,86]. La Réunion, France, exemplifies the role of grid management strategies and energy storage in addressing fluctuations caused by high solar energy penetration. These measures ensure a consistent energy supply even during periods of low renewable generation [59].

Long-term sustainability requires addressing the maintenance and lifecycle challenges of control systems and storage solutions used in Sicily and Favignana [70,71]. Kutubdia and Teuri and Yagishiri Islands [83,86] highlight scalable microgrids, but future demand will necessitate adaptable technologies. In La Réunion [59], reliance on storage and grid management raises concerns about component replacement and recycling. Modular upgrades and circular economy approaches can enhance scalability and resilience.

These cases emphasize the necessity of tailored solutions, including advanced controls, energy storage, and grid reinforcement, to support the successful integration of renewables in island energy systems.

3.5.4. Real-World Applications of Grid Stability Measures in High-Renewable Penetration Scenarios

- Sicily, Italy: Advanced control systems and energy storage solutions have enabled Sicily to manage the challenges of increasing solar and wind energy penetration in off-grid areas. These technologies stabilize the grid and reduce reliance on fossil fuels, supporting the island's renewable energy goals [70].
- Kutubdia Island, Bangladesh: By employing energy system modeling to predict and manage fluctuations in solar and wind energy, Kutubdia Island has successfully reduced its dependence on diesel generators while maintaining a reliable power supply during high renewable energy penetration [86].
- Teuri and Yagishiri Islands, Japan: Microgrids on these islands have improved energy sustainability through the integration of renewable energy. Advanced control strategies and energy storage technologies effectively balance supply and demand, addressing the intermittency of solar and wind power [83].
- Favignana Island, Italy: Increased solar energy penetration has led to grid stability concerns, such as voltage fluctuations and frequency imbalances. The island is exploring energy storage and grid reinforcement technologies to stabilize its power system and advance renewable energy integration [71].
- La Réunion, France: The island has implemented grid management strategies and energy storage solutions to manage solar energy fluctuations. These measures ensure a reliable energy supply during periods of low sunlight, supporting high renewable penetration [59].

3.5.5. Policy Strategies, Regulatory Challenges, and Community Adaptation to Grid Stability Solutions

Ensuring grid stability on islands with high renewable energy penetration relies on effective policies and active community involvement. Sicily and Favignana Island leverage regional incentives for advanced controls and storage, though public resistance

to infrastructure upgrades highlights the need for transparent communication [70,71]. In Kutubdia and Teuri and Yagishiri, community-focused microgrids gain acceptance by addressing local energy needs [83,86]. La Réunion showcases how collaborative governance and education foster public support for solar energy integration [59]. Strong policies and inclusive planning are vital to overcoming social resistance and ensuring sustainable renewable energy transitions.

3.6. *Successful Cases of Reducing Dependence on Fossil Fuels for Electricity Generation*

3.6.1. Pathways to Reducing Fossil Fuel Dependence in Insular Electricity Systems

Many insular regions around the world have made significant progress in reducing their dependence on fossil fuels for electricity generation by integrating renewable energy sources into their power grids. These successes have often involved a combination of renewable energy technologies, advanced control systems, and energy storage solutions. By transitioning to sustainable energy sources, these islands have reduced their reliance on expensive and environmentally harmful imported fuels such as diesel. This section highlights several islands that have successfully reduced their dependence on fossil fuels and discusses the strategies they implemented to achieve this transition.

