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A review of hydrogen-based hybrid renewable energy systems: Simulation and optimization with artificial intelligence

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Abstract. With the massive use of traditional fossil fuels, greenhouse gas emissions are increasing, and environmental pollution is becoming an increasingly serious problem, which led to an imminent energy transition. Therefore, the development and application of renewable energy are particularly important. This paper reviews a wide range of issues associated with hybrid renewable energy systems (HRESs). The issues concerning system configurations, energy storage options, simulation and optimization with artificial intelligence are discussed in detail. Storage technology options are introduced for stand-alone (off-grid) and grid-connected (on-grid) HRESs. Different optimization methodologies, including classical techniques, intelligent techniques, hybrid techniques and software tools for sizing system components, are presented. Besides, the artificial intelligence methods for optimizing the solar/wind HRESs are discussed in detail.

1. Introduction

Due to the massive use of traditional fossil fuels, greenhouse gas emissions are increasing. Environmental pollution is becoming an increasingly serious problem, which led to an imminent energy transition from traditional energy to clean energy, such as renewable energy. The share of renewables in global electricity generation reached nearly 28.6% in 2020 and will increase to 61.2% in 2030, see https://www.iea.org/reports/renewable-power. With the rapid development of renewable energy technology for various practical applications, a hybrid renewable energy system (HRES) is a cost-effective alternative to expensive power grid extensions. Therefore, research on renewable energy is necessary, urgent and feasible, see https://www.woodmac.com/.

Renewable energy, as clean energy, is usually obtained from nature and regenerated continuously without human participation, which is currently the most promising energy with the characteristics of cleanness and abundance [1]. For the in-depth study of renewable energy systems (RESs), many researchers from various countries have focused on single renewable energy in the early stages [2-4], such as the power generation systems of photovoltaic, wind, hydroelectric. However, to supply sufficient power for meeting load demand, single renewable energy systems (SRESs) often have excessive size, which is caused by the features of randomness and intermittence of single renewable energy sources like solar and wind [5]. Therefore, more and more researchers are interested in hybrid renewable energy systems (HRESs). As an energy vector, hydrogen can be used to store the energy generated by the systems with zero pollution [6]. The short-term and long-term storage systems that use lead-acid batteries and hydrogen technologies have proven effective solutions [7]. In response to the limitations of SRESs, hybrid renewable energy technologies have been widely used in power generation, especially in remote areas. Since it is not economical and practical to connect to the public grid in remote areas, stand-alone systems have also been widely used in remote areas. Moreover, it is necessary to develop the optimization model based on the prediction of renewable energy data using appropriate technologies, so that different renewable energy sources can be ultilized effectively and economically, and the systems' reliability of different configtations, including stand-alone and grid-connected HRESs, needs to be ensured.

At present, the objectives of most review articles on HRESs are relatively separated, only considering modeling, simulation, or optimization of HRESs. This paper reviews various issues related to HRESs, such as system configurations, energy storage options, simulation and optimization with artificial intelligence. The different types of renewable energy sources, especially solar and wind energy, and the introduction of renewable energy systems are presented in Section 2. Next, Section 3 discussed the configurations of stand-alone and grid-connected HRESs and their difference. Then, Section 4 described different energy storage technology like hydrogen and battery storage for HRESs. Besides, optimization approaches and techniques for solar/wind hybrid renewable energy systems through mathematical models are discussed in detail in Section 5. Finally, Section 6 elaborated artificial intelligence (AI) techniques used for forecasting and optimizing HRESs.

2. Solar, wind and hybrid renewable energy system

With the increasing demand and urgent call for clean energy, the application of renewable energy is extensively acknowledged to be a promising approach to replace conventional fossil fuels [8]. Renewable energy sources, including solar energy, wind energy, hydropower, biomass, wave energy, tidal energy, ocean temperature difference energy, geothermal energy, have been paid much attention recently [9]. As solar and wind are the most common energy sources globally with the fastest growing, they have received a great deal of popularity.

2.1. Single renewable energy system

According to the characteristics of energy distribution and geographical location, the types of developed and applied renewable energy sources vary from country to country. The utilization of renewable energy for electricity generation is clean and environmentally friendly, so researchers have paid much attention to the renewable energy system consisting mainly of renewable energy generators, converters and loads [10].

