

Optimization Analysis of Dual-Mode Renewable Hybrid Power Systems: A Review



B.O. Ariyo^{1,2*}, L.M. Adesina¹, A. Musa^{1,3}, O. Ogunbiyi¹, B.J. Ojuolape¹, M.O. Balogun¹

¹Department of Electrical and Computer Engineering, Kwara State University Malete, Nigeria

²Department of Electrical and Electronics Engineering, University of Ilorin, Nigeria

³Institute for Intelligent Systems, University of Johannesburg, South Africa



ABSTRACT: The escalating threat of global warming necessitates a shift towards clean energy production, with renewable energy sources emerging as a promising solution for sustainable electricity generation. However, the inherent intermittency of renewables requires hybrid systems to maintain reliable electricity. This review explores the optimization of dual-mode renewable hybrid power systems, which operate in both grid-connected and autonomous modes, to address power stability challenges. By analyzing state-of-the-art methodologies, including advancements in control algorithms, architecture sizing, and energy management strategies, this work identifies methods for enhancing system efficiency and cost-effectiveness. Key findings demonstrate that optimized dual-mode systems improve power consistency and operational resilience. The review concludes by outlining a roadmap for future research, highlighting innovations in integration techniques, environmental assessments, and regulatory collaboration as crucial steps toward maximizing the impact of dual-mode systems in achieving global energy sustainability goals.

KEYWORDS: Hybrid energy sources, optimization techniques, minimization, modeling, grid integration

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I. INTRODUCTION

Energy is a basic necessity for all aspects of human progress, including food, health, infrastructure, prosperity, education, and civilization; as such, its supply should be secure, ample, and freely available (Roy *et al.*, 2022; Majeed Butt 2021; Castro-Toro *et al.*, 2023; Le *et al.*, 2023). However, the increasing global energy demand driven by massive population growth, rapid urbanization, and industrialization poses significant challenges. The depletion of fossil fuel reserves, detrimental effects of greenhouse gas emissions, and reliance on non-renewable energy sources further exacerbate the issue, underscoring the urgent need for alternative energy solutions (Gulzar *et al.*, 2022; Giama *et al.*, 2023).

Renewable energy systems (RESs) have emerged as a promising alternative due to their numerous benefits, including cost-effectiveness, safety, cleanliness, and availability (He *et al.*, 2021; Come Zebra *et al.*, 2021; Lombardi, Pickering and Pfenninger, 2023). Despite their potential, the primary challenge facing renewable energy solutions is their inherent dependence on environmental conditions, location, and operational state, leading to fluctuations in voltage and frequency (Qays *et al.*, 2023). This research addresses the critical need for optimization strategies in dual-mode renewable hybrid systems, which are essential to overcoming these fluctuations and ensuring reliable power supply despite environmental variability.

A "dual-mode" renewable hybrid power system refers to a system that can operate in two distinct modes: grid-connected and autonomous (off-grid) (Pop *et al.*, 2023). In grid-

connected mode, the system interacts with the main power grid, supplying excess energy when production exceeds demand and drawing power from the grid when renewable generation is insufficient (Bubalo *et al.*, 2023). In autonomous mode, the system operates independently, providing power solely from its renewable sources and storage. This flexibility allows the system to adapt to varying energy demands and grid availability, thus enhancing its resilience against intermittent power supply (He *et al.*, 2023). The significance of this research lies in its comprehensive analysis of dual-mode renewable hybrid power systems, focusing on their ability to operate in both modes, which mitigates the challenges posed by fluctuating renewable energy generation.

Addressing this challenge necessitates a deeper examination of renewable hybrid systems. These systems integrate various energy generation, storage, and conversion technologies, offering improved performance, efficiency, and stability compared to single renewable energy systems. The review of renewable hybrid systems is crucial as it explores the configuration and optimization needed to enhance their reliability and effectiveness. Common hybrid system designs include Wind-Hydro, Hydro-Solar, Solar-Wind, Solar-Wind-Biomass, and Solar-Wind-Battery combinations, often supplemented with diesel generators as a backup to meet load demands. The significance of this research lies in its comprehensive analysis of dual-mode renewable hybrid power systems, focusing on their ability to operate in both grid-connected and autonomous modes. This dual-mode functionality enables the systems to adapt to varying demands

*Corresponding author: ariyo@unilorin.edu.ng

and grid availability, addressing the critical issue of intermittent power supply.

The unique contributions of this review include the in-depth exploration of optimization techniques specific to dual-mode hybrid systems, advancements in architecture sizing, energy management strategies, and economic evaluations that are essential for enhancing system efficiency and resilience. Additionally, this work identifies emerging pathways for integrating these systems into the global energy landscape, laying a foundation for achieving sustainable energy goals.

A. Hybrid Renewable Energy Systems (HRESs)

Hybrid Renewable Energy Systems (HRESs) integrate multiple renewable energy sources to enhance reliability and efficiency (Canale et al., 2021; Khosravani et al., 2023). These systems combine different technologies such as solar, wind, and biomass to mitigate the intermittency issues inherent in standalone renewable energy systems (Asiaban et al., 2021). By diversifying energy sources, HRESs can provide more stable and consistent power supply, crucial for both grid-connected and off-grid applications (Rathod and Subramanian, 2022; Salac et al., 2024).

The integration of energy storage solutions further enhances their flexibility and ability to meet varying energy demands (Shahzad and Jasińska, 2024). HRESs play a vital role in achieving sustainable energy goals by optimizing resource utilization and reducing reliance on fossil fuels, thereby contributing to environmental preservation and energy security (Al-Shahri et al., 2021). As research and development continue to advance, optimizing the design and operation of HRESs remains a focal point to maximize their effectiveness in diverse energy landscapes (Hu and Bui, 2024; Zisos et al., 2023).

