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Review Article

The Optimization of Hybrid Renewables for Rural Electrification: Techniques and the Design Problem

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Abstract *- Presently, there is mounting pressure to decarbonize the power grid via the use of renewable energy (RE) sources. However, most of these sources could perhaps not easily replace conventional power plants due to the fact that they have nonlinear characteristics, and most of these issues still need to be resolved. In order to effectively manage the non-linearity of some RE sources and improve the energy harvesting capability of these systems, various methods have been adopted. Some of these techniques have one or more objective functions and commonly use commercial packages to minimize system cost and improve output power simultaneously. Rural electrification is still pitiably prohibitive, especially in Sub-Saharan Africa, and off-grid RE technologies remain a reliable way of meeting rural electricity needs. Exploiting these sources could help offset rural electricity demand sustainably while mitigating the negative impacts of using a diesel generator and other sources that are not environmentally friendly. This study reviews issues regarding the hybrid RE system design with insights on the most often conflicting constraints. Also highlighted are the recent trends in hybrid system optimization with RE technologies and the various considerations scholars use in hybrid applications. Moreover, the study has discussed the essential aspects of evaluating the performance of a hybrid RE system and its applicability in rural electrification. The study has explored various methods and concludes that hybrid techniques based on artificial intelligence (AI) offer better performance for system optimization.*

Keywords *– Decarbonize, Power Grid, Energy Harvesting, Electricity, Constraints, Artificial Intelligence.*

1. Introduction

Increasing global electricity demand and the growing climate concerns have made the transition to renewable power a very popular topic among researchers. Even with the advancement in technological know-how in industrialized countries, approximately 1 billion of the world's population still lack electricity access, a greater percentage of which are in developing nations, especially Sub-Saharan Africa, South Asia and Latin America [1]. A greater percentage of the non-electrified communities are inaccessibly isolated areas, making grid extension uneconomical. Therefore, these distant communities, which are geographically constrained, must consider installing smaller off-grid systems [2]. The unavailability of electricity in communities could spur adverse conditions such as low-level economic development, poverty, hunger and gender inequality [3]. It also hinders economic growth and social progress, but it could also be a source of issues related to the quality of life in rural areas [4]. While diesel generators can be a salvation for these areas, empirical studies have shown that the operation and maintenance of the generators are high [5]. Besides, these generators emit gases, so their installation retards the global commitment to fight climate change. Thus, renewable energy (RE) through off-grid systems will continue to be a promising option for remote power communities far from the main electricity grid [6]. Indeed, the Sustainable Development Goal (SDG) 7 of UN Agenda 2030 has interesting ambitions regarding universal access to clean, reliable and affordable energy by 2030. While substantial progress has been made, the difficulties are enormous. Apart from improving rural energy access, renewable energy systems (RES) can also expand the income levels of rural inhabitants. Research from various regions has demonstrated that installed solar PV systems could improve rural dwellers' income levels since they will be engaged in income-generating activities [7-9]. A study conducted in Ghana on solar-based electrification installations showed that an extra revenue of \$5 - \$12 daily might well be gotten in a grocery business due to solar PV lighting [10]. Research on the income of shop owners in rural areas of Bangladesh showed that those who installed solar home systems increased sales revenue due to improved lighting from RES, attracting more clients [11]. The International Renewable Energy Agency (IRENA) had projected that solar pumps could increase the revenue generated in household income by 286 % for the extremely poor, 173 % for the poor and 47 % for the middle-income families in Zimbabwe [12].

Modelling these systems comes with many challenges as they present several modules in their various combinations. Stand-alone RES have some limitations, such as power fluctuation caused by the intermittence of solar and wind resources, which is much reduced when the systems are hybridized. Usually, these systems are merged into 2 or more (solar PV, wind, hydro, fuel cell, etc.) to form a hybrid system to improve the reliability of electricity supply. Hence, it becomes possible to achieve improved efficiency in electricity generation by optimally combining the sources to overcome their limitations [13-16]. The use of energy storage is also a means of reducing the effects of intermittency [17]. All these methods help attain a fairly smooth and constant power output [18, 19]. Harnessing maximum obtainable power output from a renewable energy system would contribute to the system's reliability and economic viability. The MPPT (maximum power point tracking) algorithm adjusts the DC-DC converter's duty cycle in order to match the source impedance with the load impedance. It has been extensively discussed in [20-22] to harvest energy from RES optimally. Other methods, such as Fuzzy Logic (FL) and neural network (NN), concentrate on the nonlinear features of solar PV [23]. Due to the present RE ambitions of countries, better ways for the generation and implementation of hybrid renewables at a small scale are crucial and need strategic measures.

The modeling of HRES for residential applications has been widely studied. However, available literature on this subject is mostly case-specific, with limited emphasis on uncertainties that affect system output. Thus, it will be stimulating to holistically explore the effects of progressive power transition and all-inclusive constraints involved in optimally modelling HRES.

2. Methodology and Contributions

This review adopted a broad literature search where a preliminary exploration was executed on a directory of open access journals (DOAJ) and research4life using the main word "Hybrid off-grid RE systems", "Hybrid renewables for rural electrification and "integrated off-grid RE systems". This internet exploration resulted in more quests on popular databases such as IEEEexplore and Elsevier. The study involved reviewing 105 articles across different peer-reviewed journals to elucidate the trends in hybrid system modelling and how different scholars are tackling optimisation issues, criteria selection, and system configuration to meet the ever-fluctuating renewable resources.

Optimum system selection involves several contradictory criteria, and available literature has shown that only techno-economic criteria are the most used criteria to choose and rank an optimal hybrid energy system [24-26]. However, hybrid energy systems chosen based exclusively on these two criteria could be unsuccessful, especially in developing countries [27, 28]. Therefore, it is vital to consider and investigate other social, policy and environmental criteria when selecting and ranking RE systems, especially in residential applications. The paper covers the classification of storage technologies in hybrid systems, discusses trends, provides schematic diagrams of hybrid system architectures, and describes hybrid system control topologies, tools and optimization methods. The paper also critically highlights the hybrid system modelling problem that makes the design of hybrid system constraints highly conflicting. Major emphasis is equally placed on the performance indicators, which we hope would assist hybrid system developers in modeling systems without compromising their reliability. Fig. 1 shows a flow chart of the structure of the paper.

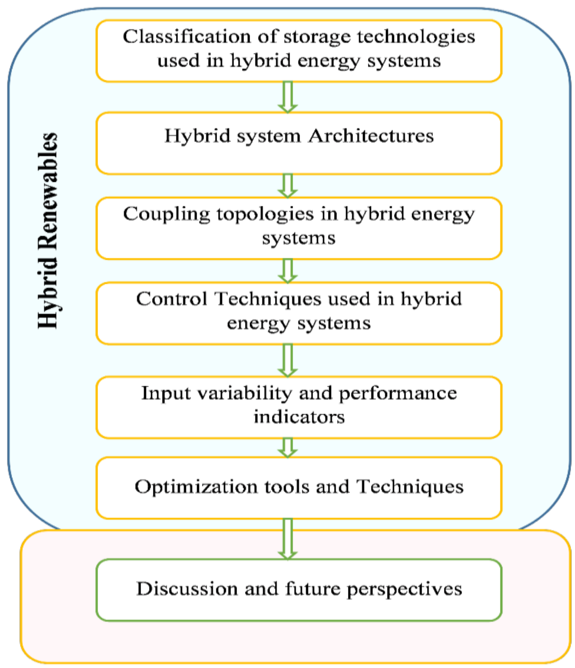

Fig. 1 Illustration of the structure of the review paper.

