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Transdisciplinary approach to accelerate the adoption of hybrid renewable energy systems through sustainable design

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The inclusion of renewable energy in the global energy mix has emerged as one of the viable solutions for addressing energy demand and ensuring decarbonization of the energy sector. However, their proliferation faces various challenges related to decision making, optimization and design complexity that cuts across various disciplines. Hence, transitioning into renewable energy is a transdisciplinary subject integrating expertise from diverse fields, including engineering, environmental science, economics, political and social sciences. This study presents a review of transdisciplinary approach to accelerate the adoption of hybrid renewable energy systems through sustainable design. The review starts with a discussion on the sustainable design principles with emphasis on lifecycle assessments, modularity, and resilience to enhance hybrid renewable energy systems (HRES) efficiency and adaptability. Next, the study surveyed various optimization techniques that have been used in the sizing of HRES, including linear programming and metaheuristics approaches. Furthermore, the study reviewed multi-criteria methods that can be used in the evaluation and prioritization of optimal HRES obtained from the optimization techniques based on multiple attributes. Also, the study examined how spatial optimization can be used to improve the adoption of HRES. Finally, the study proposed a transdisciplinary framework which synthesizes various disciplines that can help in accelerating the adoption of Hybrid Renewable Energy Systems. It is expected that this approach would provide a robust approach to the widespread adoption of HRES technologies.

KEYWORDS

hybrid renewable energy systems, sustainable design, size optimization, spatial optimization, multi-criteria decision-making

1 Introduction

As the world moves closer to the 2030 deadline for attaining sustainable developmental goals (SDG), there has been more emphasis on the urgency to propose models that can accelerate the accomplishment of the various targets specified under the sustainable development goals (SDGs) (Van Driel, 2020). A stock of reality on the ground shows that sustainability issues related to poverty eradication, reduction of hunger, quality education, gender equity, good health and wellbeing, clean and affordable energy, climate change, sanitation, employment, innovation, and inequality reduction all remain active. To mitigate these sustainability challenges—such as the environmental degradation caused by CO_2 emissions, the socioeconomic impacts of climate change on agricultural productivity, biodiversity loss, and water scarcity, as well as the reliance on fossil fuels—innovative and comprehensive efforts must be directed toward achieving the targets outlined under each Sustainable Development Goal (SDG) (Dzhunushalieva and Teuber, 2024). With respect to climate action -SDG 13, the importance of reducing climate change is underscored as it impacts agricultural and food security, biodiversity and eco-system, human settlement and health, water resources availability, economy, cultural identity and heritage, energy systems, and geopolitics (Owusu-Sekyere et al., 2024). This necessitates a reduction in the use of fossil fuels, which are major contributors to CO_2 emissions, a primary component of greenhouse gases that cause climate change (Emezirinwune et al., 2024).

As such, various research and policy initiatives have been directed at slowing down the catastrophic effects of climate change across the globe through the reduction of GHG emissions (Adebisi et al., 2022). In this context, the role of hybrid renewable energy systems (HRES) is crucial, underscoring the significance of innovations in HRES design, optimization, and decision-making. From the foregoing, to catch up with the proposed deadline of attaining SDGs 13, it is important to also innovatively invest in SDG 7-affordable and clean energy for all (Babayomi O. O. et al., 2023). Innovations such as efficient solar, wind harvesting and storage, and more efficient power electronics have been reported in various literature (Babayomi O. et al., 2023). However, to ensure that HRES technologies permeate local communities, changes in social practices, innovative business models, and radical but achievable policies are also important, thus emphasizing the criticality of a transdisciplinary approach for sustainable HRES design (Akinyele et al., 2018). Recognizing the urgent need for effective and timely contributions toward sustainability science, this paper reviews how transdisciplinary approaches can further accelerate the uptake of Hybrid Renewable Energy Systems (HRES), through sustainable design. According to the literature, transdisciplinary is necessary to address the complexity of challenges associated with HRES projects (Ozsoy and Mengüç, 2023). The aim of this paper is to present a review of limitations of single-discipline approaches to adoption of renewable energy, examine the integration of sustainable design into HRES adoption, planning and implementation. The study further proposed the synergy between size optimization strategies, Multi-Criteria Decision-Making approaches and Spatial Optimization.