SRESs usually consist of a renewable energy generator, the converter, and the load [11]. Aimed at various SRESs, many researchers carried out numerous studies by simulations and experiments [12-14]. They focused on the performance characteristics of different renewable energy for power generation, whether the power supply meets the requirements of the load and different optimization approaches for the system. However, due to the randomness and volatility of SRESs, the research focus is gradually shifting from single to hybrid RESs.

2.2. Hybrid renewable energy system

Compared with the SRESs, there are various HRESs, such as solar/wind HRESs, wind/hydro HRESs, solar/wind/biomass HRESs, wind/hydro/tidal HRESs. The solar and wind are reciprocal to each other concerning weather conditions. Therefore, combining the two energy resources is more effective and practical [15].

As is shown in Table 1, it can be seen that the advantages and disadvantages of the single and hybrid RESs. Typical HRESs are solar/wind, solar/storage, wind/storage, solar/wind/storage, solar/wind/non-renewable/storage systems [16]. In hybrid systems, electricity can be delivered to the public grid or consumed directly to power the load. Besides, it can be stored by an energy storage system for subsequent use. Many researchers performed many experiments and simulations for the systems [17-

19]. In order to find the optimal plan, they built various models of the system with different structures and configurations to compare and analyze the system's performance in terms of technical and economical. Besides, they designed various HRESs applied for different scenarios to meet the load demand. In the future, to meet the demand for electricity without having negative effects on the environment, more renewable energy sources will be utilized for power generation [20].

Table 1. Comparison of SRESs and HRESs.

Renewable energy	Advantages	Disadvantages
Solar	• Distribution universality • Simple installation and maintenance	• High construction cost • Dispensability and instability • Low efficiency
Wind	• Fast construction • Flexible installation scale	• Limited by geography and weather
Solar/wind	• High efficiency and strong reliability	• Higher initial cost

3. Stand-alone and grid-connected hybrid renewable energy systems

In addition to the classification according to the number of renewable energy sources, HRESs can generally be divided into grid-connected (on-grid) and stand-alone (off-grid) HRESs depending on whether connected to the public grid. Grid-connected and stand-alone HRESs are applied in different scenarios based on different usages and geographic locations. As is shown in Figure 1, it is the diagram of a stand-alone or grid-connected solar/wind HRES with hydrogen storage. The grid-connected system is connected to the grid, i.e., on-grid, while the stand-alone system is not connected to the grid, i.e., off-grid.

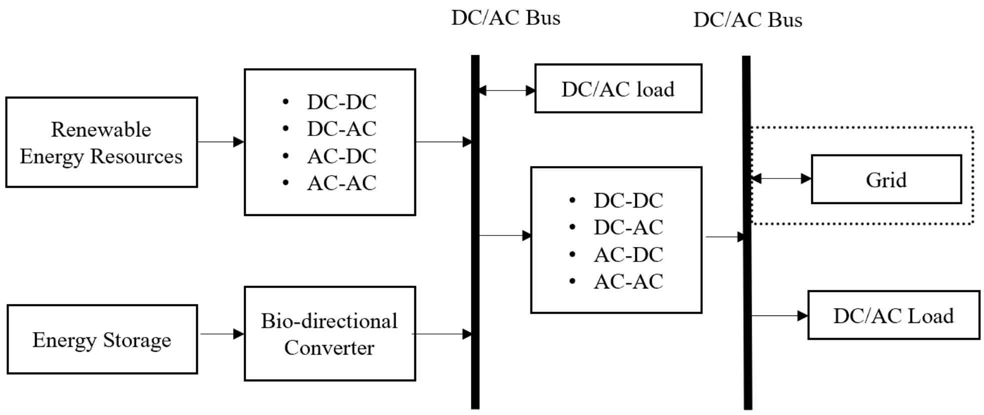

Figure 1. An overview diagram of a stand-alone or grid-connected HRES.

3.1. Stand-alone hybrid renewable energy system

Stand-alone HRESs are power generation systems independently of the public grid and are widely applied in remote mountainous areas, regions without electricity, islands, communication base stations, and street lighting. The stand-alone HRESs have no geographical restrictions and can be installed wherever renewable energy sources like solar and wind energy are available. Furthermore, they are of high practicality to supply the electricity in time in case of power failure. However, since the stand-alone HRESs are generally equipped with energy storage systems, such as battery and hydrogen storage, the systems' construction and maintenance costs are relatively expensive.