3. Literature Relevant to the Review

Many studies have been carried out on the subject of environmental, economic and technical feasibility of stand-alone and on-grid hybrid renewable energy systems (HRES) [29-32] and the results obtained have been judged to be economical for power plants that use fossil fuels. The researchers in [140] reviewed the modelling criteria and the methods of optimizing HRES. Others emphasized the impact of RE development in remote communities [34], while some focused on the modelling tools used in HRES [35, 36]. The use of HOMER for optimum hybrid RE system planning has been reviewed in [37]. The HOMER application was used by [38] to model a hybrid mini-hydro/solar/wind/diesel system with the help of input data relevant to the location and obtain an optimum configuration of the hybrid system. In their study, [39] reviewed different hybrid RE management systems, sizing methods, configurations and control methods [40]. A review on innovative sizing methods, software applications for off-grid hybrid systems [41], hybrid RE system planning, topologies, and development and optimization methods for stand-alone applications have been presented in [42]. The authors in [43] conducted the techno-economic feasibility of a hybrid micro-hydro-photovoltaic-diesel-battery-wind RE system to provide electricity in a remote village in southern Nigeria. They used system performance indicators such as the cost of energy (COE), operation and maintenance cost (O&M), net present cost (NPC), excess electricity, capacity shortage, generator fuel usage rates and expenses, load satisfaction, and CO_2 emission savings to assess the system.

The authors in [44] used 2 integration techniques to assess the realization of a hybrid hydro, wind and solar RES for isolated communities in Nepal. They concluded that the proposed RE system was best for a standard of living, cost and environmental friendliness. Some researchers have used payback periods to model stand-alone systems [45]. A cost optimization on the customers' side was conducted by [46] in a hybrid hydro, wind, and solar PV system for some locations in Ghana using the computational approach (linear programming) on the Matlab software. Their results showed that the hydro system gave a much-reduced energy cost, followed by wind and solar systems. The subject of hybrid renewable energy integration, configurations, storage, sizing methods and system control has also been presented in [47]. Other studies have focused on using distributed renewable power production plants for cost-effective rural electrification [48-51]. Most of these studies have hybridized renewable energy systems with conventional generators, including energy storage applications. Some scholars have worked on hydro-based hybrid systems has been explored in various studies [52-54]. In a study conducted by [55] in a rural community in India, they used the HOMER Pro software and Genetic Algorithm (GA) to compare various system output parameters of a rural hybrid system. Their main aim was to reduce the total NPC, COE, unmet load and system CO_2 emissions. Comparative analysis was done on the results of the 4 hybrid combinations obtained using GA and HOMER. The solar/biogas / /wind/biomass/ fuel cell with battery was identified as the best option, delivering power with 0% unmet power demand at a COE of $ 0.163/kWh. They concluded that PV penetration with GA was cheaper than that obtained using HOMER. The BBO (biogeography-based optimization) algorithm minimises cost and properly sizes a solar-wind RES in a remote area [56]. The system added a diesel plant as a standby, and the cost attained by the algorithm was satisfactory. The results obtained had remarkable convergence properties and required less computational duration. The authors in [32 considered the COE as the objective function to model a hybrid renewable system in 7 locations in rural Algeria using particle swarm optimization. When the analysis was conducted on less performant houses, hybrid PV/ wind/ battery/ diesel/ was identified as the best configuration in 2 locations. In contrast, PV/battery/diesel was the best option for the other 5 sites. For high-performant houses, the optimal combination was PV/Battery (100 % RE) with an energy cost per kWh of $0.21.

Even though the forgoing studies have immensely addressed a range of particular contemporary issues on hybrid RES sizing, research that integrates their deployment's societal, technical, financial, ecological, and policy aspects is lacking. Besides, as highlighted by SDG 7 on the necessity for clean, reliable and cheap energy for all, it is equally important to generally identify all the constraints that should preoccupy developers of hybrid renewables since several studies address only particular issues. Due to the potential of hybrid renewables to provide households with clean and affordable energy, this study tackles the emerging issues of hybrid renewable off-grid development and operation for remote household use. Table 1 shows some relevant literature on off-grid systems for rural electrification.

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Table 1. Some relevant literature on HRES for rural electrification

SN	Type of System	Optimization Software/ Algorithm	Objective Function	Country	Author
1	Biomass/ biogas / solar PV/ wind turbine / fuel cell / hydrogen storage tank	HOMER / Genetic Algorithm	NPC, COE, Unmet load	Rural India	[55]
2	PV-wind-diesel-battery	HOMER	NPC. COE	Nigeria	[57]
3	Solar/wind/diesel/battery	Particle Swarm Optimization	COE, system reliability, a renewable fraction (RF)	Rural Algeria	[32]
4	PV/Diesel/Battery	HOMER	NPC, COE	Rural Bangladesh	[58]

5	PV/diesel/Fuel Cell	Crow Search Algorithm	NPC, loss of power supply probability (LPSP), renewable energy contribution (REC)	Residential building, Iran	[59]
6	Solar PV/wind/diesel	HOMER	NPC, COE	Ethiopia	[31]
7	PV/Wind/ Battery/Supercapacitor	Genetic Algorithm	COE and LPSP	Residential building (Tunisia)	[60]
9	Wind/DG/battery	HOMER	NPC, COE, CO2 emission	Residential Community China	[61]
10	Micro-hydro /photovoltaic/diesel /battery/wind	HOMER	NPC, COE, CO_2 emission, fuel consumption rates, load fulfillment, excess electricity, capacity shortage	Rural Nigeria	[43]

4. Storage Technologies used in HRES

The reliability of RE systems is improved by adding backup systems in the form of storage devices, especially to mitigate the impacts of constantly changing RE sources such as wind and solar. In some cases, standby diesel generators or other energy storage devices are used for this purpose. Energy storage devices are useful for HRES because they store energy in times of abundance and use up during peak load. Generally, off-grid systems are usually equipped with energy storage systems (ESS) which are coupled to the main system with the help of power electronic devices. Energy storage systems generally smooth variations, enhance system flexibility, offset peak load and quickly intervenes when other generators, for some reason, cannot fully support the load [62]. The importance of storage is much visible and important in a rural areas where sharp increases in the power demand characterize evening periods. Supposing these sharp load increases are to be powered by conventional generators, it could cause a situation of excess capacity with a tendency to increase system cost and, subsequently, the COE. Hence, ESS interconnection in the network helps to shave sharp load increase and eliminates power deficits. Figure 2 shows an illustration of ESS.