3.6.2. Global Examples of Islands Transitioning to Renewable-Dominated Energy Systems

- **Hawaii, USA:** Hawaii has been a global leader in reducing its dependence on fossil fuels through the integration of solar, wind, and battery storage systems. Research [100] highlights Hawaii's ambitious goal of achieving 100% renewable energy by 2045. The state has successfully implemented large-scale renewable energy projects, reducing its reliance on imported fossil fuels. Hawaii's use of advanced control systems and energy storage technologies has played a key role in stabilizing the grid and ensuring a reliable energy supply during periods of low renewable generation.
- **Sicily, Italy:** Sicily has made significant progress in reducing its dependence on diesel generators, particularly in off-grid areas. Studies [70] indicate that Sicily's integration of solar and wind power, combined with battery storage systems, has allowed the island to reduce its reliance on fossil fuels while improving energy reliability. Sicily's approach provides a model for other islands seeking to transition to renewable energy.
- **La Graciosa, Spain:** La Graciosa has successfully implemented renewable energy systems to reduce its dependence on fossil fuels. Research [53,54] shows that the island's solar energy projects, supported by battery storage, have provided a reliable and sustainable energy supply, reducing the need for diesel-based backup generation. La Graciosa's efforts have resulted in a more stable energy system that is less vulnerable to fuel price fluctuations.
- **Bali, Indonesia:** Bali is another example of a region that has successfully reduced its dependence on fossil fuels. Studies [65] highlight how the island's integration of renewable energy has helped reduce its reliance on imported diesel while simultaneously lowering emissions and improving energy security. Bali's renewable energy projects, which include solar, wind, and micro-hydro systems, are supported by energy storage technologies and advanced grid management strategies.
- **Kakorotan Island, Indonesia:** Kakorotan Island, located in the Talaud Island regency of North Sulawesi province, serves as a case study for renewable energy infrastructure development in remote island communities. Research [63] used HOMER software to model a renewable energy-based power generation system tailored to the island's local energy needs. The study emphasized that while renewable energy provides a sustainable solution, the relatively high costs of electricity generation necessitate policies and strategies to ensure energy security for remote island communities.

- **Miangas Island, Indonesia:** Miangas Island, another remote Indonesian island in the Talaud Island regency near the Philippines, has been the focus of a techno-economic study on a hybrid PV–diesel power system. Research [64] demonstrated that the proposed system, comprising 150 kW PV arrays, a 50 kW diesel generator, and energy storage components, could meet the island’s energy demands efficiently. The hybrid system produces 80.7% of its electricity from PV and 19.3% from diesel, with an excess electricity generation of 109,063 kWh annually. The cost of energy (COE) is calculated at 0.318 USD/kWh, highlighting the potential for reducing fossil fuel reliance while maintaining energy affordability.
- **Milos Island, Greece:** Milos Island has been analyzed as a case study for integrating hydrogen storage technologies with renewable energy systems. Research [46] highlighted the potential of Metal Hydride Hydrogen Compressors (MH2Cs) in autonomous power systems for remote communities, such as off-grid islands. Using HOMER software, a renewable energy and hydrogen-based storage system was proposed to increase RES penetration while addressing economic, environmental, and social considerations. This study identified hydrogen technologies as a critical component in overcoming the limitations of intermittent renewable energy sources and reducing reliance on diesel generators.
- **Orkney Islands, Scotland:** The Orkney Islands serve as a case study for the integration of ocean renewable energy into insular power systems. Research [111] highlighted the benefits of incorporating wave and tidal energy alongside traditional renewable sources in microgrid modeling scenarios for 2030, 2040, and 2050. Findings demonstrated that marine energy integration reduces the need for installed capacity, minimizes energy storage requirements, decreases excess generation, and results in overall cost savings. This case underscores the potential of ocean renewable energy to enhance the sustainability and efficiency of islanded power systems while addressing the unique challenges of variable renewable energy integration.