2 The need for transdisciplinary approaches in HRES adoption

Developing Hybrid Renewable Energy Systems (HRES) requires a holistic approach that transcends the limitations of single-discipline methodologies, leveraging insights from multiple fields to address complex design, implementation, and operational challenges. This section discusses the limitations of considering the development of HRES using a single discipline approach. It also explores the benefits of integrating knowledge from other essential disciplines to the development of HRES.

2.1 Limitations of single-discipline approaches in addressing the complexity of HRES adoption

The challenges presented by the design and development of hybrid renewable energy systems are complex and cut across many disciplines like technical, economic, social, and environmental (Babatunde et al., 2020a). However, single-discipline approaches that are traditionally employed cannot deal adequately with these multi-faceted issues (Babatunde et al., 2019a). Typically, engineers tend to dwell on optimizing performance, while economists are more interested in cost-benefit analysis (Babatunde et al., 2019a). In such a segmented approach, there is no place for socio-environmental impacts of the stakeholder engagement which are also critical in successfully implementing HRES. The integration of multiple renewable energy sources and energy storage requires various power electronic devices and dispatch strategies which make its design complex (Babatunde et al., 2020b). Apart from these technical challenges, considerations for environmental and social requirements also present another challenge that cannot be solved through a single based approach (Akinyele et al., 2018), the development and design of HRES, therefore, requires a comprehensive and multidisciplinary approach. Moreover, single-discipline approaches tend to fragment knowledge and strategies; for example, a technical solution that offers the highest energy efficiency might not be economically viable, nor will it be socially acceptable (Babatunde et al., 2019a). Hence, an economically viable solution might not provide environmental sustainability or be socially equitable (Babayomi O. O. et al., 2023). Hence, a single-disciplined approach to HRES development can lead to suboptimal results in which the installed system is not fully utilized or optimized in terms of performance or sustainability, let alone acceptance (Babatunde et al., 2019a).

2.2 Potential benefits of integrating knowledge and methods from various disciplines

A transdisciplinary approach can achieve a much higher degree of HRES adoption by integrating knowledge and methods from diverse disciplines (Beckett and Terziovski, 2023). A transdisciplinary approach will enhance HRES adoption through in-depth perception and appreciation of the challenges and opportunities in developing innovative and effective solutions (Zebra et al., 2021). A transdisciplinary approach has several benefits in the following ways:

2.2.1 Comprehensive problem-solving

A transdisciplinary approach draws expertise from multiple disciplines and can be used to address a wide range of problems related to HRES adoption (Babayomi O. O. et al., 2023). Engineers can work together with environmental scientists, economists, as well as social scientists to arrive at solutions that are technically sound, environmentally sustainable, economically viable, and socially acceptable (Cherp et al., 2018). This capability for comprehensive problem solving becomes a critical tool for overcoming the complex challenges associated with HRES (Hassan et al., 2023).

2.2.2 Innovative solutions

Transdisciplinary collaboration tends to trigger innovation, as diversified views and approaches are brought on one platform, for example, ecological insights combined with engineering knowledge can provide bio-inspired technologies that enhance the efficiency and resilience of HRES (Zheng et al., 2013). Also, knowledge of economic analysis brought into social science research can give birth to innovative policy frameworks, which would encourage the adoption of renewable policies, while concurrently addressing social equity concerns (Sovacool and Dworkin, 2015).

2.2.3 Increased stakeholder engagement

Transdisciplinary approaches facilitate the inclusion of stakeholders within the decision-making process. Such engagement is essential so that solutions developed for HRES align with the needs and desires of communities, policy and decision-makers, industry, as well as other relevant stakeholder groups (Lang et al., 2012). By embedding the community, policy, and decision-makers, industry, and the academic sector within the process, transdisciplinary approaches increase the legitimacy and acceptance of HRES projects (Wiek and Lang, 2016). This simply increases the chance of success as well as the long-term sustainability of the projects (Thompson Klein, 2004).