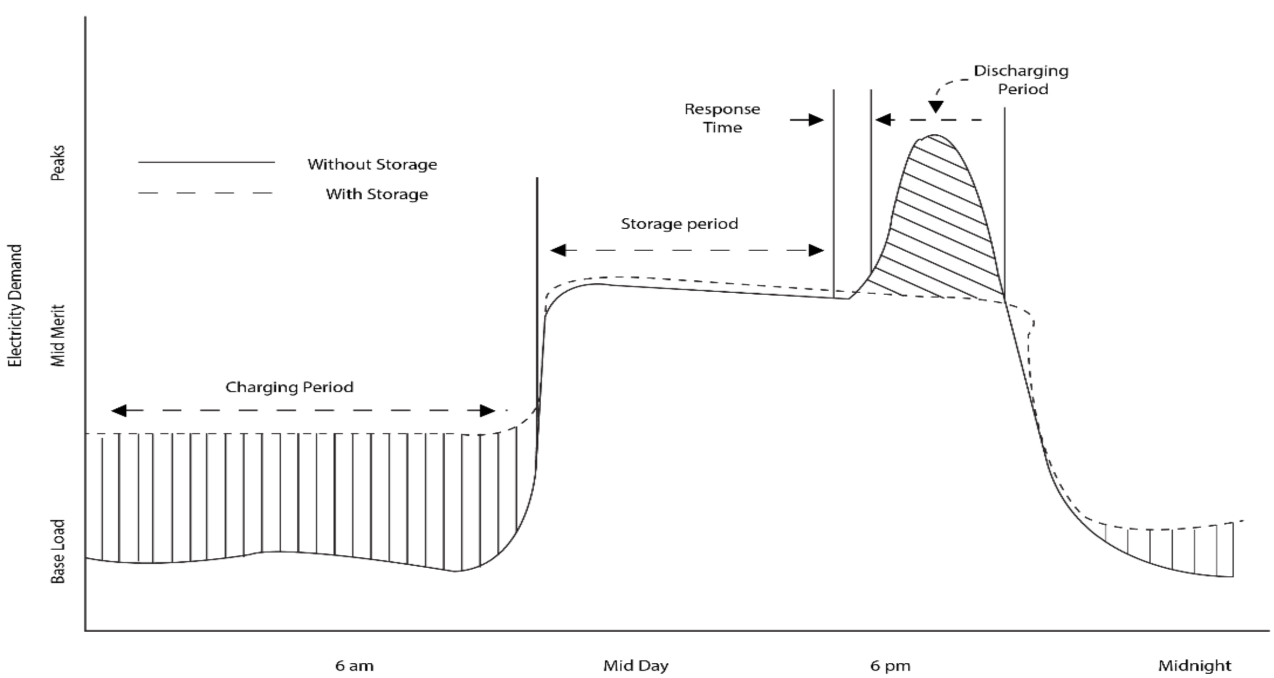

Fig. 2 Power production control with and without ESS [63].

The ESS usually has three modes of operation (charging mode, storage mode and discharging mode), as seen in figure 2. As the energy system generates more power than needed, the surplus electricity is put in the storage device (charging period) to be used when the power demand rises. When the load, at any given instant, surpasses the power generated, the energy stored in the ESS is deployed to support the network (discharging period). Figure 3 illustrates how storage systems are categorized.

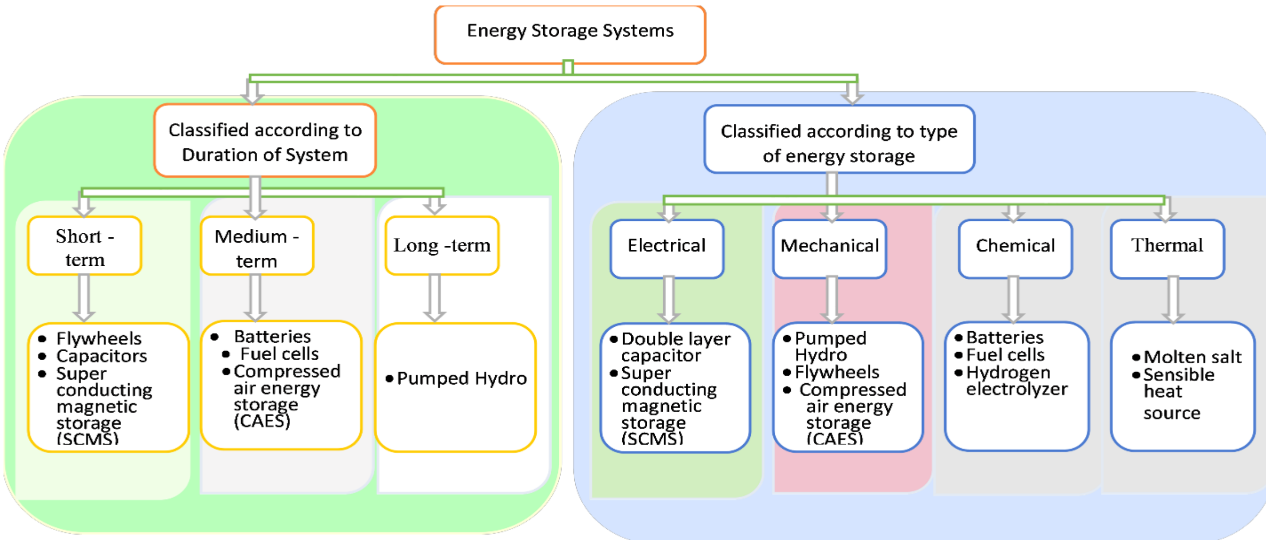

Fig. 3 Classification of Energy storage

5. Hybrid RES Architecture

Several system combinations in a hybrid RE system include hydro, solar, biomass, hydrogen, wind turbine, fuel cell and battery system. These systems are often connected parallel to each other and aim to handle the power demand of the network. The main goal of combining energy systems into a hybrid system is to evade the shortcomings presented by single RE systems. For example, the energy generated by an off-grid solar-hydro energy system has improved reliability than the individual systems [29]. Nonetheless, energy storage devices are added to the hybrid system to efficiently exploit the RE resources and evade power shortage. Figure 4 shows the possible combinations of a typical common hybrid system. These combinations are coupled with the help of various power electronics devices.