3.6.3. Key Insights into Strategies for Phasing Out Fossil Fuels in Insular Contexts

Islands are advancing renewable energy integration through diverse strategies that reduce reliance on fossil fuels and enhance energy system resilience. Hawaii exemplifies leadership with solar, wind, and battery systems supported by advanced controls, ensuring grid stability while progressing toward its 2045 goal of 100% renewable energy [100]. Sicily and La Graciosa effectively combine solar, wind, and battery storage to stabilize grids and reduce diesel reliance, offering replicable models for insular regions [53,54,70]. Bali demonstrates the benefits of integrating solar, wind, and micro-hydro systems with advanced grid management to cut emissions and lower diesel dependency [65]. Remote Indonesian islands like Kakorotan and Miangas Islands highlight the potential of hybrid renewable–diesel systems, balancing sustainability with cost-efficiency. Miangas Island obtains over 80% of its energy from solar PV at a COE of 0.318 USD/kWh [63,64]. Milos Island showcases hydrogen storage technologies, such as Metal Hydride Hydrogen Compressors (MH2Cs), as vital for managing intermittent renewable sources and reducing diesel reliance [46]. The Orkney Islands emphasize the advantages of marine energy integration, with wave and tidal energy reducing storage needs, excess generation, and overall costs, while enhancing grid efficiency [111].

Long-term sustainability for reducing fossil fuel dependence requires addressing storage and infrastructure challenges. In Hawaii [100], recycling aging battery systems will be critical to sustaining the 2045 renewable target. Sicily and La Graciosa [53,54,70] must mitigate the environmental impacts of battery disposal. Islands like Miangas and Kakorotan Islands [63,64] need policy support to maintain affordability as systems are

scaled. Milos [46] highlights hydrogen's potential, but cost reductions are essential for long-term viability. The Orkney Islands [111] demonstrate ocean energy's promise, though infrastructure durability remains a key challenge. Scalable, adaptable solutions are vital for lasting impact.

3.6.4. Case Studies of Successful Renewable Energy Transitions in Island Regions

- Hawaii, USA: Hawaii's integration of solar, wind, and battery storage has provided a replicable model for achieving renewable energy goals. Advanced control strategies ensure grid stability during periods of high renewable generation, supporting the state's ambitious target of 100% renewable energy by 2045 [100].
- Sicily, Italy: Sicily's transition combines renewable energy sources with battery storage, particularly in off-grid areas. These measures reduce diesel dependency and improve energy reliability, demonstrating a scalable solution for islands with similar challenges [70].
- La Graciosa, Spain: La Graciosa exemplifies effective renewable energy integration by utilizing solar power with battery storage to stabilize energy supply and minimize reliance on diesel backup, ensuring a sustainable and reliable energy system [53,54].
- Bali, Indonesia: Bali's renewable energy projects integrate solar, wind, and micro-hydro systems supported by storage technologies and grid management strategies. This approach has significantly reduced emissions and dependence on imported diesel [65].
- Kakorotan and Miangas Islands, Indonesia: These islands showcase the potential of hybrid renewable–diesel systems tailored to local needs. Miangas Island, for example, obtains over 80% of its energy from solar PV, demonstrating the feasibility of hybrid systems in remote communities [63,64].
- Milos Island, Greece: The use of hydrogen storage, particularly Metal Hydride Hydrogen Compressors (MH2Cs), highlights an innovative solution for managing intermittent renewables. This system supports off-grid communities by reducing diesel reliance and addressing environmental challenges [46].
- Orkney Islands, Scotland: The integration of wave and tidal energy into microgrids highlights the advantages of marine energy in reducing storage needs, excess generation, and costs. This case underscores the importance of diverse renewable energy portfolios for island systems [111].
- These insights reflect how tailored renewable energy strategies and advanced technologies can address the specific needs of islands, promoting energy resilience, sustainability, and independence.

3.6.5. Policy Mechanisms, Governance Structures, and Community-Driven Approaches to Fossil Fuel Reduction

Effective policies and community engagement are crucial for reducing fossil fuel dependence on islands. Hawaii and Sicily benefit from strong renewable energy policies but require public awareness to sustain momentum [70,100]. La Graciosa and Bali address social resistance through participatory planning and equitable benefit-sharing [53,54,65]. Scaling hybrid systems in Kakorotan and Miangas needs financial incentives to offset high initial costs [63,64]. Milos showcases hydrogen's potential, relying on partnerships to lower costs [46]. The Orkney Islands emphasize governance frameworks to manage complex marine energy projects [111]. Inclusive policies and local involvement are vital for successful and sustainable energy transitions in insular regions.