2.2.4 Resilience and adaptability

Integration of knowledge from other disciplines will increase resilience and the capacity of HRES to adapt. For instance, technical knowledge can be integrated with environmental and social concerns to make the energy system more resilient thereby enabling it to swiftly recover from any disruption (Folke et al., 2016). An integrated approach ensures that HRES can adjust to changing environmental variables, technological developments, and new societal demands over its lifetime, making it more resilient and adaptable (Akinyele et al., 2018).

2.3 The necessity of transdisciplinary collaboration for effective HRES implementation

Transdisciplinary collaboration is crucial for the successful implementation of hybrid renewable energy systems because the approach brings on board relevant stakeholders such as researchers, engineers, economists, legislators, policymakers and analysts, and community members to work towards a common goal or objective (Babayomi O. O. et al., 2023). Stakeholders' collaborative efforts on this scale enable holistic planning and design because technical, economic, social, and environmental perspectives are integrated. Engineers can work with environmental scientists to ensure that HRES have the least possible ecological impacts; social scientists, in cooperation with the communities, ensure that they are socially acceptable and economically beneficial (Piwowar-Sulej et al., 2023). Transdisciplinary collaboration in policy and governance enables the formulation and implementation of regulations, incentives, and support mechanisms conducive to adopting HRES: their policies are informed by the most recent scientific research and practical insights (Lawrence et al., 2022).

Capacity building and knowledge transfer also play a significant role because transdisciplinary collaboration supports educational programs, training initiatives, and knowledge-sharing platforms that enhance the skills and knowledge of stakeholders so that they become well-equipped in the implementation and management of HRES (Medved et al., 2023). Continuous monitoring and evaluation are also necessary for the long-term success and sustainability of HRES. Transdisciplinary collaboration enables comprehensive monitoring and evaluation frameworks considering technical indicators, economic indicators, social indicators, and environmental indicators (Carbajo and Cabeza, 2019). These would allow stakeholders to assess performance and impact against their benchmark, identify areas for improvement, and make relevant decisions about future projects. As a result, transdisciplinary collaboration would precipitate a shared understanding of the challenges and opportunities of adopting HRES and a sense of ownership as well as the commitment of all stakeholders (Akinyele et al., 2018). Thus, transdisciplinary collaboration can harness the strengths of diverse perspectives to appropriately address the complexity and interdependence of issues that have restricted the diffusion of HRES. This collaboration expedites the transition to sustainable energy systems and supports the global achievement of sustainability goals (Haywood et al., 2019).

3 Sustainable design principles in HRES planning and implementation

Sustainable design principles are essential in the design of a viable HRES. This section examines the role of sustainable design in the adoption of HRES while discussing the principles behind sustainable design as it applies to HRES.

3.1 The role of sustainable design in enhancing the environmental, social, and economic performance of HRES

Application of the principles of sustainable design can significantly enhance the environmental, social, and economic performance of HRES (Elkadeem et al., 2021). The use of renewable sources reduces the reliance on fossil fuels, hence reducing carbon emissions and air pollution while also delaying non-renewable resource depletion and mitigating adverse impacts of GHGs on the environment (Babatunde O. M. et al., 2022). Socially, sustainable design serves the community by engaging local communities right from the design stage to the implementation stage, ensuring that systems are tailored to meet specific needs and preferences to earn greater acceptance and support for renewable energy projects (Toniolo et al., 2023). Improved access and affordability particularly in underserved or isolated communities also contribute to social welfare and progress in attainment of SDG 7 (Zebra et al., 2023). In economic terms, sustainable design enhances cost efficiency through resource optimization and reduction in operational and maintenance costs (Babatunde et al., 2020b). Furthermore, energy-efficient systems consume less energy to perform the same task than their conventional counterparts, thus reducing energy bills. Additionally, lifecycle assessments are another perspective of sustainable design that create opportunities for savings through the use and selection of environmentally friendly and cost-effective materials and processes (Akintayo et al., 2024), at the same time, resilient and adaptive designs reduce the requirement for costly repairs and upgrades (Babatunde et al., 2020a).