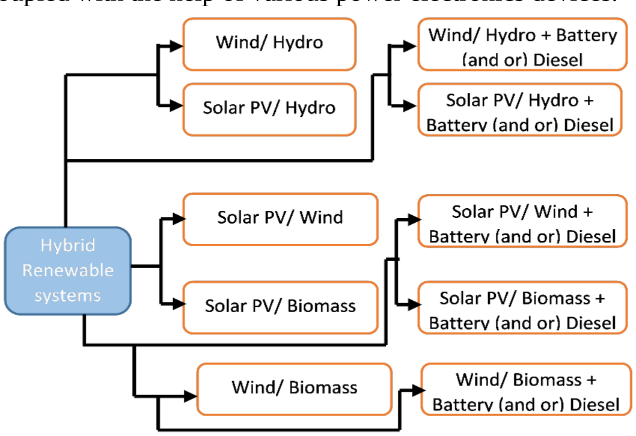

Fig. 4 Common hybrid system combinations

6. Coupling Topologies used in HRES

6.1. DC Bus Topology

In this structure, the main output terminal of the RES is linked to a DC bus with the help of appropriate power converters. The energy storage is coupled to the main bus using a charge controller called a bi-directional converter. This topology is intended to power DC appliances, but in case AC appliances exist, a DC-AC power electronic converter should be connected. This architecture is advantageous because it is not complex and eliminates the issues of synchronization. However, any faults on the DC-AC converter at the consumer side would lead to the disconnection of the AC section.

6.2. AC Bus Topology

The AC topology consists of the RE Systems linked to an AC bus using appropriate converters. The sources could be wind turbines, hydroelectric plants, solar PV, diesel, etc., whose output is linked directly to the AC bus with the help of similar converters. Similarly, the storage system is coupled to the DC – bus through a charge controller. There is also a provision to power DC appliances using a rectifier. This architecture has been widely used in remote and urban areas. However, this topology equally faces the problem of synchronization.

6.3. Hybrid System with Dual Bus

The hybrid dual bus configuration has both buses (AC /DC). This architecture ensures that RE sources whose power output is AC are linked to the AC bus. In contrast, their DC counterparts are coupled to the DC bus, thus, minimizing the number of converters and power losses resulting from conversion [41, 64]. So, a hybrid dual bus topology improves the total system efficiency while simultaneously decreasing system size. This configuration is modular and capable of combining the RES and loads, irrespective of their characteristics [65-68]. These are some reasons why the dual bus hybrid configuration is the most widely adopted. The main discouraging factor to adopting this architecture is the complex nature of the control and energy management system. The hybrid coupled configuration operates in a way that all AC energy generators feed AC appliances via the AC bus, whereas DC-based power generators feed DC appliances via the DC main bus. This topology reduces the number of power converters, reduces power losses, enhances system efficiency and decreases the total investment expenses. It is worth noting that there is no universally accepted best structure when combining renewable energy sources since it generally depends on the application and installation site. Fig. 5 shows some commonly used topologies.

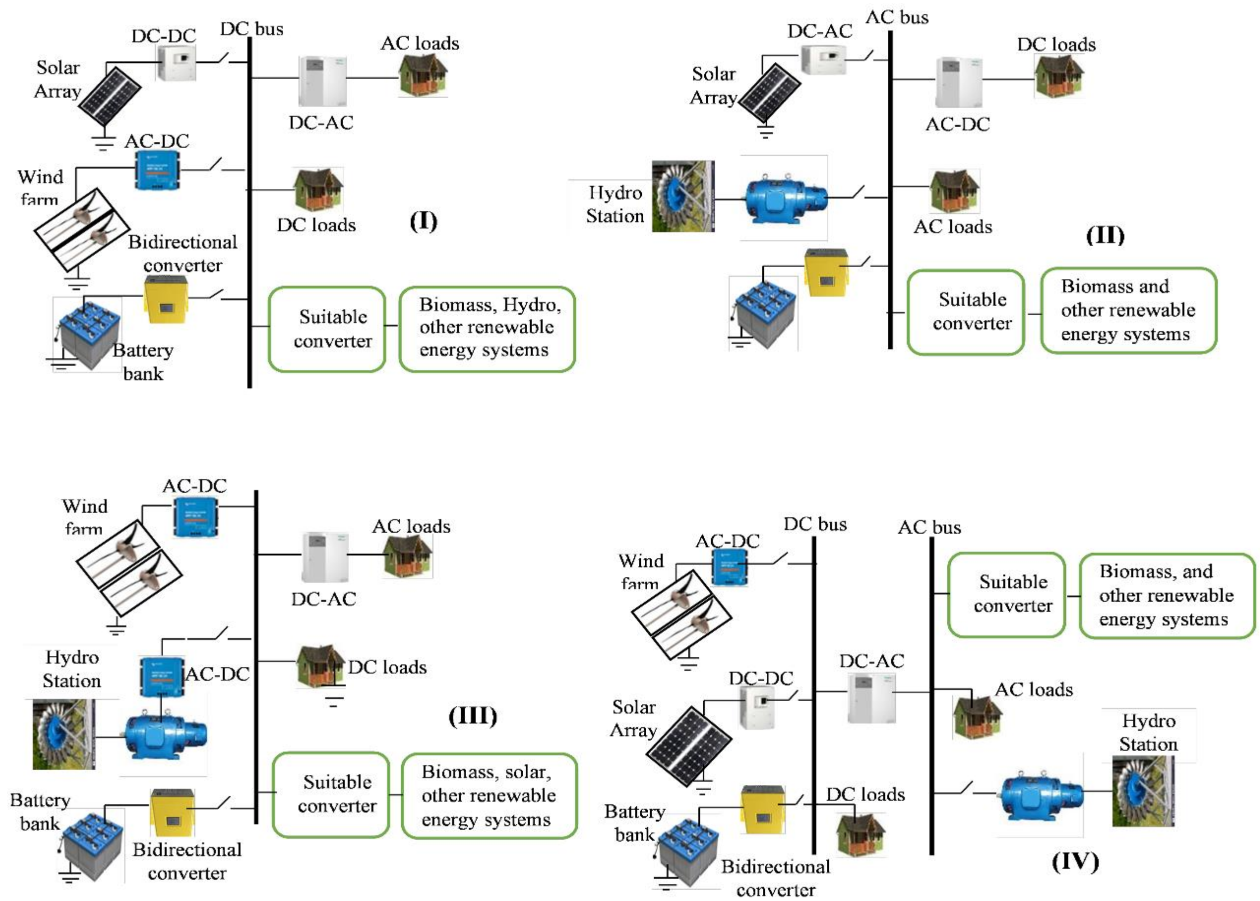

Fig. 5 HRES Architectures (I) DC-bus based system (II) AC-bus based system (III) DC-bus with a rectified Hydro based system (IV) Dual-bus based system

7. Control Techniques commonly used in Hybrid Renewable Systems

The flow of energy among power sources (renewables, storage systems and conventional generators) in a hybrid system could cause challenges such as power quality issues, voltage fluctuation, instability in the network, and frequency and dispatch issues. Ensuring system reliability, suitable power management, and optimum system operation involve an appropriate control strategy that guarantees smooth energy flow. Also, a suitable control scheme will equally improve the system's cost-effectiveness. The control scheme adjusts and assigns generated power from generators and stabilizes the voltage and frequency of the hybrid system to acceptable levels. In hybrid renewable systems, control schemes can be categorized into 3 types: centralized, decentralized and hybrid schemes. A brief discussion of the various control strategies is outlined below.