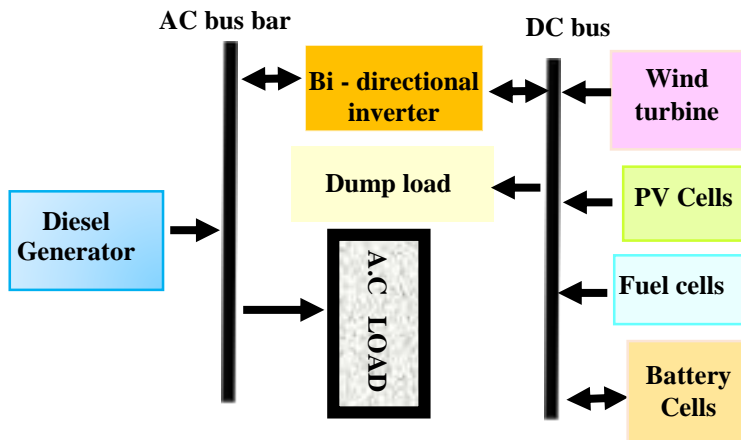


Fig. 1: Schematic diagram of a renewable hybrid power systems

Figure 1 presents the schematic diagram of an HRES, each component plays a crucial role: Photovoltaic (PV) cells convert sunlight into electricity, complemented by wind turbines that harness wind energy for renewable power generation. Fuel cells provide continuous electricity through chemical

reactions, acting as a reliable backup source. Batteries store excess energy from PV cells and wind turbines for later use, ensuring stable power supply during fluctuations. The direct current (DC) bus bar distributes direct current power among components like PV cells, wind turbines, batteries, and DC loads, which consume DC electricity directly. A dump load safeguards the system by absorbing surplus energy that cannot be stored or used, preventing overvoltage. Inverters then convert DC electricity into alternating current (AC), compatible with AC loads and grid connections, essential for distributing power to household and industrial appliances. Power management systems monitor and optimize the operation of these components, ensuring efficient energy conversion, load balancing, and system stability. Together, these components and systems optimize energy efficiency, enhance system reliability, and support sustainable energy solutions in diverse operational environments.

Figure 2 summarizes the benefits of hybrid renewable energy systems by integrating diverse energy sources such as PV, Wind, Hydro, etc., enhancing system robustness amid climate change. This integration improves power supply quality, avoiding frequency drift that can disrupt sensitive loads (Rasolomampionona et al., 2024).

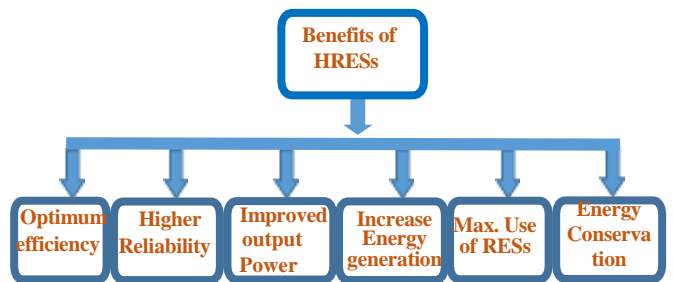


Fig. 2: Merits of renewable hybrid power systems

The remainder of this study is organized as follows: Section II covers the optimization objectives for hHRESs, while Section III discusses hybrid system modeling. Section IV addresses key findings, implications, and comparisons with relevant research, along with strategies to mitigate the HRES energy crisis, a research gap assessment, research limitations, and future directions to enhance the study's value. Finally, Section V presents the conclusion.

II. THEORETICAL ANALYSIS

A. The HRES Optimization Objectives:

The capacity of various renewable energy sources to generate energy varies (Erdiwansyah et al., 2021). To build and implement the power grid effectively, the government and utility corporations must be aware of the precise capacity of various renewable energy sources at various places (Fabra and Llobet, 2022). The cost of operating and maintaining energy-

producing units will eventually decrease with the appropriate deployment of renewable energy sources (Bhuiyan, 2022). When preparing for the implementation of renewable energy sources, minimizing costs and optimizing power generation are the two key goals (Ammari *et al.*, 2022). Various optimization methods have been suggested to accomplish these two goals (Hassan, Kamel and Hussien, 2023).

Numerous optimization models are available in the literature, including control models for the effective use of renewable energy sources, system capital cost optimization objectives (Panda and Das, 2021), emission minimization objectives (Ahmed *et al.*, 2022), energy optimization objectives (Rahman *et al.*, 2021), profit maximization objectives for Distribution Companies (Basu *et al.*, 2022), and energy forecasting objectives (AlKandari and Ahmad, 2024). Recent advancements encompass AI-based predictive algorithms (Firoozi Fard and Hajimirza amin, 2023) to manage renewable energy fluctuations, effectively applied in smart grid systems for dynamic, real-time supply-demand balancing. Machine learning techniques, such as deep neural networks (Shafi *et al.*, 2023) are increasingly employed in energy forecasting, with utility companies leveraging them to improve load balancing in hybrid renewable setups. Genetic algorithms (GA) (Khatri *et al.*, 2023) have also been applied to optimize hybrid configurations by selecting efficient combinations of energy storage and generation, lowering both capital and operational costs.

Additionally, reinforcement learning (RL)-based optimizers (Sankaran *et al.*, 2022; (Ding *et al.*, 2023), are applied to adaptive energy pricing in smart grids, promoting market efficiency and balanced energy consumption across peak times. A thorough analysis of optimization techniques used with renewable energy sources can be found in (Okundamiya, 2021), however, there are always new optimization techniques being presented in this area. Consequently, an updated assessment of optimization techniques being applied to various issues about the installation and operation of electricity-generating units based on renewable energy sources is presented in this study (Schulz *et al.*, 2021; (Elaziz *et al.*, 2022).

B. Hybrid System's Optimal Sizing:

Different methods for optimal sizing of HRES in the literature include the graphical construction method (Elmelegi *et al.*, 2021), Probabilistic methods (Fernández-Guillamón *et al.*, 2022), Iterative methods (Khan *et al.*, 2022), Analytical methods, and artificial intelligence methods (Hoarcă *et al.*, 2023). These approaches use computer models to characterize the various HRES components, enabling system designers to evaluate the performance of various HRES configurations and determine the techno-economic viability of the system. For instance, a hybrid biomass and photovoltaic system in a rural Spanish municipality achieved a 20% reduction in electricity

costs and a 6.13% internal rate of return (IRR) over 12 years (Roldán-Porta *et al.*, 2023).

Similarly, a study at Afe Babalola University in Nigeria evaluated a hybrid energy system (HES) for large buildings, demonstrating potential energy cost reductions of 45% and a 32.09% decrease in CO₂ emissions (Gbadamosi *et al.*, 2022). Currently, several computer software tools have been created to evaluate HRES performance, most famous of them are the hybrid optimization model for electric renewables (HOMER), iHOGA / MHOGA, Hybrid 2, Hybrid Designer, iGRHYSO, SOMES, SOLSTOR, RETScreen, and SOLSIM. (Chisale *et al.*, 2023; Arif *et al.*, 2023; Liu and Rodriguez, 2021).