3.2 Sustainable design principles and their application to HRES

To develop a comprehensive solution for HRES it is essential to integrate sustainable design principles into every aspect of its development (Akinyele et al., 2022). Hence, sustainable design should be systematically baked into every level of the energy system—from initial planning down to its implementation and, hence, in operation. At the planning stage, lifecycle assessments inform the selection of materials and technologies with lower environmental impacts (Babatunde et al., 2024). During the implementation stage, adoption of energy-efficient technologies and practices would help to optimize the system performance (Babatunde et al., 2020b), while continuous monitoring and evaluation of the system is also essential; it makes the energy system resilient and adaptive to changes over its lifespan (Abdulsalam et al., 2023a).

Sustainable design is critical in the development and implementation of HRES because it creates systems that are efficient, cost-effective, environmental-friendly, and socially responsible (Akinyele et al., 2018). Sustainable principles include energy efficiency (Moustakas et al., 2020), life cycle assessment (Babatunde et al., 2024), resilience, modularity and adaptability (Yazdanie, 2023). Energy efficiency deals with the optimization of energy used to prevent wastage while supporting effective performance. With regards to HRES, energy efficiency essentially manages the integration of different renewable energy sources to ensure a balance between produced and consumed energy. This can be achieved through smart grids or demand response mechanisms that manage supplies in line with changing demand patterns (Adebisi and Ndjuluwa, 2024; Abdulsalam et al., 2023b), hence improving system efficiency. Life Cycle assessment (LCA) assesses the environmental impacts of a system over its entire life cycle and provides a basis for the choice of raw materials with reduced environmental impact (Babatunde et al., 2024). LCA also gives insights into process optimization that can reduce the total environmental impact. Resilience is defined as the ability of the system to withstand and recover from disruptions, such as extreme weather events or technical failures (Babatunde et al., 2020c). Resilient designs feature redundancies and backup systems, including the use of multiple energy storage technologies to provide alternative pathways of energy supply in case of disruption (Adebisi et al., 2023). Modular approaches in design facilitate ease of maintenance or upgrade, thereby also increasing system resilience and lifetime of the system (Shaik et al., 2015), while adaptability ensures the system's responsiveness to new technologies or being able to take care of changing needs from both the environment and society by embracing advanced, learnable, and integrative solutions (Tang et al., 2020). Considering these design principles, to attain sustainable design in HRES, size optimization strategies, multi-criteria decision making as well as spatial optimization strategies are all essential (Babatunde et al., 2019a).

4 Size optimization strategies for HRES

Planning and implementation of the HRES requires optimal sizing mainly because the energy system should be able to match the demand without overcapacity that increases the costs unnecessarily or under-capacity that brings reliability issues (Ajiboye et al., 2023). The optimization of component size and configuration maximizes the efficiency of the HRES while the costs are kept at a minimum for optimal performance (Modu et al., 2023). Proper sizing also involves estimating the appropriate mix of various types of renewable energy sources such as solar, wind, biomass, and energy storage-system that offers effective operation under various conditions (Babatunde et al., 2020b). Proper size optimization has a significant impact on the performance and adoption of HRES. An optimized system will be more efficient, cost-effective, and reliable; hence, stakeholders will find it more acceptable, and the possibility of its adoption will increase (Babatunde et al., 2020a). Optimal sizing ensures that HRES meets any energy demand reliably, reducing operational costs through decreased dependence on backup power sources (Babatunde O. et al., 2022). Size optimization will make the HRES project more economically viable, enhancing its attraction for investors and policymakers. Also, size optimization minimizes the environmental impact of HRES because it ensures resource efficiency and that systems operate at their optimum performance level and hence minimize waste and emissions (Mayer et al., 2020). Also, size optimization techniques can be incorporated into energy systems to handle uncertainty and variation in energy production and consumption, leading to its overall stability and resilience (Bamshad and Safarzadeh, 2023).