7.1. The Centralized Scheme

In the centralized controller, the individual power generators (including battery storage) are linked to their separate local controller (enslaved person). In contrast, a central controller (master) manages all the local controllers (figure 6). All the data collected by the slave controls are transmitted to the master for scrutiny and response. The master control functions as the core power management device. However, this type of controller is disadvantageous because it is computationally complex and could incur single-point failures [64]. Figure 6 shows a schematic of the communication within a centralized control structure.

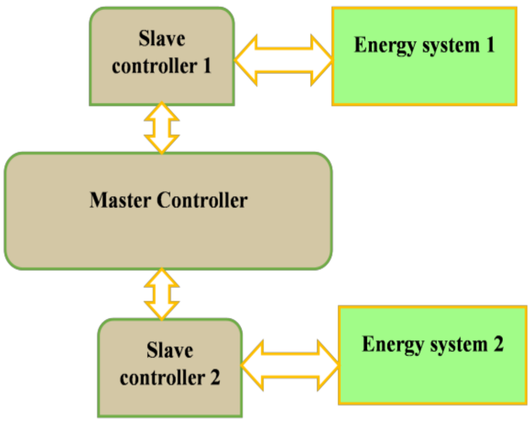

Fig. 6 Centralized control topology.

7.2. The Distributed Control

For distributed control, there is no master control, but the slave controls of the separate generators interact with each other to make decisions based on stated goals. It is advantageous in that the use of computer memory is less and does not face similar issues that arise from connecting controllers in series, such as complete system failure when one controller is damaged [64, 69]. However, this approach faces the issue of complex communication amongst slave controllers. Figure 7 shows a schematic of the communication within a decentralized control structure.

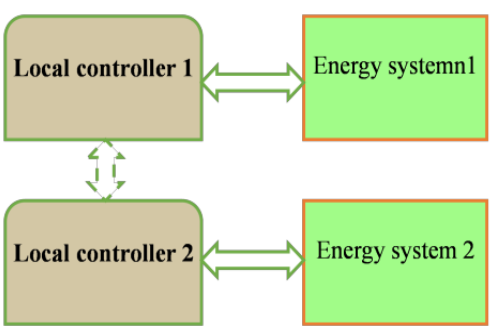

Fig. 7 Decentralized control topology.

7.3. Hybrid Control

In hybrid control, the architecture is a blend of centralized and distributed control approaches where generators with similar characteristics within the hybrid system are connected to one slave control [69, 70]. They are further joined to a master control that interacts with one another. Hence, the centralized structure manages each set of related power generators, whereas the decentralized control coordinates the clusters of generators. Intrinsically, optimization is attained locally using central control, whereas the decentralised controller realises universal optimisation [47]. Hence, the hybrid control structure decreases the total computational load. Figure 8 shows a schematic of the communication within a hybrid control structure.

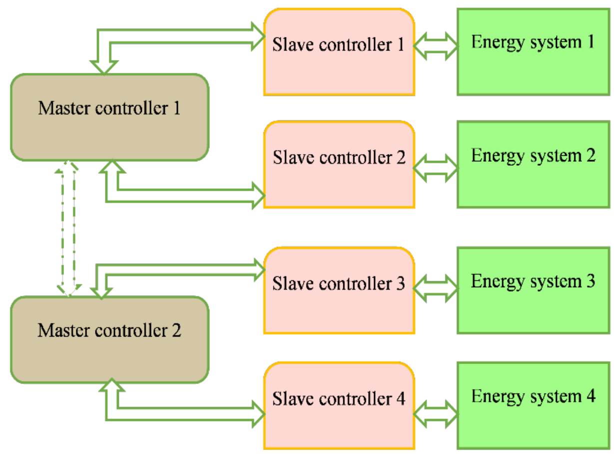

Fig. 8 Hybrid control topology.

8. The Hybrid System Modelling Problem

Hybrid renewable energy system design involves numerous unpredictable events that are often difficult to manage. These events are related to policy, economic, resource availability, social, technical, regulatory and environmental [71]. For example, the intermittent nature of wind and solar resources will cause technical and economic variables in an energy model to change. Hence, any design must include these uncertainties using suitable mathematical models and algorithms. It can be approached through scenario development, probabilistic study and sensitivity analysis [72]. An optimal hybrid RE system's capacity and generation mix require an assessment approach that ensures adequate system enhancement and effective utilization. Deciding on the best performing system could be hinged on single or multiple criteria, but sustainable systems are based on multiple criteria. Therefore, it is important to classify and select hybrid renewable energy systems based on multiple performance indicators when designing energy systems. Earlier, renewable energy projects have been considered optimal using a single criterion such as project life cycle cost [73], levelised COE, renewable fraction etc. For an entirely sustainable system, aspects of technical sustainability (conformity with grid codes and standards, stability of the network, loss of power supply), economic sustainability (effect of government regulation, subventions, access to finance), environmentally sustainable (emissions saved, environmental impact assessment, sustainable land use patterns) and the societal context have to be considered. Applying multiple criteria techniques is vital in striking a balance between these aspects. It gives a step-by-step way of choosing the most appropriate substitute from several options using multiple performance indicators [74]. Fig. 9 shows some commonly found uncertainties in hybrid renewable energy models.