Finally, a comparative summary highlighting the key opportunities and challenges identified in the islands analyzed in this study is presented in Table A1 in the Appendix. Additionally, Table A2 provides an overview of the major energy storage technologies

employed, including their essential specifications, such as energy density, lifespan, and capital cost.

3.6.6. Insights and Lessons from Insular Energy Systems

The diverse range of insular energy systems examined in this study illustrates that renewable energy integration can yield significant reductions in fossil fuel use and associated emissions. However, the scalability and transferability of these strategies depend heavily on regional circumstances and enabling conditions. For instance, on Flinders Island (Australia), the Hybrid Energy Hub—combining wind, solar PV, and battery storage—has successfully decreased annual diesel consumption by approximately 60% and cut CO₂ emissions by over 1500 tons, demonstrating that well-structured hybrid systems can enhance both reliability and sustainability [68]. In the Galápagos Islands (Ecuador), a carefully managed integration of solar and wind power supported by battery storage systems has resulted in around a 30% reduction in diesel use, aligning with the stringent environmental protections imposed to preserve the archipelago's unique ecosystems [52].

However, such successes are not universally replicable, as they are deeply influenced by enabling conditions. Hawaii's energy transition provides a salient example: backed by robust state-level legislation, investment capital, and research capabilities, Hawaii surpassed 30% renewable electricity generation by 2020 [31], aligning regional initiatives with broader international goals such as the Paris Agreement and the United Nations' Sustainable Development Goals. This success, though impressive, may not be directly replicable in regions with limited financial resources or weaker institutional support. On Ometepe Island in Nicaragua, for example, community-driven funding mechanisms, international development assistance, and incremental technology adoption have been essential in deploying small-scale solar and wind solutions. While Ometepe's approach lacks the large-scale policy scaffolding seen in Hawaii, it demonstrates how grassroots financing and phased integration can foster local buy-in and long-term resilience [77].

Financial and technical barriers remain persistent challenges. In Sicily, where the high cost of battery storage has impeded rapid decarbonization, recent studies highlight the importance of tailored policy incentives, concessional loans, and aggregator-driven business models that reduce investment risks for stakeholders [70]. Additionally, open-source predictive control models and digital energy management platforms have begun to emerge as valuable tools, allowing isolated utilities and local operators to optimize generation and storage dispatch more cost-effectively. In parallel, cross-island knowledge-sharing initiatives—facilitated by international organizations and academic consortia—are spreading lessons from pioneering cases like Flinders or the Galápagos Islands to other archipelagos in the Pacific and Mediterranean, thus improving the global circulation of best practices. While renewable energy transitions bring clear environmental benefits, they also present challenges. Islands integrating advanced storage technologies, such as Flinders Island (Australia) or certain projects in the Canary Islands (Spain), benefit from enhanced grid stability and reduced diesel use, yet the battery manufacturing process—often involving critical minerals like cobalt, lithium, and nickel—can lead to habitat disruption, water contamination, and other ecological impacts distant from the islands themselves. The logistics of transporting batteries, solar panels, and wind components to remote territories also contribute to their carbon footprint. End-of-life management poses an additional challenge, especially on sensitive islands like those in the Galápagos Islands (Ecuador), where some renewable projects rely on lead-acid batteries known for their hazardous lead content and limited recycling infrastructure; while these installations support a cleaner energy mix and reduce diesel spills and air pollution, they introduce future e-waste streams that must be handled responsibly. Effective recycling protocols, for instance, remain underdeveloped in

many regions, and while Hawaii's deployment of lithium-ion battery projects illustrates the need for global collaboration and robust supply chain standards, the Galápagos Islands highlight that even widely available but less environmentally friendly battery chemistries—like lead-acid—necessitate proper disposal and material recovery to prevent soil and water contamination. Although some islands, such as Porto Santo (Portugal), are beginning to explore circular economy models and incentivized recycling measures, these efforts are still evolving, underscoring the importance of adopting a holistic approach that integrates renewable energy expansion with strict environmental regulations, sustainable supply chains, and international cooperation on waste management to ensure that the ecological integrity and long-term resilience of insular environments are not compromised by the very technologies intended to protect them.