The following features set these software categories—among many others—apart: they offer remarkably precise simulation results for analysis, evaluation, and optimization, lowering initial capital cost, figuring out a renewable system's ideal capacity, predicting long-term system performance, and swiftly solving numerous system configurations, which makes it simple to compare thousands of options in a single run. The following are some of the major shortcomings of these software packages: certain solutions require lengthy and sluggish processes; some software packages, like HOMER, cannot perform thermal analysis of systems; and some software packages cannot guess key values of sizes in the event that they are absent. Moreover, some software packages necessitate the use of experienced-based criteria in order to produce a satisfactory result.

III. MATERIALS AND METHODS

A. Hybrid system modeling:

To model any proposed renewable hybrid power system and meet its design objectives, the main focus is on identifying all system variables and components using appropriate techniques. The next step is to create an objective function that includes all necessary restrictions and variables, as well as components, to make sure that the load requirement is met economically and consistently. The objective function of the optimization problem with its overall system components can thus be determined if the following three requirements are satisfied:

- I. Formulating an objective function that, if the anticipated energy generation from the renewable hybrid systems is not fulfilled, that is, optimizing the system's capital cost and minimizing the kilogram of CO₂ emissions, then, a diesel generator is considered in the configuration to augment energy deficiency.
- II. Selecting the hybrid system configuration's ideal renewable energy mix.
- III. Evaluating the ideal system configuration to ascertain the financial and technological prerequisites for implementing the suggested system configuration for any case study.

Considering Figure 1 as a case study, the effective modeling of the Solar-Wind-Battery system configuration is presented as follows:

1) The Hybrid System's Total Capital Cost:

This is represented by the symbol (C^{TC}) and represents the total of the expenses associated with each of the following parts of the hybrid system:

a- The total cost price of wind energy conversion system: This covers the wind turbine's capital cost as well as installation, inverter, and replacement costs. This is according to Eqn. (1).

$$TC^{WT} = \sum_{i=1}^{M_{WT}} C_i^{C_{WT}} + \sum_{i=1}^{M_{WT}} C_i^{I_{WT}} + C^{V_{WT}} + C^{R_{WT}} \quad (1)$$

Where:

TC^{WT} = Total cost of the wind energy conversion system

C_{WT} = Wind turbine's capital cost

I_{WT} = Wind turbine installation cost

V_{WT} = Wind turbine inverter cost

R_{WT} = Wind turbine replacement cost

i = number of renewable energy sources in Eqn. (1), ranging from $\{1,2,\dots,M\}$

b- The solar system's total capital cost: This includes the capital cost of the solar PV system as well as the costs associated with installation, inverter and replacement. Eqn. (2) provides this.

$$TC^{PV} = \sum_{k=1}^{M_{PV}} C_k^{C_{PV}} + \sum_{k=1}^{M_{PV}} C_k^{I_{PV}} + C^{V_{PV}} + C^{R_{PV}} \quad (2)$$

Where:

TC^{PV} = Total capital cost of the solar system

C_{PV} = Solar system's capital cost

I_{PV} = Solar system's installation cost

V_{PV} = Solar system's inverter cost

R_{PV} = Solar system's replacement cost

k = number of renewable energy sources considered in Eqn. (2) ranging from $\{1,2,\dots,M\}$

c- The battery bank's overall cost: Eqn. (3) provides the value as the total of the battery bank's capital cost and replacement cost.

$$C^{BB} = \sum_{i=1}^{M_{BB}} C_i^{C_{BB}} + C^{R_{BB}} \quad (3)$$

Where:

C^{BB} = Overall cost of the battery bank

C_{BB} = Capital cost of the battery bank

$C^{R_{BB}}$ = Replacement cost of the battery bank

Eqn. (4) provides the renewable hybrid system's total capital Cost, which may be obtained from Eqns. (1) through (3).

$$C^{TC} = TC^{WT} + TC^{PV} + C^{BB} \quad (4)$$

d- Replacement cost: This gives the annual cost value of replacing any system component (s) over the project's duration, as shown in Eqn. (5). (Xiong et al., 2023):

$$C^{RP} = C^{CC} \cdot \delta(r, y) \quad (5)$$

where:

C^{CC} = Capital cost of each component,

δ = The sinking fund factors

r = Annual interest rate, y = the system component's lifespan.

It is important to note that, as shown in Eqn. (6), the sinking fund factor depends on the system lifetime and yearly interest rate.

$$\delta = \frac{1}{(1+r)^y - 1} \quad (6)$$

2) Estimation of Output Energy:

The energy production from each hybrid system's component is provided as:

a- Photovoltaic System: Equations and manufacturer specifications can be used to calculate a photovoltaic panel's power output. Eqn. (7) provides the power output from the PV panel:

$$P^{PV} = G^R + A^{PV} + \eta^{PV} \quad (7)$$

where:

P^{PV} = Power generated by solar panels

G^R = Global solar irradiance (kW/m²)

A^{PV} = The solar panel's surface area measured in (m²)

η^{PV} = PV module efficiency

Eqn. (8) provides the annual energy generated by the photovoltaic cells.

$$J^{PV} = P^{PV} \times \frac{9 \text{ hrs}}{\text{day}} \times 365 \text{ days [kWh]} \quad (8)$$

where: 9 hrs/day is the average assumed sunshine hours per day at the case study site within West African.

b- Wind Energy Conversion System: The wind energy system's hourly power output is represented by Eqn. (9) (Saleem and Abas, 2024; Wang et al., 2022):

$$P^{WEC} = \left\{ \begin{array}{ll} 0 & V^W < V^{ci} \text{ or } V^W \geq V^{co} \\ P_R \frac{V^W - V^{ci}}{V^r - V^{ci}} & V^{ci} \leq V^W \leq V^r \\ P_R & V^r \leq V^W < V^{co} \end{array} \right\} \quad (9)$$

where:

P^{WEC} = The total power produced by the wind energy conversion systems

P_R = Wind turbine rated power

V^W = The wind turbine's speed at hub height (h).