Size optimization, therefore, makes HRES projects scalable to different sizes and capacities; this becomes very important during deployment in varied geographical and socio-economic contexts (Babayomi O. O. et al., 2023). Thus, size optimization forms one of the most critical components in the planning and execution of HRES. Advanced optimization techniques and tools ensure that systems are optimally designed to efficiently and cost-effectively match energy demand. Proper size optimization leads to the adoption and successful implementation of HRES that can contribute to the broader goals of sustainable energy transition and development. Optimal sizing has implications that extend beyond immediate cost savings and efficiency gains; it also enhances the long-term sustainability and resilience of HRES, supporting the global shift towards renewable energy and sustainable development (Babatunde et al., 2020b). Various objective functions may be examined in the design of an HRES; such objectives include, minimizing total costs or life cycle costs, maximizing reliability, maximizing renewable energy fractions, and minimizing the cost of energy (Ajeigbe et al., 2020). Others include minimizing emissions, maximizing employment creation, minimizing imported energy, and maximizing profits. These objectives, with their associated constraints, can be dealt with using optimization techniques. According to research, minimization of associated costs and maximization of reliability are considered as significant objectives involved in HRES sizing, modeling, and optimization (Modu et al., 2023). Several optimization strategies have been developed for determining the appropriate size of HRES components. The techniques can be categorized as traditional optimization techniques, heuristics and meta-heuristics, hybrid techniques, and commercially accessible software.

The following are some classical optimization techniques that have been applied in the modeling and optimization of HRES: Linear Programming (LP), Nonlinear Programming (NLP), Integer Programming (IP), Mixed-Integer Programming (MIP), Dynamic Programming (DP), Quadratic Programming (QP), Conic Programming, Stochastic Programming (SP), Constraint Programming, Sequential Quadratic Programming (SQP), Gradient-Based Methods, and Lagrangian Relaxation, Dantzig-Wolfe decomposition, multi-objective goal programming, branch and bound method, process graph, Generalized Reduced Gradient, Quasi-Newton algorithm, multi-objective programming, multi-objective goal programming (Ajeigbe et al., 2020). Metaheuristic optimization techniques are solution-space search procedures for finding near-optimal solutions based on a set of logical or empirical rules, either social behavior, natural, biological, or physical occurrences (Ajeigbe et al., 2020). Examples of meta-heuristic optimization techniques that have found applications in HRES modeling and design include simulated annealing (Zhang et al., 2018), particle swarm optimization (Wu et al., 2022), genetic algorithm (Torres-Madroñero et al., 2020), ant colony algorithm (Güven et al., 2022), fruit fly optimization algorithm (Zhao and Yuan, 2016), artificial bee colony (Singh et al., 2022), artificial bee swarm (Maleki and Askarzadeh, 2014), Cuckoo Search algorithm (Khadanga et al., 2022), discrete harmony search (Alshammari and Asumadu, 2020), biogeography-based optimization (Abuelrub et al., 2020), Imperial Competitive Algorithm (Shokouhandeh et al., 2022), Mine Blast Algorithm (Ranjan et al., 2021), and Brainstorm Optimization (Gang et al., 2020). Hybrid optimization techniques combine two or more single heuristics and classical optimization techniques by exploring the advantages of the individual methods (Babatunde et al., 2019a).

5 Multi-criteria decision making in HRES adoption

The decision to adopt hybrid renewable energy systems involves very complex decision-making processes, which need to consider several technical, economic, environmental, and social criteria. In this context, multi-criteria decision-making methods also play a key role due to their robust and systematic approach for assessing and selecting best HRES configurations upon trade-off of various criteria (Li et al., 2020). Multi-Criteria Decision-Making (MCDM) methods are essential when it comes to the selection of HRES configurations due to having a high level of complexities and trade-offs in renewable energy projects (Ribó-Pérez et al., 2020). For instance, while a HRES solution may be appealing with regards to its technical performance, it may come at a cost that is unaffordable for potential users. Furthermore, engineers may indicate that a particular HRES is optimal for a particular location with regards to cost, technical details and environmental impact, it may not be socially compatible with the users. MCDM tools can help in navigating this complex terrain by bringing together multifaceted and often-competing factors like costs, efficiency, environment concerns, reliability and social acceptance into an integrated framework of decision making (Li et al., 2020). By deploying the efficacy of MCDM method, designers can plan and operate HRES configuration whose solution is technically feasible, economically viable and sustainable and socially accepted.