Social acceptance is another critical determinant of project success in insular contexts. In tightly knit communities, opposition can quickly stall or derail wind, solar, or battery storage initiatives. Public perception often hinges on the extent to which local residents feel included in decision-making, trust the entities behind the projects, and perceive tangible benefits—ranging from stable electricity prices to local job creation—outweighing any ecological or aesthetic trade-offs. On Jeju Island (South Korea), for instance, the push to integrate offshore wind farms has prompted both enthusiasm for reduced fossil fuel reliance and concerns over visual impacts, fishing grounds, and cultural heritage sites. Similar tensions have surfaced in the Canary Islands (Spain), where some communities have questioned the landscape alteration caused by wind turbines, despite recognizing the potential for cleaner air and a more stable energy supply. On Ometepe Island (Nicaragua), the successful integration of small-scale solar and wind installations owes much to community-driven financing mechanisms, participatory workshops, and transparent communication about long-term environmental and economic gains. Even in environmentally sensitive areas like the Galápagos Islands (Ecuador), rigorous consultation processes and local stakeholder engagement have been pivotal in maintaining support for renewable projects, as communities closely watch for any adverse effects on the unique ecosystems that sustain both their livelihoods and cultural identity. Likewise, in Hawaii's energy transition, community outreach programs, benefit-sharing schemes, and proactive policy frameworks have helped forge a collective sense of ownership over the renewable agenda. These examples underscore that engineering solutions alone cannot secure a sustainable energy future in insular contexts; rather, the path to durable renewable energy transitions depends on inclusive planning, equitable benefit distribution, transparent dialog, and the capacity to align new infrastructure with the community's values, aspirations, and sensitivity to both natural and cultural landscapes.

4. Conclusions

The reliance on fossil fuels for electricity generation in insular regions presents significant challenges, particularly due to their environmental, economic, and logistical vulnerabilities. These isolated systems, often dependent on imported hydrocarbons, face issues such as volatile energy prices, limited energy security, and the damaging impact of emissions on fragile ecosystems. This review explored the historical dependence on fossil fuels and the urgent need for islands to transition towards renewable energy sources to mitigate these challenges.

The objective of this paper was to identify and analyze practical strategies for reducing fossil fuel dependency in insular energy systems by synthesizing the existing literature through the PRISMA methodology. The systematic review covered 2205 studies from two major databases, Scopus and Web of Science, focusing on articles published between 2014 and 2024. Following rigorous screening and evaluation criteria, 80 high-quality articles

were selected for in-depth analysis. The review concentrated on various renewable energy technologies, energy storage solutions, hybrid systems, and advanced control strategies as key factors in enabling energy transition on islands.