V^{ci} = The wind turbine Cut-in speed
 V^{co} = The wind turbine Cut-out speed
 V^r = The wind turbine rated speed

Expression (10) (Khan *et al.*, 2022; Alham *et al.*, 2023) provides the wind turbine's wind speed using a power law equation at the hub height (h), and reference height, h_{ref} .

$$V^W = V^r \left\{ \frac{h}{h_{ref}} \right\}^\alpha \quad (10)$$

where:

α = The range of the shear coefficient, which ranged between 0.10 to 0.40 (Kim *et al.*, 2021; Finnah, 2022). Eqn. (11) expresses the annual energy generated by the wind turbine.

$$J^{GWT} = P^{WEC} \times 8760 (h/yr) [kWh] \quad (11)$$

c- Battery Bank: The battery bank's state of charge can be ascertained using equations (12) and (13), which consider the energy balance relationship between the battery bank and the hybrid system's overall energy demand.

1- Charging state of the battery bank: The process of charging the battery banks begins when the energy produced by alternative energy sources, such as solar, wind, and distributed generation (DG), exceeds the demand for power. This excess energy must be stored in the battery banks for later use. Eqn. (12) provides an expression for the battery bank's available capacity at hour (h).

$$J^{G_{BB}}(h) = J^{G_{BB}}(h-1) \times (1 - \sigma) + \left[J^G(h) - \frac{J^{D_M}(h)}{\eta^{inv}} \right] \times \eta^{BB} \quad (12)$$

2- Battery bank's state of discharge: On the other hand, when the total energy produced by the several sources is not enough to fulfill the load requirement, the battery bank comes in to provide the remaining energy needed. During this process, the battery bank depleted. The battery bank's available capacity at any given hour (h) can be found using Eqn. (13).

$$J^{G_{BB}}(h) = J^{G_{BB}}(h-1) \times (1 - \sigma) + \left[\frac{J^{D_M}(h)}{\eta^{inv}} - J^G(h) \right] \quad (13)$$

where:

$J^{G_{BB}}(h)$ = Energy produced by the battery bank in hour (h) expressed in kWh.

$J^{G_{BB}}(h-1)$ = The battery bank's energy production in hours ($h-1$), measured in kWh.

σ = Battery bank's rate of self-discharge.

$J^G(h)$ = Energy generated in kWh by the renewable hybrid system.

$J^{D_M}(h)$ = Hourly hybrid system energy demand, expressed in kWh

η^{inv} = Inverter efficiency

η^{BB} = Charge efficiency of the battery bank

The total energy produced in an hour by the renewable energy system is estimated as given in Eqn. (14)

$$J_{GRES}(h) = \sum_{m=1}^{NPV} J_m^{G_{PV}} + \sum_{q=1}^{NWEC} J_q^{G_{WEC}} \quad (14)$$

where:

$J_m^{G_{PV}}$ = Energy produced by the photovoltaic modules

$J_q^{G_{WEC}}$ = Energy supply by wind energy conversion devices

m, q = the first renewable component in Eqn. (14) respectively

3) Objective Function:

The two objective functions considered in this work are:

- (1) Minimizing the Levelized Cost of Energy (LCOE); and
- (2) Maximizing system reliability.

a. Minimizing the Levelized Cost of Energy (LCOE):

Minimizing the Levelized Cost of Energy (LCOE) refers to the process of reducing the total cost of producing electricity from the renewable hybrid power system over its lifespan, divided by the total energy output expected over that same period. LCOE is a key metric used to compare the economic viability of different energy technologies.

$$\text{Minimize } LCOE = \frac{\sum_{t=0}^T \frac{C_t^T}{(1+d)^t}}{\sum_{t=1}^T \frac{J_{GRES}(t)}{(1+d)^t}} \text{ (\$/MWh)} \quad (15)$$

Subject to:

$$\text{Maximize } R = \frac{J_{GRES}(h)}{J^{D_M}(h)} \quad (16)$$

Eqn. (16) is subject to the following constraints:

i- Energy balance:

$$\sum (J^{PV} + J^{GWT} - J_{BESS\ LOSS}) \geq J_D(t) \quad (17)$$

ii- Operational limit of renewable energy sources:

$$\left\{ \begin{array}{l} J_t^{PV} \leq J_{Max}^{PV} \\ J_t^{GWT} \leq J_{Max}^{GWT} \\ J_t^{G_{BB}} \leq J_{Max}^{G_{BB}} \end{array} \right\} \quad \forall t \in \{1, 2, 3, \dots, T\} \quad (18)$$

Where:

C_t^T is the renewable hybrid system's total capital cost, including capital, installation, inverter, and replacement costs.

$J_{GRES}(t)$ is the total energy generated from the renewable hybrid system in a specific year

$J^{D_M}(h)$ is the hourly hybrid system energy demand, expressed in kWh

$J^{G_{BB}}(h)$ is the Energy produced by the battery bank in hour (h) expressed in kWh

d = is the discount rate to encourage the use of renewable energy

t = is the time intervals over the renewable hybrid system's operational life

T = is the lifespan of the renewable system, considered to be 25 years.

$J_D(t)$ is the total energy demand as a function of time

R = is the system reliability

4) Application of Advanced Energy Storage Systems:

Advanced energy storage systems, including Lithium-Ion Batteries, Flow Batteries, Solid-State Batteries, Hydrogen Storage Systems, Compressed Air Energy Storage (CAES), and Sodium-Sulfur (NaS) Batteries, are integral to optimizing dual-mode renewable hybrid power systems by addressing the intermittent nature of renewable energy. These technologies store surplus energy during peak production and release it during high demand, enhancing the reliability and operational efficiency of hybrid systems through consistent power delivery and effective load management. By improving demand response strategies, these storage solutions mitigate fluctuations in energy availability, supporting a stable and resilient supply while optimizing system performance in both grid-connected and autonomous modes. Furthermore, the integration of these advanced energy storage technologies tackles current challenges, such as energy density limitations and long-term storage inefficiencies, paving the way for more robust and optimized hybrid systems. Collectively, these advancements promise to enhance the performance and adaptability of dual-mode renewable hybrid power systems, ultimately supporting a sustainable energy future.