By summarizing different literature, it is found that the systems are usually equipped with energy storage devices to ensure the system's stability. Based on different geographical characteristics, many researchers conducted many experiments. They built different models to study the stand-alone HRESs

[21-23] to simulate the systems and optimize the performance of different systems to supply stable power for the loads in various application scenarios.

3.2. Grid-connected hybrid renewable energy system
Grid-connected HRESs must be connected to the public grid to work effectively. When the electricity generated by the systems is greater than the load's electricity consumption, the excess electricity is fed through the systems to the public grid. When the electricity generated by the systems is less than the load's electricity consumption, the public grid will automatically replenish the electricity to the load. The whole process is intelligently controlled without manual operation.

With the development and application of renewable energy generation technology, more and more HRESs are connected to the public grid, which results in the security and stability in the systems becoming a widespread concern. Therefore, grid-connected HRESs have become the major concern when renewable energy resources, such as wind and solar energy, slowly replace conventional fossil fuels [24].

4. Solar/wind hybrid renewable energy system with energy storage
Due to the complementary nature of solar and wind energy in the time dimension, the solar/wind HRESs have become the research focus. Usually, as is shown in Figure 2, a solar/wind HRES can have one or more energy storage devices. Many energy storage technologies exist with the development of science and technology, such as hydrogen storage and battery storage.

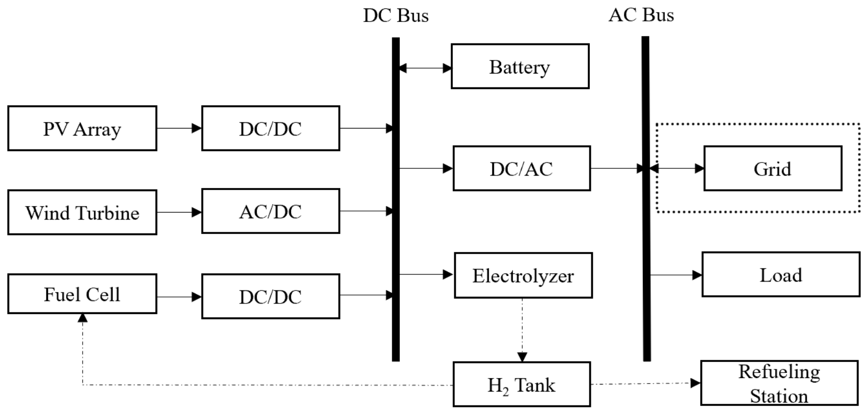

Figure 2. Diagram of a stand-alone or grid-connected PV/wind/battery/fuel cell HRES.

4.1. Hydrogen energy storage for solar/wind hybrid renewable energy system
At present, there are different ways to store hydrogen. Generally, hydrogen storage methods include compression hydrogen storage, liquid hydrogen storage, metal hydride hydrogen storage, adsorption hydrogen storage, each of which has its characteristics [25].

In our previous work, thermodynamic models were established to study the hydrogen performance [26], heat transfer analysis is performed for compressed hydrogen storage tank [27]. For metal hydride hydrogen storage, hydrogen is absorbed directly into the bulk of the material for absorptive hydrogen storage. The phase change materials were considered to be added to the system to improve the hydrogen storage performance of the metal hydride system [28]. The performance of hydrogen storage was analyzed by simulation and experiment in Ref.[29]. Adsorption hydrogen storage requires highly porous materials to maximize the surface area available for easy uptake and release of hydrogen from the material, such as activated carbon [30], metal-organic framework [31].

A solar/wind HRES with hydrogen storage mainly consists of photovoltaic (PV), wind turbine, electrolyzer, compressor, storage tank, fuel cells, converter. Under the influence of the power management system, the excess electricity will supply power to an electrolyzer to produce hydrogen, which will be delivered to fuel cells for power generation [7, 32]. Besides, the systems are also widely used to produce hydrogen, which can be stored and transported to refuelling stations as fuel for hydrogen fuel cell vehicles. Our previous works have dealt with hydrogen storage, refuelling and their safety. The analytical solutions of hydrogen temperature and pressure in compression hydrogen storage tanks were derived based on lumped parameter models to evaluate and optimize the performance of the hydrogen storage system [33, 34]. An artificial neural network model was used to predict and optimize the refueling system [35].