The findings from the reviewed literature reveal a broad spectrum of renewable energy solutions and strategies currently being implemented or studied worldwide, showcasing the diverse pathways toward reducing fossil fuel dependency in insular contexts. Beyond reiterating known challenges, this synthesis highlights actionable solutions, such as deploying cost-effective and durable energy storage technologies (e.g., advanced lithium–sulfur batteries or green hydrogen), implementing open-source predictive control models that can be tailored to local conditions, and engaging communities through participatory planning, energy cooperatives, and transparent benefit-sharing mechanisms. For example, medium-sized islands like Jeju (South Korea) and Porto Santo (Portugal, Madeira) are demonstrating how careful policy design, storage integration, and stakeholder cooperation can shift the energy mix away from imported fuels. Meanwhile, smaller islands with limited infrastructure, such as Baltra–Santa Cruz (Galápagos, Ecuador), are testing hybrid solar–wind systems combined with battery storage and community engagement to protect unique ecosystems and achieve local buy-in. The success of islands like Flinders Island (Australia), Ometepe Island (Nicaragua), and La Graciosa (Spain) in deploying hybrid renewable systems provides replicable models for other regions, emphasizing that technology alone is insufficient without equitable socio-economic frameworks. Indeed, the Galápagos Islands (Ecuador) illustrate how adaptive policy environments, appropriate funding mechanisms, and inclusive stakeholder participation can align advanced storage solutions with both environmental preservation and reliable electricity supply. These principles—community involvement, targeted technology choice, flexible policy frameworks, and regional customization—can inform not only other insular settings but also remote mainland microgrids and emerging economies, ensuring that lessons learned translate into broader relevance for global decarbonization efforts.

Despite these promising results, challenges remain. The intermittency of renewable sources such as solar and wind, compounded by outdated grid infrastructure, continues to pose significant barriers to their widespread adoption. Energy storage solutions, such as large-scale batteries and hydrogen storage, have emerged as critical technologies for stabilizing grids and ensuring reliable energy supply during periods of low renewable generation. However, the high initial capital costs and maintenance requirements of these systems are significant barriers to broader deployment, especially in economically constrained insular regions.

Furthermore, this review highlights the importance of advanced control strategies and optimization models in managing the high penetration of renewable energy in island grids. The use of real-time optimization and predictive control systems has proven essential in balancing supply and demand, reducing curtailment, and ensuring grid stability. For instance, studies from Hawaii and Sicily emphasize the role of intelligent control systems in minimizing reliance on fossil-fuel-based backup generation, leading to improved energy efficiency and lower emissions. However, financial and technical barriers still hinder the full-scale implementation of these advanced systems in many regions.

Future research should focus on several key areas to overcome the remaining challenges. First, developing more cost-effective and durable energy storage technologies is essential for increasing the viability of renewable energy integration in insular regions. Second, there is a need for deeper exploration of hybrid renewable energy systems that can optimize the mix of solar, wind, and bioenergy, particularly in isolated island contexts. Third, advancing predictive control models and intelligent grid management systems will be crucial for ensuring grid stability and reducing dependence on fossil-fuel-based backup

power. Finally, more attention should be given to the socio-economic and regulatory frameworks that can facilitate a just transition for island communities, ensuring that the benefits of renewable energy projects are distributed equitably and that local populations are actively involved in the energy transition process. Addressing these research gaps will be vital in accelerating the decarbonization of insular energy systems and ensuring their long-term sustainability.

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Appendix A

Details of the Literature Review Process Following the PRISMA 2020 Statement Standard

Table A1. Comparative analysis of opportunities and challenges for renewable energy integration in insular regions.

Island	Opportunities	Challenges	Refs.
Hawaii, USA	Large-scale renewable projects reduce fuel imports and stabilize grid with advanced control systems.	High electricity costs, outdated infrastructure, and grid instability.	[82,83,100]
Hong Kong, China	Hybrid solar–wind systems provide stable energy in urban settings.	Fossil fuel dependency, outdated grid systems, and logistical difficulties in dense urban areas.	[84,85]
Sicily, Italy	Integration of solar and wind with storage improves grid reliability and reduces diesel dependency.	High costs, infrastructural barriers, and pilot-stage renewable projects.	[70,74]
La Graciosa, Spain	Solar projects with battery storage reduce diesel reliance and enhance energy security.	Outdated grid and high implementation costs limit renewables’ adoption.	[53,68]
Jeju Island, Korea	Model for renewables’ adoption with significant solar and wind integration.	Grid instability due to lack of modern energy storage and smart grid infrastructure.	[76,86,87]

Table A1. Cont.