5. Some Research Works on Optimization of HRESs

This section provides a comparative analysis of the current study with relevant research on HRESs, employing a rigorous methodology for article selection. Peer-reviewed publications and conference proceedings were retrieved from reputable databases, including IEEE Xplore, Scopus, and Web of Science, focusing on studies from 2021–2024 to ensure contemporary relevance. Keywords such as "hybrid renewable energy systems," "dual-mode systems," and "optimization techniques" were used with Boolean operators like AND, OR,

and NOT for refined searches. Inclusion criteria emphasized studies on dual-mode HRESs, the novelty of optimization techniques enhancing system efficiency and resilience, practical case studies demonstrating real-world effectiveness, and evaluations of operational and economic performance. Non-peer-reviewed or unrelated articles were excluded from total initial search of 134 journals. Titles, abstracts, and full texts were systematically screened, resulting in 66 articles selected for detailed review. This process ensured a comprehensive exploration of advancements in dual-mode HRESs, focusing on their adaptive, efficient operations and real-world applicability.

While previous studies have comprehensively addressed sizing and other technical aspects of HRESs, there remains a need for a holistic survey that integrates social, technical, economic, environmental, and policy factors in HRES deployment, particularly in low-income settings. **Table 1 presents comparative analysis of relevant optimization research works on HRESs** and highlights key studies addressing these factors. Given the Sustainable Development Goals' emphasis on "clean and affordable energy for all," it is essential to discuss affordability for low-income earners. This review fills this gap by examining emerging challenges in off-grid HRES acquisition for households in developing countries, enhancing the field's understanding of HRES potential for universal, affordable, and clean energy.

Table 1: Comparative Analysis of relevant Optimization Research Works on HRESs

Comparison Criteria	Liu et al. (2022)	Maiya et al. (2023)	Maślak & Orłowski (2022)	Menesy et al. (2023)	Miracle et al. (2023)	Mohammed & Ali (2024)	Ramesh et al. (2022)	Nikolai dis (2023)	Shafi et al. (2021)	Shezan et al. (2023)	Singh & Gope, (2021)	Singh et al. (2024)
Relevance to Dual-Mode Renewable Systems	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Novelty of Optimization Techniques	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Case Study Relevance	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	
Advanced Control Algorithms	✓	✓	✓	✓		✓	✓		✓	✓	✓	
Adaptive Configuration		✓	✓			✓	✓	✓		✓	✓	✓
Economic and System Performance Evaluation	✓			✓	✓	✓		✓				
High Cost-Effectiveness				✓	✓	✓		✓				
Enhanced Resilience	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓
Integrated Energy Management	✓		✓	✓		✓	✓	✓		✓	✓	✓
Future Research Roadmap	✓	✓	✓	✓	✓		✓	✓	✓			✓
Publication year	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓
Peer-Reviewed Status	✓	✓	✓			✓	✓	✓		✓	✓	✓

Legend: Double tick: Current-trend significant contribution / Highly relevant recent literature (3 yrs), Single tick: Criteria implemented, Blank: No contribution in that criterion.

From the review outcome, it is evident that there is an urgent need for grid integration as a timely alternative energy solution. The effectiveness of smart grids and microgrids in maintaining system stability is particularly noteworthy, as they facilitate seamless interaction between renewable energy sources and the main grid. This study emphasizes the importance of enhancing the integration methods outlined in the reviewed papers, highlighting their potential for improving operational resilience amid evolving energy demands and climatic variability. By advancing these technologies, we can better address the challenges of intermittent energy supply and ensure a more stable and reliable power system.

IV. DISCUSSION OF FINDINGS

A. Research Key Findings, Implications, and Comparison

The key findings of this work emphasize the effectiveness of Dual mode HRES in optimizing power generation and minimizing operational costs. The comprehensive review of optimization techniques reveals that integrating diverse renewable sources such as PV, Wind, and Hydro etc., enhances system robustness and reliability. This study underscores the

pivotal role of Dual mode HRES in achieving sustainable energy goals by mitigating the adverse impacts of climate change and ensuring a stable power supply. Specifically, optimizing HRES not only improves power supply quality by reducing frequency drift but also supports cost-effective energy production. Interpreting these findings highlights the flexibility and adaptability of HRES in balancing energy generation with fluctuating demand. By leveraging multiple renewable sources, HRES effectively manages energy availability variations, thereby enhancing grid stability and reliability. This adaptability is crucial for meeting current and future energy demands sustainably, facilitating the global transition away from fossil fuel dependence.

The implications of the research findings are significant for policymakers, energy planners, and researchers. They highlight the potential of HRES to serve as a cornerstone in sustainable energy transitions worldwide. Compared to existing literature, this research contributes updated insights into evolving HRES optimization techniques. It corroborates previous findings on the benefits of integrating renewable sources, as evident in (Conteh *et al.*, 2021), and highlights ongoing advancements in enhancing system performance and operational efficiency, as documented by (Solomin *et al.*,

2021). Additionally, it recognizes the role of HRES in optimizing consistent power generation, as affirmed by (Reddy et al., 2021), while also focusing on reducing operational costs and improving system reliability, as supported by (Al Hasibi and Haris, 2023).

Additionally, the review affirms the pivotal role of HRES in mitigating climate change impacts and ensuring sustainable energy supply. However, differences in perspectives exist regarding specific operational challenges and regional implementation strategies, highlighting the need for context-specific approaches in deploying HRES. Dual-mode HRESs are particularly relevant in this context, as they offer enhanced flexibility in both grid-connected and autonomous operations, ensuring a resilient, reliable, and adaptive energy supply in diverse geographical and operational settings.

B. Crucial Ways to Mitigate HRES Energy Crisis

The increasing need for energy and the finite supply of non-renewable energy sources, including fossil fuels, are referred to as the "energy crisis." Concerns over environmental damage, economic instability, and energy security have grown because of this situation. The growing population is one of the main causes of the energy issue. Does the demand for energy increase in tandem with the growth of the world population? The population of the globe is predicted to reach 9.7 billion people by 2050 according to the United Nation (Singh and Gope, 2021) which will raise the need for energy to meet necessities like heating, lighting, and transportation.

Economic expansion is one of the main causes of the energy issue. Growing economies are frequently linked to rising energy prices. Energy demand rises as nations continue to industrialize and modernize. The International Energy Agency projects that by 2040, the world's energy consumption will have grown by 30% because of population and economic expansion (Soares et al., 2023). Economic expansion is a significant contributing factor to the energy dilemma. Increased energy use is frequently linked to economic growth.