4.2. Battery energy storage for solar/wind hybrid renewable energy system

In HRESs, batteries are usually applied as the components of HRESs for energy storage to improve the systems' reliability. Currently, battery storage technologies are one of the most commonly used worldwide. In batteries, energy is stored in a group of multiple batteries in electrochemical energy, connected in series, parallel or series/parallel hybrid to reach the values of voltage and capacity based on the systems' requirements. Each battery, made up of two-conductor electrodes and an electrolyte, is usually placed in a sealed container and connected to the external power source or the load. The electrochemical process stores chemical energy in the battery and releases it when needed. The battery storage system is suitable for the stand-alone HRESs among various storage technologies with the characteristics of flexibility, reliability and rapid response. With the increasing number of industrial applications, sodium-sulfur (NaS) battery, flow batteries include zinc bromide battery (ZnBr) and polysulphide bromide battery (PSB), and lithium battery technologies have been developed rapidly and have made significant breakthroughs in energy conversion efficiency. Furthermore, from the perspective of safety and economy, these batteries technologies have been further enhanced. For example, NaS batteries, whose energy density is three times that of lead-acid batteries, can achieve an energy conversion efficiency of almost 90% and has a longer service life [36].

5. Optimization approaches for hybrid renewable energy system

Nowadays, the research on optimizing the configuration and size of HRESs is relatively mature. As shown in Figure 3, establishing an optimization model is from three aspects: design variables, objective functions and constraints.

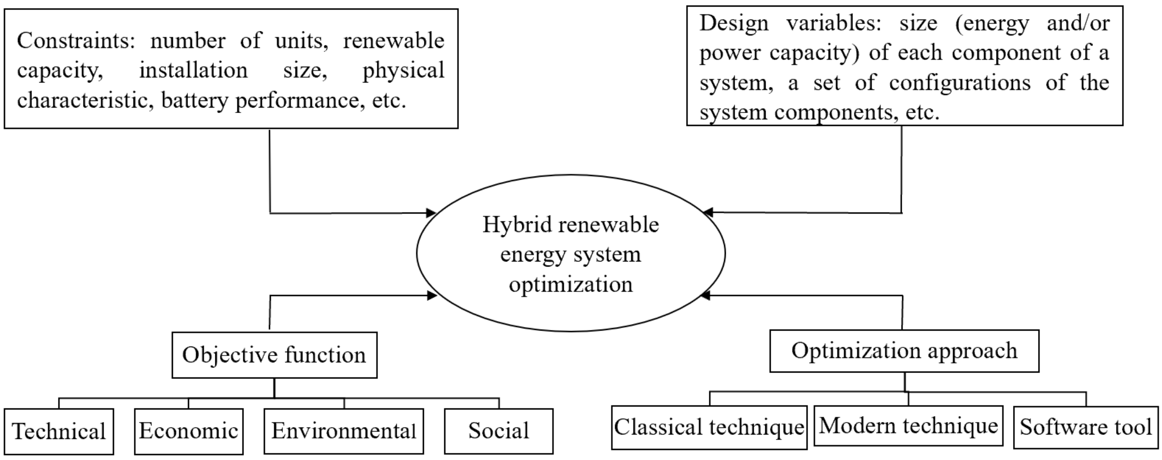

Figure 3. Diagram of the optimization design of HRESs.

The indicators of objective functions can usually be divided into four categories, including technical, economic, environmental, and social, which are used to analyze and evaluate the availability and feasibility of the HRESs, to contribute to the design and construction of an optimal HRES. Economic indicators are used to determine the desirable minimum initial, maintenance, replacement, and other mandatory costs of the systems. Technical indicators are employed to evaluate the comprehensive ability of the systems to ensure the reliability and stability of the systems to satisfy the load demand. Environmental indicators are utilized to evaluate the greenhouse gas emission, such as carbon dioxide, and some other obnoxious emissions produced by the systems for a certain period. Social indicators are applied to evaluate the capability of the systems to produce energy, which will be beneficial to increase the human development index. Furthermore, social indicators can also evaluate the acceptance of people for installing the HRESs and job creation [37]. So far, the optimization approaches can be classified into three categories, including classical technique, modern technique, and software tool.

5.1. Classical techniques of optimization for hybrid renewable energy system

Classical techniques use linear programming, iteration, numerical analysis, graph theory, dynamic programming, integer programming, and probabilistic methods [37], successfully solving small-scale problems. For instance, a deterministic approach is proposed to determine the optimal size of a solar/wind/diesel HRES [38]. Based on Hammersley Sequence Sampling, the ε-constraints method [39] is applied to achieve the multi-objective optimization of the systems.