Island	Opportunities	Challenges	Refs.
Crete, Greece	Load-shifting strategies and microgrids improve flexibility and reduce costs in energy systems.	Requires high investment in advanced control systems and energy storage solutions.	[44,88]
Thailand	Localized solutions improve wind energy sustainability with material reuse strategies.	High emissions and energy intensity of vertical-axis wind turbines.	[80]
Porto Santo, Portugal	Smart EV charging increases renewable integration and reduces CO ₂ emissions.	High upfront costs of electric vehicle infrastructure and reliance on imported technologies.	[72]
Rakiura/Stewart Island, NZ	Multi-carrier microgrid with solar, wind, and hydrogen storage cuts electricity costs by 54%.	Initial investment and complexity in managing diverse energy sources.	[78]
Sardinia, Italy	Renewable production could fully sustain commuter mobility with EV integration.	Imbalances caused by spatial segregation of production and consumption areas.	[69]
Cyprus	Achieving grid parity through declining solar PV costs reduces dependency on high-cost primary energy.	Vulnerability to fluctuating solar generation during low sunlight periods.	[82]
Fernando de Noronha, Brazil	Photovoltaic installations could supply up to 199% of annual energy needs, reducing diesel reliance.	High cost of implementing decentralized systems and maintaining renewable technologies.	[76]
Froan Islands, Norway	Hydrogen-based systems reduce emissions and offer cost-effective renewable energy solutions.	Local conditions, such as CO ₂ intensity and cable length, strongly impact outcomes.	[89]
Tenerife, Spain	Wave energy systems have potential for high renewable integration with energy storage support.	Oscillatory wave energy causes grid instability without storage solutions.	[55]
Terceira Island, Azores	Synthetic inertia and control systems maintain grid stability with high renewable penetration.	Limited implementation of advanced grid stabilization measures.	[73]
Ushant, France	Renewable energy scenarios improve grid reliability and reduce dependency on fossil fuels.	Initial reliance on limited data for assessing grid reliability and planning.	[60]
Aero and Vis	Multi-vector energy communities enhance self-sufficiency with tailored renewable solutions.	High costs of battery storage and limited hydrogen availability for seasonal storage.	[75]

Table A2. Energy storage technologies and their applications in insular regions.

Storage Technology	Applications	Energy Density (Wh/kg)	Lifespan (Cycles/Years)	Capital Cost (USD/kWh)	Islands and Ref.
Lithium-Ion Batteries	Grid stabilization and hybrid systems	150–250	3000–5000/10–15	200–400	Hawaii [84,100], La Graciosa [53,68], Java [101]
Pumped Hydro Storage	Large-scale renewable integration	N/A	40–60	50–150	Canary Islands [56], Hong Kong [84], Ometepe Island [77], K Island [79]

Table A2. Cont.

Storage Technology	Applications	Energy Density (Wh/kg)	Lifespan (Cycles/Years)	Capital Cost (USD/kWh)	Islands and Ref.
Hydrogen Storage	Remote and off-grid seasonal storage	33–120	5000+ / 20–30	300–600	Grimsey Island [103], Milos Island [46], Aero [75]
Thermal Storage (Molten Salt)	Solar thermal plants	N/A	30–50	30–100	Crete [88]
Flow Batteries (Vanadium)	Long-duration energy storage and microgrids	20–50	10,000+ / 20–30	150–300	La Réunion [59]
Compressed Air Energy Storage (CAES)	Bulk energy storage	N/A	20–40	50–100	Canary Islands [56]
Lead-Acid Batteries	Early-stage renewable integration	30–50	500–1500 / 5–8	100–150	San Cristobal Island, Galápagos [51,52], Bali [65]