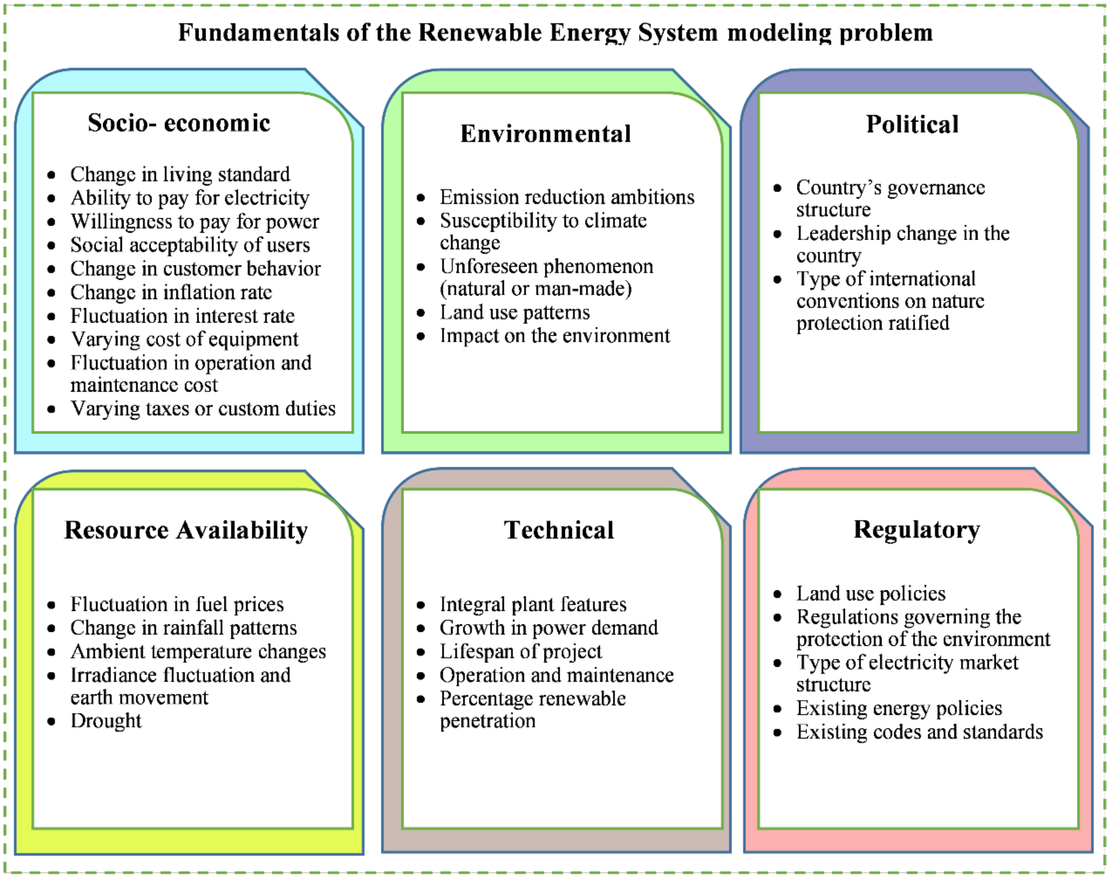

Fig. 9 Some sources of constraints in HRES.

8.1. Modeling the Performance Indices of Hybrid Systems

The evaluation of the performance of HRES with regards to reliability and sustainability has used some indicators (technical, economic, environmental and social). These pointers often assist energy developers, and policymakers make wise choices in executing projects and formulating policies. The most common indicators available in the literature are mostly categorized into social, technical, economic and environmental indicators. The socio-economic indicators assess how affordable a hybrid RES could be accessible to everyone in society [75]. When a hybrid RES is oversized, it increases all the costs (capital expenditure - CAPEX, operational expenditure – OPEX, total NPC and COE).

In contrast, an under-sized system will increase the percentage of the unmet load. Therefore, the design must consider acceptable reliability levels through the utilization of either technical or economic indicators in the form of mathematical functions or inequalities. Some available literature on reliability pointers have been discussed in areas of a renewable fraction [61, 66], loss of load risk [76, 77], loss of power supply probability [78-81], loss of load expectation [76, 77], anticipated energy not supplied [82, 83], duration of autonomy [84], the deficit of power supply probability [85], annual capacity unavailability [86], the surplus of power generation [85, 87], equivalent loss factor [88]. Figure 10 gives a summary of the performance indices for a hybrid renewable system.

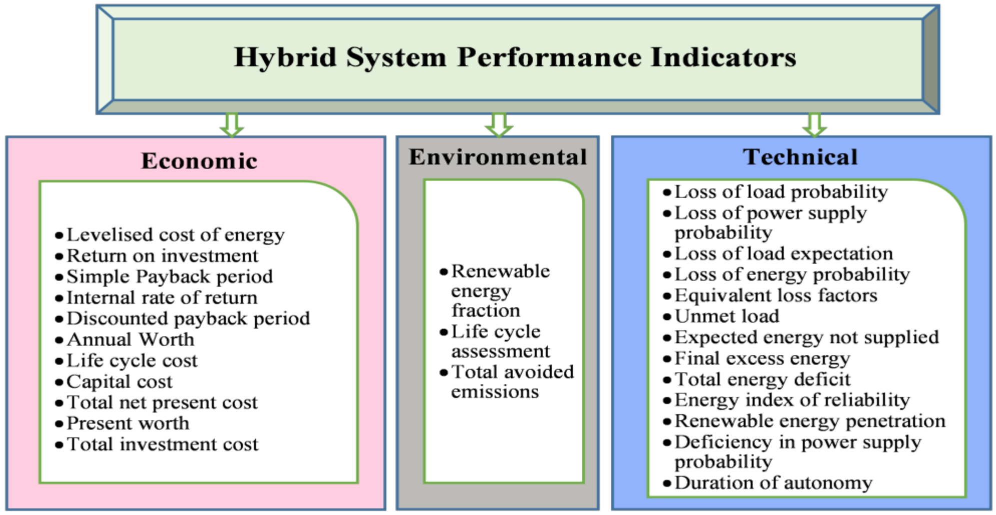

Fig. 10 Performance indices used in hybrid RE systems.

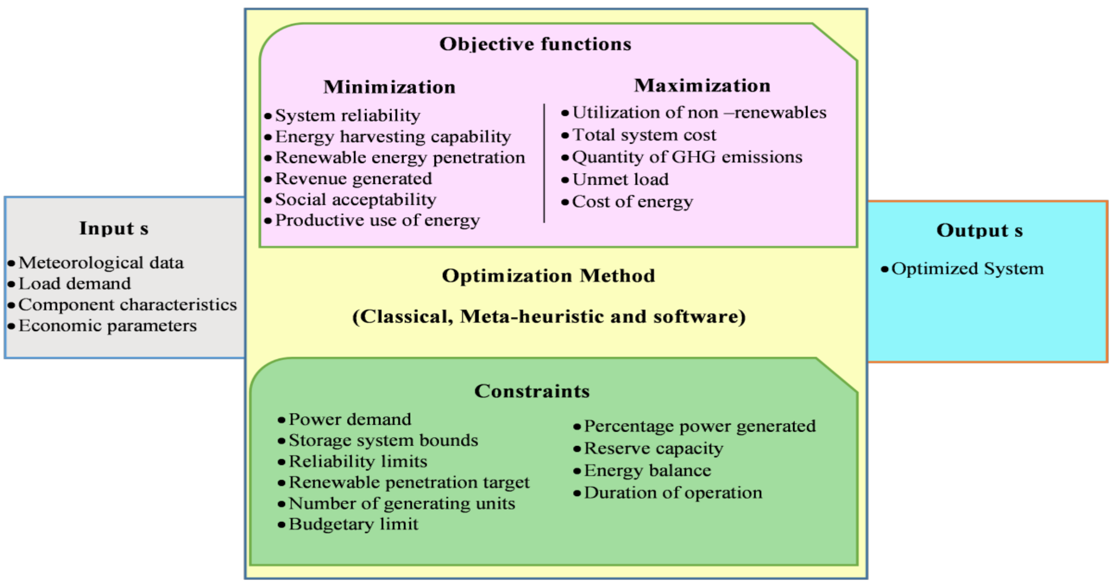

Fig. 11 General optimization procedure for RE Systems.

8.2. The General Hybrid RES Optimization Process

These rules for approximating the highest or least values of mathematical expressions are intensively used in modeling hybrid RES. Common objectives include overall system cost minimization, maximizing system reliability, maximizing the proportion of renewable energy, minimizing the cost of energy, minimizing system emissions, maximizing job creation level and minimizing imported power from the grid etc. Usually, system cost minimization and reliability enhancement are the main objectives considered in HRES modeling and optimization [42]. Figure 11 shows the hybrid RES optimization procedure.