Using MCDM techniques helps decision-makers to prioritize their preferences and objectives, therefore enabling the choice of HRES configurations that complement the strategic goals. (Babatunde et al., 2019b). Furthermore, applying MCDM methods increases the transparency and accountability of the decision-making process since all stakeholders will be able to realize how different criteria have been considered and weighed against each other (Sahoo and Goswami, 2023). Furthermore, MCDM techniques are flexible and adaptive especially and can help in real life applications of HRES in cases where huge variations exist concerning the availability of resources and diverse stakeholder preferences (Alghassab, 2022). Some of the MCDM approaches utilized within HRES design domain are Analytic Hierarchy Process (AHP) (Ransikarbum and Pitakaso, 2024), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Babatunde et al., 2019b), Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) (Mohammad Husain et al., 2024), Elimination and choice translating reality (ELECTRE) (Dumrul et al., 2024), Evaluation based on distance from average solution (EDAS) (Dumrul et al., 2024), VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) (Büyüközkan et al., 2024) and many more. Various Fuzzy MCDM methods are also available in the literature (Kaya et al., 2019); fuzzy MCDM can capture various uncertainties that occur in the decision-making process (Mardani et al., 2015).

6 Spatial optimization strategies for HRES

Spatial analysis is crucial for optimizing the performance and acceptance of HRES by strategically locating energy systems to achieve maximum efficiency and feasibility. One of the main advantages of spatial optimization in HRES design and development is the mitigation of transmission losses (Ayodele et al., 2018). Spatial optimization reduces energy loss and improves system efficiency by strategically placing renewable energy sources near demand centers, minimizing the distance power needs to travel (Shao et al., 2022). Spatial analysis is also useful for determining appropriate locations that achieve a balance between energy generation and environmental and social factors. Spatial optimization in HRES development improves sustainability and minimizes negative effects on local ecosystems and populations by avoiding environmentally sensitive areas and considering land use policies (Messaoudi et al., 2020). Spatial optimization also supports the integration of HRES into existing energy infrastructure and enhances the reliability and stability of the energy supply through strategic placement of energy storage systems and grid infrastructures, hence making renewable energy more attractive to investors and policymakers. Spatial analysis also facilitates microgrids and other decentralized systems of energy that can offer reliable and resilient energy supplies at a local level in remote and unserved communities, thereby increasing access to energy and promoting more significant social equity.

Various methods and spatial optimization tools have been used in literature with each having its distinct advantages and applications. One such method includes geographic information systems (GIS) (Ayodele et al., 2018), which have been applied in many instances of spatial analysis and optimization. GIS can be used to integrate and visualize the spatial data of renewable energy resource availability, land uses and availability, and socioeconomic factors. GIS can be deployed to identify locations with maximum renewable energy potential by overlaying and analyzing several levels of spatial information. Spatial autocorrelation is another method which measures the degree of similarity between observations in geographic space (Yang et al., 2024). This helps identify the patterns and clusters of high renewable energy potential, guiding how best to position HRES facilities. Spatial interpolation methods such as kriging can be used to assess the availability of renewable energy resources at unsampled locations. Meta-heuristic methods can also be integrated into spatial optimization to explore a large search space and identify near-optimal solutions based on multiple criteria and constraints (Belmahdi and El Bouardi, 2020). Overall, spatial optimization helps to achieve the overarching goals of sustainable energy transition and development by making HRES more appealing, reliable, and accessible.

7 Accelerating HRES adoption: a transdisciplinary framework

In this section, a Transdisciplinary Framework is proposed for Accelerating HRES Adoption (Figure 1). The framework represents a new frontier in accelerating the diffusion of HRESs through a transdisciplinary integration of sustainable design, size optimization, multicriteria decision-making, and spatial optimization. The framework is designed to help users overcome complex issues in the implementation process of HRES by offering a comprehensive, adaptive, user-centric platform. These four interfaced pillars are: the Sustainable Design Nexus (SDN), Adaptive Size Optimization (ASO), Holistic Multi-Criteria Decision-Making (HMCDM), and the Geospatial Optimization Engine (GOE). These four pillars are controlled by an Adaptive Synergy Hub-a central nervous system of the framework that improves smooth data exchange, analysis, and decision-making across modules. A key innovation of the proposed framework lies in its holistic approach to HRES planning and implementation.