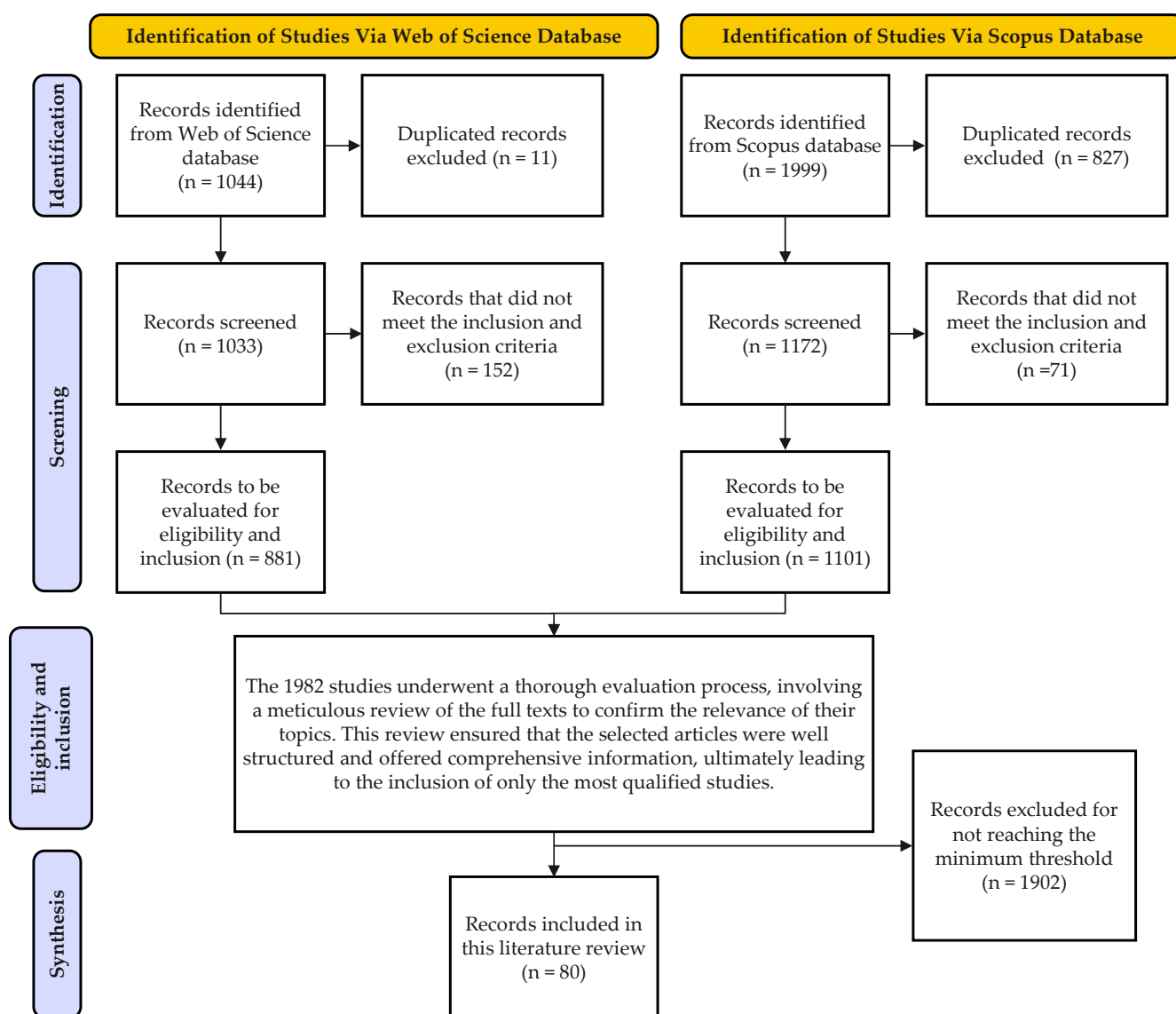


Figure A1. Standardized PRISMA 2020 statement flowchart for designed literature review [43].

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