Renewable energy sources, such as solar, wind, hydro, geothermal, biomass, and tidal energy, offer a practical solution to the energy crisis by increasing the availability of clean, sustainable, and reliable energy. Solar energy is among the most promising forms of renewable energy. It might potentially help the globe reduce its dependency on fossil fuels while meeting a significant portion of its energy needs. According to the International Energy Agency (IEA) forecasts, solar energy might provide up to 16% of global electricity needs by 2050 (Singh et al., 2024).

C. Research Gap Assessment

Several researchers have used various approaches to determine the ideal size of an autonomous renewable HRES that consists of diesel generators, PV arrays, wind turbines, and battery banks at various points in time. There have been many studies on optimizing hybrid energy systems using various computational intelligence techniques, including stochastic

and deterministic approaches (Shezan et al., 2023). However, there have been few comparisons between simulation tools and strategies inspired by nature. Additionally, there have not been many attempts to create a hybrid approach for maximizing renewable energy systems using various resources to suit rural society's energy needs. Therefore, academia and researchers are urged to focus on these subject areas and beyond to determine the variables and parameters appropriate for a given problem (Maiya and Aithal, 2023).

D. Research Limitations

Amid pressing environmental challenges, dual-mode renewable hybrid power systems stand as a promising solution for sustainable energy. However, their effectiveness varies across global regions and climates, necessitating targeted optimization for efficiency and cost-effectiveness. This review highlights key challenges that hinder broader deployment:

I. High initial capital costs limit widespread adoption of HRES.

1. Readiness and regulatory differences pose barriers to extensive implementation.
2. Social acceptance and supportive governmental policies are crucial beyond technical and economic aspects.
3. Safety concerns call for adequate safety measures and upgrades to existing protection mechanisms.
4. The inflexibility of autonomous systems to adapt to load changes can risk system-wide failures during significant load shifts.
5. Establishing intelligent mini-grids with inter-communicating generators is essential yet challenging.
6. Reliable communication between system components requires real-time management frameworks, such as IEEE Standard 1547 and IEC 61850 (Demertzis et al., 2021).
7. Transient studies are critical to address stability issues in HRES, especially with variable parameters.
8. Government subsidies are pivotal to facilitate HRES deployment.
9. Further research on advanced semiconductor technologies, including silicon carbide and gallium nitride, is essential to optimize HRES performance.

Addressing these complexities through innovation and collaboration will be critical to realizing the full potential of dual-mode hybrid systems, paving the way for a sustainable future.

E. Future Direction

Future research should focus on addressing key challenges identified in optimizing dual-mode renewable hybrid power systems, particularly in enhancing integration techniques for diverse renewable sources and storage technologies. Developing advanced control algorithms and predictive models to manage energy fluctuations more effectively in dual-

mode operations is crucial. Furthermore, there is a need to explore innovative approaches in system architecture design, energy management strategies, and economic assessments to maximize system efficiency and cost-effectiveness. Longitudinal studies should assess the environmental and socio-economic impacts of these systems to ensure sustainable deployment and scalability. Collaborative efforts between researchers, policymakers, and industry stakeholders are essential for advancing regulatory frameworks and financing mechanisms that support widespread adoption of dual-mode hybrid systems globally.

V. CONCLUSION

In our urgent quest for sustainable energy solutions, dual-mode renewable hybrid power systems stand as beacons of innovation and hope. This review highlights their critical role in addressing challenges such as the inherent dependence of HRES on environmental conditions, location, and operational state, which result in voltage and frequency fluctuations that can disrupt sensitive equipment, impair system stability, and affect overall system reliability. Key findings in this work underscore the effectiveness of integrating grid-connected and autonomous operational modes to ensure a reliable power supply and enhance system efficiency. The unique contributions of this research include a comprehensive analysis of optimization techniques tailored for dual-mode systems, advancements in architecture sizing, energy management strategies, and economic evaluations—critical elements for improving system resilience and cost-effectiveness. This work identifies avenues for improving system performance and cost-effectiveness, thereby laying a foundation for future advancements in renewable energy solutions. To add value to the work, further research should focus on refining integration technologies, developing advanced optimization algorithms, and addressing socio-economic barriers to widespread adoption. These efforts will be crucial in realizing the full potential of dual-mode hybrid systems and advancing global energy sustainability goals.

AUTHOR CONTRIBUTIONS

Ariyo, B.O.: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Resources; Software; Validation; Visualization; Writing - original draft; Writing - review & editing.

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REFERENCES

- Afanasov, C., Atănăsoae, P., Ifrim, V.C., Milici, L.D., Pentiu, R.D., Pop, T. and Ungureanu, C. (2023).** Off-Grid Hybrid Renewable Energy System Operation in Different Scenarios for Household Consumers. *Energies*, 16(7), 1–21.
- Ahmad, I., Aziz, A., Habibi, D., Mahmoud, T., and Qays, M.O. (2023).** System strength shortfall challenges for renewable energy-based power systems: A review. *Renewable and Sustainable Energy Reviews*, 183(June), 113447.
- Ahmed, I., Rehan, M., Basit, A. and Hong, K. S. (2022).** Greenhouse gases emission reduction for electric power generation sector by efficient dispatching of thermal plants integrated with renewable systems. *Scientific Reports*, 12(1), 1–21.
- Al-Shahri, O. A., Ismail, F. B., Hannan, M. A., Hossain Lipu, M. S., Al-Shetwi, A. Q., Begum, R. A., Al-Muhsen, N. F. O. and Soujeri, E. (2021).** Solar photovoltaic energy optimization methods, challenges and issues: A comprehensive review. *Journal of Cleaner Production*, 284, 1–18.
- Alham, M.H., Fathy Gad, M. & Khalil Ibrahim, D. (2023).** Potential of wind energy and economic assessment in Egypt considering optimal hub height by equilibrium optimizer. *Ain Shams Engineering Journal*, 14(1), 1–12.
- AlKandari, M. & Ahmad, I. (2024).** Solar power generation forecasting using ensemble approach based on deep learning and statistical methods. *Applied Computing and Informatics*, 20(3–4), 231–250..
- Ammari, C., Belatrache, D., Touhami, B. and Makhoulf, S. (2022).** Sizing, optimization, control and energy management of hybrid renewable energy system—A review. *Energy and Built Environment*, 3(4), 399–411.
- Arif, R., Arief, Y.Z., Wilyanti, S., Pangestu, A. and Al-Hakim, R.R. (2023).** Using HOMER Simulation Method for Renewable Energy Power Generation Design in South Sumatra Indonesia, *International Journal of Sustainability in Research (IJSR)*, 1(2), 73–92. https://www.researchgate.net/profile/Rosyid-Ridlo-Al-Hakim-2/publication/373900510_Using_HOMER_Simulation_Method_for_Renewable_Energy_Power_Generation_Design_in_South_Sumatra_Indonesia/links/6502b8758d6da36cc877ecf9/Using-HOMER-Simulation-Method-for-Renew.
- Asiaban, S., Kayedpour, N., Samani, A.E., Bozalakov, D., De Kooning, J.D.M., Crevecoeur, G. and Vandeveld, L. (2021).** Wind and solar intermittency and the associated integration challenges: A comprehensive review including the status in the belgian power system. *Energies*, 14(9), 1–41.
- Basu, J.B., Dawn, S., Saha, P.K., Chakraborty, M.R. and Ustun, T.S. (2022).** A Comparative Study on System Profit Maximization of a Renewable Combined Deregulated Power System'. *Electronics (Switzerland)*, 11(18), 1–29.