The SDN embeds principles of circular economy, biomimicry, and regenerative design within HRES projects and guarantees their environmental sustainability. The fundamental building blocks of the system dynamic network include the life cycle assessment (LCA) Engine, Circular Resource Optimizer, Biomimetic Design Database, and Social Impact Assessment Tool. These components would interact to perform detailed LCAs for all HRES components, choose materials while optimizing pathways of material recycling, propose designs inspired by nature, and measure and maximize the positive socio-economic outcome created by HRES projects. ASO deploys the latest algorithms and machine learning to estimate the optimal capacities and configurations of the HRES components. Critical elements of ASO include a Demand Forecasting Neural Network, a Stochastic Resource Modeler, a Multi-Objective Meta-Heuristic, Algorithm, and a Dynamic Sizing Adaptation Engine. This ensures HRES components are correctly sized to meet the energy demands efficiently without over-or under capacity and optimizes performance at least cost. Based on several, often contradictory criteria, HMCDM ranks and assesses HRES designs to guarantee balanced and best design solutions. HMCDM's main elements are the Stakeholder Engagement Platform, Fuzzy Analytic Network Process (FANP) Module, Multi-Criteria Ranking and Visualization Tool (MCRVT), and Robustness and Sensitivity Analyzer. These modules compile and synthesize preferences from several stakeholder groups, apply FANP to ascertain criteria weights under uncertainty, rank options using the MCRVT technique, and run sensitivity studies to ensure that the decision is resilient. This in-depth approach ensures that all important criteria are considered, therefore, resulting in decision-making that is more knowledgeable and equitable.

The primary goal of GOE is to optimize the geographical placement of HRES facilities, based on both technical and socio-environmental constraints. The essential elements of GOE comprise the GIS Integration Platform, Remote Sensing Processor, Land Use Conflict Resolution Algorithm, and Network Analysis Optimizer. These technologies combine and examine spatial data from multiple sources, evaluate satellite images to obtain current land use information, address potential conflicts in land use through multi-objective optimization, and optimize the placement of HRES for grid integration. GOE ensures the efficient and sustainable utilization of renewable energy supplies, while reducing environmental consequences and maximizing grid integration efficiency. The Adaptive Synergy Hub (ASH) functions as the framework's central control system, enabling smooth decision-making and integration across all modules. The essential components of this module are the Big Data Analytics Engine, Blockchain-based Data Management System, IoT Integration Platform, Machine Learning Orchestrator, and Explainable AI Interface are some of ASH's essential parts. These components facilitate the integration of real-time IoT data for system monitoring, analyze and aggregate large-scale datasets, guarantee secure and transparent data transactions, coordinate machine learning models across modules, and provide justifications for AI-driven choices. The framework's overall efficiency and effectiveness are improved by the harmonization of all data flows and analytical processes, which is ensured by this central center.

Although the proposed framework provides a comprehensive approach for HRES design and implementation, it also comes with potential barriers. These include extensive data requirements, computational complexity, and potential implementation challenges in resource-constrained contexts. The framework's success will be determined by effective solutions for overcoming these hurdles, including interdisciplinary collaboration, data standardization efforts, computational efficiency enhancements, and targeted capacity-building programs. By addressing these challenges and leveraging its innovative features, the proposed framework has the potential to considerably accelerate the adoption of HRES and contribute to a more sustainable and resilient global energy system.