In the current research progress, one of the constraints on the size of the system is that the number of solar panels, the numbers of wind turbines and batteries must be in integer, so many researchers have studied different optimization algorithms. The mixed integer linear programming (MILP) algorithm is used to optimize the design of solar/wind HRESs that solves the generators' location and the microgrid's design to meet the power requirements of the load and utilize the energy supply potential [40]. Amrollahi et al. [41] optimized the size of micro-grid components by demand response (RD) procedures and MILP algorithms. In addition, the MILP algorithm is also used to calculate the optimal size of an HRES in the Rome area, and the results show that the optimal size can meet the needs of industrial plants and the achievable savings [42].

5.2. Modern techniques of optimization for hybrid renewable energy system

Modern optimization techniques, such as genetic algorithm (GA) and particle swarm optimization (PSO), are extensively applied to optimize solar/wind HRESs. Many researchers have used the GA for optimizing the HRESs to determine the design and operation of the systems. Gonzalez et al. [43, 44] calculated the Pareto front through the GA and provided a set of optimal results. Besides, they determined the optimum size of a grid-connected PV/wind HRES and concluded that the net present value (NPV) obtained from the GA increases when operation and maintenance (O&M) expenditures increase, whereas decreases when the efficiency of renewable energy technologies improves. Traditional GA cannot effectively solve multi-objective optimization problems, and many researchers have proposed many improved GA, such as non-dominated sorting genetic algorithm (NSGA), NSGA-II, NSGA-III, improved non-dominated sorting genetic algorithm-II (INSGA-II), multi-objective genetic algorithm (MOGA), MOGA-II.

The PSO algorithm is another algorithm that is often used to optimize renewable energy systems. Triviño et al. [45] introduced a novel energy management system for optimizing a grid-connected PV/wind/battery/fuel cell HRES using the particle swarm optimization (PSO) method and conducted simulation tests on the HRES. Hossain et al. [46] proposed the PSO algorithm for optimizing an energy management system to find the optimal control strategy of a community grid-connected microgrid HRES that mainly consisted of PV, wind, and battery.

5.3. Hybrid algorithm of optimization for hybrid renewable energy system

Compared with traditional approaches, artificial intelligence algorithms have been widely used during the last decade with less computation time, better accuracy, and good convergence. The hybridization of optimization algorithms makes different algorithms complement each other and produce better optimization efficiency. A single optimization algorithm has certain limitations, whose optimization results are often not ideal. Therefore, based on the single algorithms, the hybrid algorithms have developed into an effective way to improve algorithm optimization performance.

Zhang et al. [47] proposed a chaotic search-simulated annealing-harmony search-artificial neural network algorithm (CS-SA-HS-ANN) to optimize a solar/wind HRES, which gave better results than the single optimization approaches (SA-ANN and HS-ANN). By hybridization of two or more algorithms, Sinha et al. [48] proposed to use hybrid algorithms to overcome the constraints of a single algorithm.

5.4. Software tools of optimization for hybrid renewable energy system

At present, various software tools are available for determining the optimal HRESs, such as HOMER, Matlab, RETScreen, HYBRID2 [49]. Nowadays, the most widely applied software tool in HRESs for optimization is HOMER software [37].

Many other software tools are also available to design HRES, such as RETScreen, iHOGA, H2RES. Table 2 presents the summary of different optimization methods. An optimization algorithm is commonly combined or interfaced with simulation software tools to achieve the optimization function. Amrollahi et al. [41] designed a demand response program through HOMER and GAMS software tools. They optimized the size of micro-grid components by MILP algorithms, which can implement effective component size optimization and cost-reducing application strategies. Based on HOMER software, Aziz et al. [50] obtained the optimal configuration of a stand-alone PV/hydro/diesel/battery HRES for a remote rural area in Erbil. Besides, They conducted a sensitivity analysis of different parameters like water pipe losses, generator minimum load and battery state of charge. Caballero et al. [51] proposed a commercial optimization design method for a small grid-connected PV/wind HRES through HOMER software. They presented sensitivity analysis on parameters of PV panel and wind turbine. A stand-alone PV/wind/diesel HRES is modelled and implemented in Matlab/Simulink software by Merei et al. [52]. Besides, they used genetic algorithms to change the size and settings of the components to minimize the total cost.

Table 2. Summary of different optimization methods.