- Bhuiyan, M.R.A. (2022).** Overcome the future environmental challenges through sustainable and renewable energy resources., *Micro and Nano Letters*, 17(14), 402–416.
- Bubalo, M., Bašić, M., Vukadinović, D. and Grgić, I. (2023).** Hybrid Wind-Solar Power System with a Battery-Assisted. *Energies*, 16(3), 1–24.
- Canale, L., Di Fazio, A. R., Russo, M., Frattolillo, A. and Dell’Isola, M. (2021).** An overview on functional integration of hybrid renewable energy systems in multi-energy buildings. *Energies*, 14(4), 1–33.
- Castro-Toro, I. (2023).** Techno-economic models of hybrid systems with renewable energy for rural applications. *DYNA (Colombia)*, 90(226), 115–123.
- Chisale, S.W., Eliya, S. & Taulo, J. (2023).** Optimization and design of hybrid power system using HOMER pro and integrated CRITIC-PROMETHEE II approaches. *Green Technologies and Sustainability*, 1(1), 100005.
- Come Zebra, E.I. (2021).** A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. *Renewable and Sustainable Energy Reviews*, 144, 1–23.
- Conteh, F. (2021).** Analysis of hybrid grid-connected renewable power generation for sustainable electricity supply in sierra leone. *Sustainability (Switzerland)*, 13(20), 1–20.
- Ding, Y., Chen, X. & Wang, J. (2023).** Deep Reinforcement Learning-Based Method for Joint Optimization of Mobile Energy Storage Systems and Power Grid with High Renewable Energy Sources. *Batteries*, 9(4), 1–16..
- Elaziz, M.A., Nikoo, M.R. & Gandomi, A.H. (2022).** Wind, Solar, and Photovoltaic Renewable Energy Systems with Advanced Machine Learning and Deep Learning Techniques. *Energies*, 15(578), 1–26.
- Elmelegi, A. (2021).** Optimized Tilt Fractional Order Cooperative Controllers for Preserving Frequency Stability in Renewable Energy-Based Power Systems. *IEEE Access*, 9, 8261–8277.
- Erdiwansyah (2021).** A critical review of the integration of renewable energy sources with various technologies. *Protection and Control of Modern Power Systems*, 6(1), 1–18.
- Fabra, N. & Llobet, G. (2022).** Auctions With Privately Known Capac Ities. :, 133(November), 1106–1146.
- Fernández-Guillamón, A., Muljadi, E. & Molina-García, A. (2022).** Frequency control studies: A review of power system, conventional and renewable generation unit modeling. *Electric Power Systems Research*, 211, 1–15.
- Finnah, B. (2022).** Optimal bidding functions for renewable energies in sequential electricity markets’ *OR Spectrum*, 44(1), 1–25.
- Firoozi Fard, A. & Hajimirza amin, N. (2023).** Leveraging Machine Learning for Prediction and Optimizing Renewable Energy Systems. 1–9.
- Gbadamosi, S.L. (2022).** Techno-Economic Evaluation of a Hybrid Energy System for an Educational Institution: A Case Study. *Energies*, 15(15), 1–12. <https://doi.org/10.3390/en15155606>.
- Giama, E. (2023).** Energy and Environmental Analysis of Renewable Energy Systems Focused on Biomass Technologies for Residential Applications: The Life Cycle Energy Analysis Approach. *Energies*, 16(11).
- Gulzar, M.M. (2022).** Load Frequency Control (LFC) Strategies in Renewable Energy-Based Hybrid Power Systems: A Review. *Energies*, 15(10), 1–23.
- Al Hasibi, R.A. & Haris, A. (2023).** An analysis of the implementation of a hybrid renewable-energy system in a building by considering the reduction in electricity price subsidies and the reliability of the grid. *Clean Energy*, 7(5), 1125–1135.
- Hassan, M.H., Kamel, S. & Hussien, A.G. (2023).** Optimal power flow analysis considering renewable energy resources uncertainty based on an improved wild horse optimizer. *IET Generation, Transmission and Distribution*, 17(16), 3582–3606.
- He, M. (2023).** Optimal Design of Hybrid Renewable Systems, Including Grid, PV, Bio Generator, Diesel Generator, and Battery. *Sustainability (Switzerland)*, 15(4), 1–16.
- He, W. (2021)** ‘Optimal analysis of a hybrid renewable power system for a remote island. *Renewable Energy*, 179, pp. 96–104.
- Hoarcă, I.C. (2023).** Sizing Design for a Hybrid Renewable Power System Using HOMER and iHOGA Simulators. *Energies*, 16(4), 1–25.
- Hu, J.L. & Bui, N.H.B. (2024).** The Future Design of Smart Energy Systems with Energy Flexurers: A Constructive Literature Review. *Energies*, 17(9), 1–32.
- Khan, A.A. (2022).** Optimal Sizing, Control, and Management Strategies for Hybrid Renewable Energy Systems: A Comprehensive Review. *Energies*, 15(17), 1–29. **Khatri, K.C.A. (2023).** Genetic Algorithm Based Techno-Economic Optimization of an Isolated Hybrid Energy System, (Online). *Ictact Journal on Microelectronics*, 08(04), 1–5.
- Khosravani, A. (2023).** Challenges of reaching high renewable fractions in hybrid renewable energy systems. *Energy Reports*, 9, 1000–1017. **Kim, D.Y., Kim, Y.H. & Kim, B.S. (2021).** Changes in wind turbine power characteristics and annual energy production due to atmospheric stability, turbulence intensity, and wind shear. *Energy*, 214, 1–30.
- Le, T.S. (2023).** Optimal sizing of renewable energy storage: A techno-economic analysis of hydrogen, battery and hybrid systems considering degradation and seasonal storage. *Applied Energy*, 336, 1–19.
- Liu, B. & Rodriguez, D. (2021).** Renewable energy systems optimization by a new multi-objective optimization technique: A residential building. *Journal of Building Engineering*, 35, 1–32.