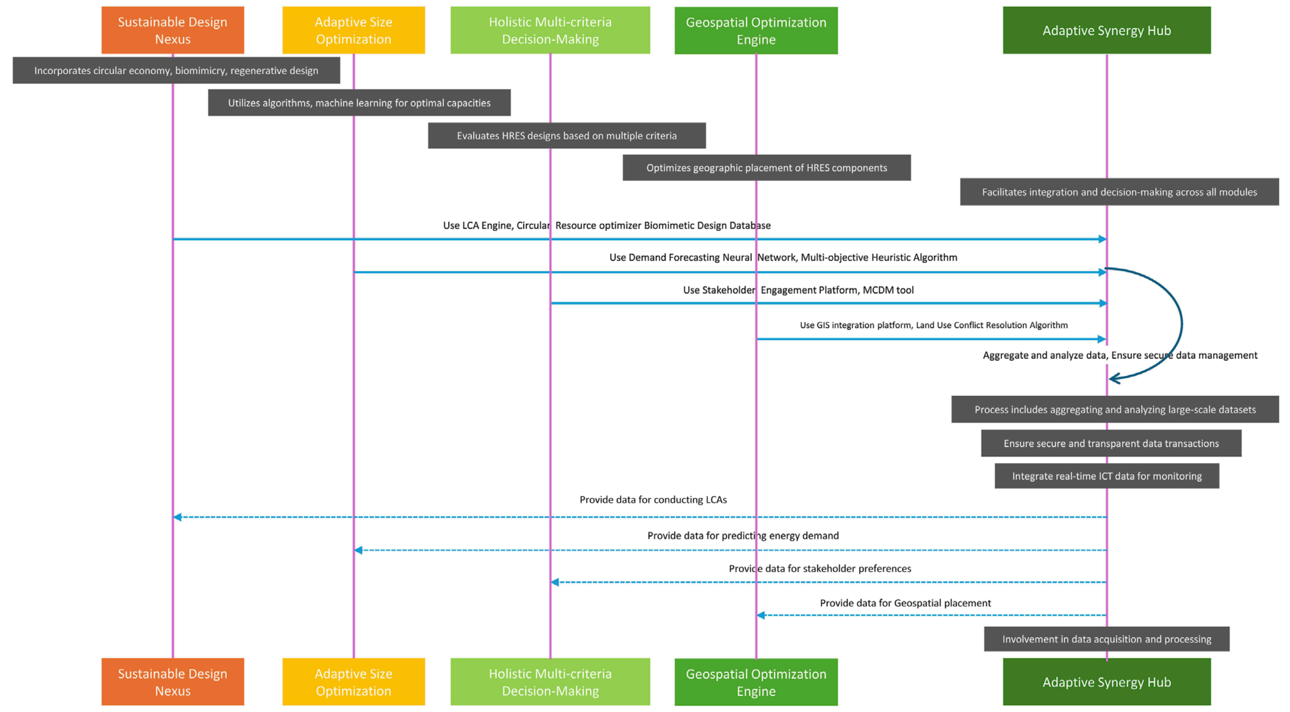

FIGURE 1
Proposed transdisciplinary framework is proposed for accelerating HRES adoption.

8 Conclusion

This article presents a mini review of sustainable design principles with regards to the sizing and implementation of hybrid renewable energy systems from the size optimization, multi-criteria decision-making (MCDM), and spatial optimization perspectives. By doing so, the paper addresses the complex problem involved in the implementation of sustainable hybrid renewable energy systems. The size optimization typically considers various objective functions guided by conflicting constraint that must be satisfied by the optimal solutions. When such solutions are available, decision makers are typically faced with contradicting criteria when selecting the most preferred energy option. Thus, MCDM approaches are deployed to rank energy systems based on conflicting criteria. Finally, locating these energy systems involves identifying the best locations for the energy systems; this is usually achieved through spatial optimization. Also in this study, an integrated framework that combines sustainable design principles, size optimization techniques, multi-criteria decision-making (MCDM), and spatial optimization strategies for HRES implementation is proposed.

The proposed framework underscores the importance of transdisciplinary approaches in overcoming the limitations of traditional single-discipline methodologies. By integrating into diverse fields such as engineering, environmental science, economics, and social sciences, the framework enhances the efficiency, sustainability, and social acceptability of HRES projects. As we move towards the 2030 Sustainable Development Goals, the adoption of this framework will be pivotal in driving the global transition to sustainable energy systems, ensuring a more resilient and sustainable future for all.

Author contributions

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