8.3. Techniques Applied in Hybrid RES Optimization

Several studies have been conducted on hybrid system sizing and designing using different methods. These methods could be categorized into classical, meta-heuristic, hybrid, and commercial software. The various approaches are discussed below.

8.3.1. Classical Methods of Optimization

In general, classical optimization methods have been used to obtain the best results for continuous functions that can be differentiated with the help of differential calculus. This method can handle problems that have one variable function and multivariate functions with or without constraints [89]. However, a limitation of the classical method is its inability to solve functions that are dscrete and non-differentiable [42, 72]. Some available literature on hybrid renewable system modeling using classical optimization methods includes:

Dantzig-Wolfe decomposition [90], linear programming [91, 92], branch and bound [93, 94], dynamic programming [95], Quasi-Newton algorithm [96], multi-objective goal programming [97], process graph method [98], generalized reduced gradient [93], multiple objective coding [99], Quadratic programming [100], analytical method [76], non-linear programming [96].

8.3.2. Meta-Heuristic Methods

Most real-life optimisation problems involve nonlinear, discontinuous, contradictory multiple objective constraints, and these characteristics make optimization problems cumbersome. These types of models are usually challenging and, at times, unfeasible to obtain a solution using classical methods. In fact, no classical optimization method has been proven to optimally solve functions that cannot be differentiated [141]. These complex functions can be solved with the use of heuristic algorithms. Even though these algorithms have no sound mathematical foundation, they have been recounted to give fairly accurate solutions in acceptable computer run time [89]. Due to their relatively improved program speed, ease of application, and capability to solve multifaceted problems, several meta-heuristic methods have found applications in hybrid renewable RE modelling. Most meta-heuristic methods mimic biological or natural phenomena with stochastic characteristics, and solutions to problems are obtained by performing several searches on the solution space to locate the near-optimal solution through a collection of logical procedures based on either social activities or natural occurrences [102]. Some meta-heuristic methods used in hybrid renewable energy system modeling includes simulated annealing (SA) [103], brain storm optimization (BSO) [104], particle swarm optimization (PSO) [105-109], artificial bee colony (ABC) [110-112], genetic algorithm (GA) [55, 105, 113, 114], ant colony (AC) algorithm [115, 116], artificial bee swarm (ABS) [117], imperial competitive algorithm (ICA) [118, 119], Modified Evolutionary Strategy [120], Cuckoo Search algorithm [105, 121], harmony search [122], biogeography based optimization (BBO) [56, 123], mine blast algorithm [124], fruit fly optimization algorithm (FOA) [125]. Figure 12 shows a flow chart of literature's most commonly used algorithms.

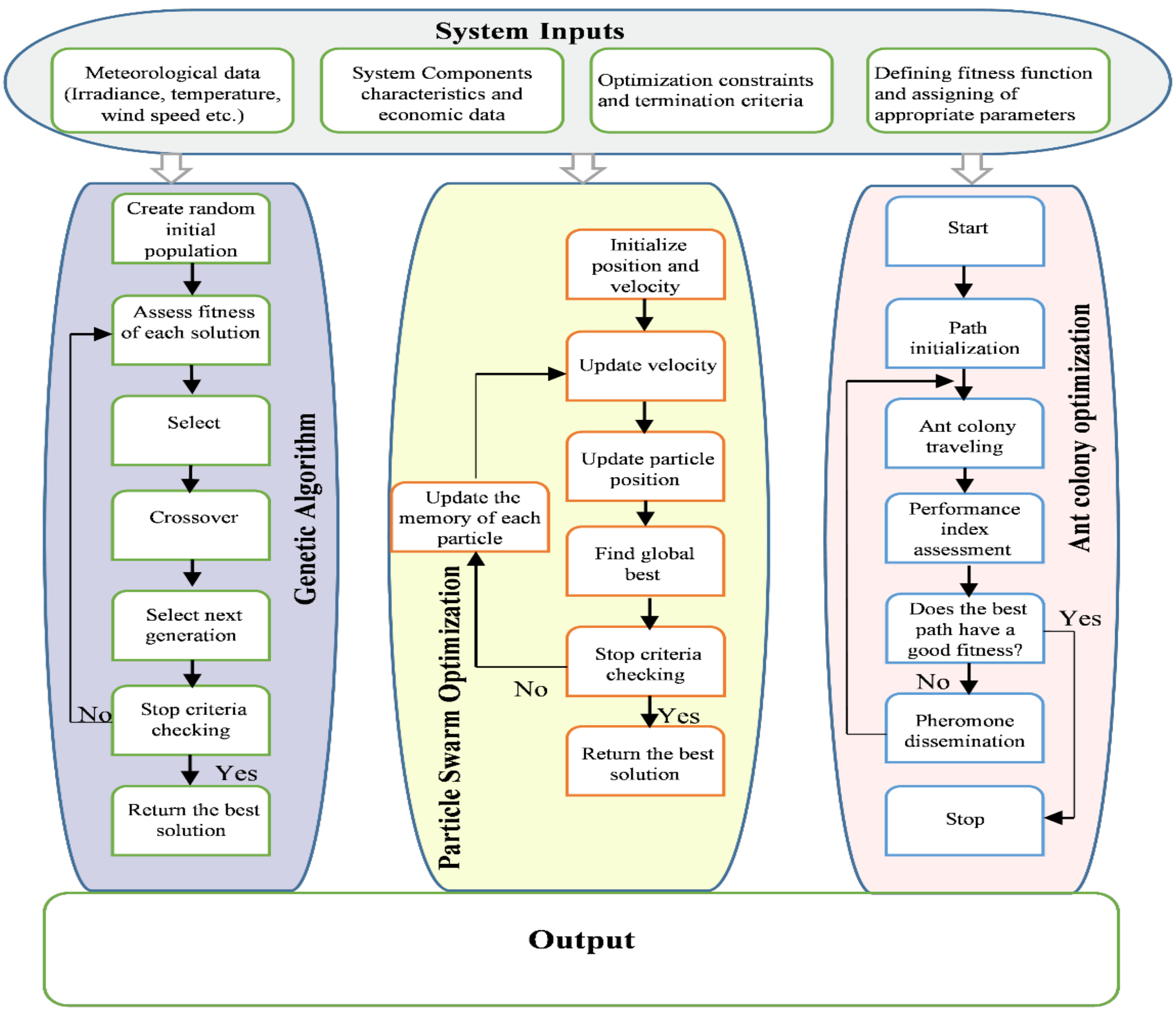

Fig. 12 Flowchart of GA, PSO and ACO.