- Lombardi, F., Pickering, B. & Pfenninger, S. (2023).** What is redundant and what is not? Computational trade-offs in modelling to generate alternatives for energy infrastructure deployment. *Applied Energy*, 339, 1–29.
- Maiya, A.K. & Aithal, P.S. (2023).** A Review based Research Topic Identification on How to Improve the Quality Services of Higher Education Institutions in Academic, Administrative, and Research Areas. *International Journal of Management, Technology, and Social Sciences*. 8(3), 103–153.
- Majeed Butt, O., Zulqarnain, M. & Majeed Butt, T. (2021).** Recent advancement in smart grid technology: Future prospects in the electrical power network. *Ain Shams Engineering Journal*, 12(1), 87–695.
- Okundamiya, M.S. (2021).** Size optimization of a hybrid photovoltaic/fuel cell grid connected power system including hydrogen storage. *International Journal of Hydrogen Energy*, 46(59), 30539–30546.
- Pagnini, L., Bracco, S., Delfino, F. and de-Simón-Martín, M. (2024).** ‘Levelized cost of electricity in renewable energy communities: Uncertainty propagation analysis’, *Applied Energy*, 366, pp. 1–20. Available at:
- Panda, D.K. & Das, S. (2021).** Smart grid architecture model for control, optimization and data analytics of future power networks with more renewable energy. *Journal of Cleaner Production*, 301, 1–25.
- Rahman, M.M. (2021).** Prospective methodologies in hybrid renewable energy systems for energy prediction using artificial neural networks. *Sustainability (Switzerland)*, 13(4), 1–28.
- Rasolomampionona, D.D. (2024).** A Comprehensive Review of Load Frequency Control Technologies’. *Energies*, 17(12), 1–74.
- Rathod, A.A. & Subramanian, B. (2022).** Scrutiny of Hybrid Renewable Energy Systems for Control, Power Management, Optimization and Sizing: Challenges and Future Possibilities. *Sustainability (Switzerland)*, 14(24), 1–35.
- Reddy, C.R. (2021).** Power quality improvement in hres grid connected system with fopid based atom search optimization technique. *Energies*, 14(18), 1–29.
- Roldán-Porta, C. (2023).** Optimising a Biogas and Photovoltaic Hybrid System for Sustainable Power Supply in Rural Areas. *Applied Sciences (Switzerland)*, 13(4), 1–20.:
- Roy, P. (2022).** Recent Advances of Wind-Solar Hybrid Renewable Energy Systems for Power Generation: A Review. *IEEE Open Journal of the Industrial Electronics Society*, 3, 81–104.
- Salac, A. (2024).** Off-Grid Electrification Using Renewable Energy in the Philippines: A Comprehensive Review. *Smart Cities*, 7(3), 1007–1043.
- Saleem, M.S. & Abas, N. (2024).** Optimizing renewable polygeneration: A synergetic approach harnessing solar and wind energy systems. *Results in Engineering*, 21(January), 101743.
- Sankaran, K.S., El-Bayeh, C.Z. & Eicker, U. (2022).** Design of Multi-Renewable Energy Storage and Management System Using RL-ICSO Based MPPT Scheme for Electric Vehicles. *Sustainability (Switzerland)*, 14(8), 1–21.
- Schulz, J. (2021).** Renewable on-site power generation for manufacturing companies-technologies, modeling, and dimensioning. *Sustainability (Switzerland)*, 13(7), 1–27.
- Shafi, I. (2023).** An Artificial Neural Network-Based Approach for Real-Time Hybrid Wind-Solar Resource Assessment and Power Estimation. *Energies*, 16(10), 1–18.:
- Shahzad, S. & Jasińska, E. (2024).** Renewable Revolution: A Review of Strategic Flexibility in Future Power Systems. *Sustainability (Switzerland)*, 16(13), 1–24.
- Shezan, S.A. et al. (2023)** ‘Optimization and control of solar-wind islanded hybrid microgrid by using heuristic and deterministic optimization algorithms and fuzzy logic controller’, *Energy Reports*, 10(March), pp. 3272–3288.
- Singh, K.M. & Gope, S. (2021).** Renewable energy integrated multi-microgrid load frequency control using grey wolf optimization algorithm. in *Materials Today: Proceedings. Elsevier Ltd.*, (pp. 2572–2579).
- Singh, S. (2024).** Optimum Power Forecasting Technique for Hybrid Renewable Energy Systems Using Deep Learning. *Electric Power Components and Systems*, 0(0), 1–18. .
- Soares, I., Alves, M.J. & Antunes, C.H. (2023).** A deterministic bounding algorithm vs. a hybrid meta-heuristic to deal with a bilevel mixed-integer nonlinear optimization model for electricity dynamic pricing. *Computers and Operations Research*, 155(January).
- Solomin, E. (2021).** Hybrid floating solar plant designs: A review’, *Energies*, 14(10), 1–25.
- Wang, S., Moan, T. & Jiang, Z. (2022).** Influence of variability and uncertainty of wind and waves on fatigue damage of a floating wind turbine drivetrain. *Renewable Energy*, 181, 870–897.
- Xiong, B., Guo, Y., Zhang, L., Li, J., Liu, X. and Cheng, L. (2023).** Optimizing electricity demand scheduling in microgrids using deep reinforcement learning for cost-efficiency. *IET Generation, Transmission and Distribution*, 17(11), 2535–2544.
- Zisos, A., Sakki, G.K. & Efstratiadis, A. (2023).** Mixing Renewable Energy with Pumped Hydropower Storage: Design Optimization under Uncertainty and Other Challenges. *Sustainability (Switzerland)*, 15(18), 1–21.