8.3.3. Commercial Software used in Hybrid Renewable System Modelling

In addition to classical, heuristic and hybrid methods used in designing hybrid renewable energy systems, there also exists much commercial software used to design various aspects such as sizing, economic optimization, and power dispatch, as well as sensitivity analysis. HOMER is widely used in HRES design by researchers and policymakers. HOMER is a product of the National Renewable Energy Laboratory (NREL) capable of performing system optimization and sensitivity analysis of hybrid RE systems [126]. The HOMER package requires inputs such as component data, control specifications and network constraints, and resource data. At the same time, its generated outputs include net present cost, levelized COE, total investment cost, emissions avoided, RE penetration level, unmet load, fuel consumption and excess energy. The Hybrid2 software is a probabilistic time-series application developed by NREL which can perform detailed performance analysis for several hybrid RE models over a long period [127]. The iHOGA (Improved Hybrid Optimization by Genetic Algorithms) is a C++ based RE system sizing tool developed for modeling hybrid renewables [128]. The RETScreen software is an engineering application developed in Canada with the ability to conduct studies on the technical and economic viability of RE projects [128, 129]. There exist other commercial tools such as HYDROGEM, RPSIM, TRNSYS [128], HYBRIDS [128], INSEL [130], SOLSI [130], SOMES [130].

9. Discussion and Future Perspectives

This section gives the outcomes and discussions on the literature reviewed regarding HRES modeling for rural electrification. This paper has widely discussed key issues surrounding hybrid renewable energy system modeling, such as planning, system design problem, optimization constraints, design tools, control strategies, configurations, and energy storage systems. In remote areas, stand-alone energy technologies with only one energy resource (say solar PV) could serve the energy needs of a small locality. Still, as the energy demand increases, stand-alone energy technologies become deficient to power the energy needs owing to low reliability and relatively high investment costs. Hence, hybrid energy systems eliminate the limitations of stand-alone energy systems with just one energy resource. From the review, the most commonly seen hybrid configurations are solar–wind systems, and scholarly materials on hydro-based hybrid systems are scarce. Hence, research on hydro-based hybrid systems is highly encouraged.

Several classical and meta-heuristic optimization methods have been used to optimally model energy systems. Meta-heuristic techniques commonly used in hybrid energy system modelling are PSO, GA, ABC, SA and BBO. To improve the solutions by optimizing hybrid energy systems, some scholars have suggested merging some of these techniques to form a hybrid method. While this endeavor gives some enhanced overall performance, it has been reported to have drawbacks. For example, a situation of partial optimism has been reported in the hybrid Monte Carlo simulation / PSO method used by [133]. A hybridized approach to optimally sizing a solar-wind system was used by [134] in a combination of 3 algorithms comprising SA, chaotic search (CS) and harmony search. They concluded that this combined method gave better results than the individual methods. However, there are several limitations observed in these hybrid methods, such as suboptimal results observed in the iterative-GA hybrid method [135], complications in designing a system with a hybrid ANN-Genetic Algorithm-Monte Carlo Simulation [136], and complexities in computer programming as observed in the hybrid response-surface-based / Monte Carlo technique [137], arbitrary modification of initial parameters of the evolutionary algorithm executed [79] and the techno-economic compromise [138, 139]. Besides the previous optimization approaches, some widely used commercial software has been developed for renewable energy system modelling and optimization, such as RETScreen, HOMER, and HYBRID HOGA. The HOMER software has been widely used because of its robustness, ability to perform least cost optimization of lifetime electricity cost and provision of further environmental study for specific solutions. However, commercial software which uses classical methods to search best solutions could incur a long simulation time when solving complex problems. And so, optimization models using artificial intelligence (AI) methods have proven to be relatively better than classical approaches due to their enhanced flexibility. Unlike classical software tools, AI-based tools offer users the opportunity to make several adjustments to the program to solve single or multi-objective design problems. The most studied tools in the literature include; GA, PSO, HSA, SA, ACA, Bacterial Foraging Algorithm (BFA), ABC, Cuckoo Search (CS), or a hybrid of these techniques.

Energy storage (mostly battery) has been used extensively in solar/wind-based hybrid energy systems with intermittency challenges as the storage system stabilizes the effects of intermittent generation. The storage systems also help in shaving the peak periods and smoothen the power demand fluctuations.

Most research on hybrid energy systems suggests minimizing the total NPC, levelized COE and annualized system cost to find the most economical system. The optimization of these systems has accompanying constraints related to reliability, power balance, component capacity, maximum budget and state of the storage device. Reliability metrics used in hybrid energy system modeling include unmet load, power supply probability, loss of load probability, and expected energy not supplied. Other decision variables scholars include the capacity of components (solar PV, generators, batteries, wind turbines) and renewable fractions.

The preceding optimization methods are joined to solve optimization problems in hybridized optimization techniques to improve the results obtained and achieve computational efficiency. These hybrid methods combine two or more single heuristic and classical techniques by using the advantages of the individual methods. The modeling of a hybrid renewable energy system involves numerous conflicting variables and constraints that must be carefully integrated to achieve the desired objective; hence, rigorous strategic planning is required. Therefore, there is a continuous need in the evolution of AI-based approaches to optimize HRES such that a significant percentage of constraints can be considered during optimization.

10. Conclusion

HRES have a huge potential as countries seek to decarbonize the power network and simultaneously improve energy access. The transition to renewables is even more promising with the rapid decrease in the cost of these technologies. Rural areas with often low electricity access have an option to leapfrog from this positive decrease in cost. Techno-economically, the technologies, if hybridized in rural installations, do not require transmission lines and greatly reduce power losses and costs. To achieve universal access to clean and affordable energy, studies need to focus on the deployment and adoption of renewables since most regions have an abundance of renewable energy resources which can be tapped for power generation. This research is an up-to-date review on aspects of hybrid energy systems such as optimization methods, control techniques, commonly used energy storage in hybrid systems, the HRES design problem, performance indicators used to evaluate system reliability and cost-effectiveness and various hybrid system configurations. A periodic assessment of these aspects will facilitate the identification of research gaps that could engage scholars in the future to advance hybrid energy system development. While remarkable research has been made so far on hybrid system modeling and optimization, this review indicates that more work could still be done with several evolving algorithms having the potential to provide more optimal global solutions.

Nomenclature

AC	Alternating Current
ABC	Artificial Bee Colony
AI	Artificial Intelligence
ANN	Artificial Neural Network
BBO	Biogeography Based Optimization
COE	Cost of Energy
DC	Direct Current
ESS	Energy Storage System
FL	Fuzzy Logic
GA	Genetic Algorithm
HRES	Hybrid Renewable Energy System
HSA	Harmony Search Algorithm
HYBRIDS	Hybrid System Simulation Models
HYDROGEM	Hydrogen Energy Model
INSEL	Integrated Simulation Environment Language
IRENA	International Renewable Energy Agency
MPPT	maximum power point tracking
NN	Neural Network
NPC	Net Present Cost
PSO	Particle Swarm Optimization
PV	Photovoltaic
RE	Renewable Energy
RES	Renewable Energy System
RPSIM	Remote Area Power Supply Simulator
SDG	Sustainable Development Goal
TRNSYS)	Transient Energy System Simulation Program
UN	United Nations

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