Methods	Advantage	Disadvantage	Algorithm
Classical algorithms	• Mature • Definite answer	• Many iterations • Slow speed	MILP, DIRECT, graph theory
Intelligent algorithms	• Fewer calculation times • Higher accuracy • Good convergence	• Complex • Each execution is slightly different	GA, PSO, INSGA-II, MOGA, MOGA-II
Hybrid algorithms	• Good robustness	• High hardware requirements • More complex	SA-ANN, HS-ANN, CS-HS-SA-ANN
Software tools	• Accurate physical model	• Few choices and limitations	HOMER, H2RES、RETScreen, iHOGA

6. Artificial intelligence methods of optimization for hybrid renewable energy system

The artificial intelligence methods mainly used to optimize the HRESs are meta-heuristic algorithms, including biological heuristic algorithms (swarm biological heuristic algorithms and non-swarm biological heuristic algorithms) and physical or chemical heuristic algorithms [53]. The classification diagram of the algorithm is shown in Figure 4.

The non-swarm biological heuristic algorithms include the GA, biogeography-based, artificial immune, whale and flower pollination algorithms. To optimize a solar/wind HRES, Yang et al. [54] used the GA, which dynamically searched for the optimal configuration and minimized the annualized cost of the system under the condition of meeting the requirement of loss of power supply probability. Abdelkader et al. [55] adopted a multi-objective genetic algorithm to minimize the total cost of electricity and loss of power supply probability, which are set as objective functions to determine the sizing of stand-alone PV/wind HRESs considering all storage dynamics. Askarzadeh [56] proposed a memory-based genetic algorithm (MGA) to optimize the configuration of an HRES to minimize the cost of energy production. Gupta et al. [57] applied a biogeography-based optimization algorithm to determine the size of a solar/wind/battery HRES. Hatata et al. [58] used the clonal selection algorithm to optimize the size of a solar/wind/battery HRES under the premise of low fluctuation rate and minimum cost. Yin et al. [59] proposed a modified non-dominated sorting whale optimization algorithm to realize the multi-objective optimization of an HRES.

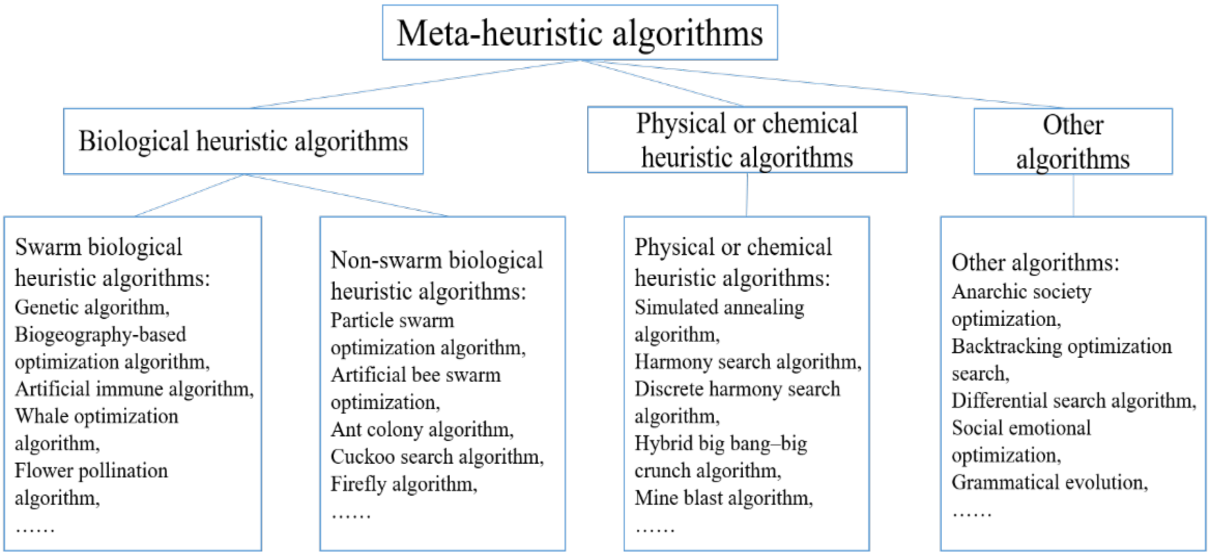

Figure 4. Diagram of classification of meta-heuristic algorithms (modified from [60]).

The third class of meta-heuristic optimization algorithms consisted of physical or chemical heuristic algorithms, such as simulated annealing, harmony search, discrete harmony search, hybrid big bang-big crunch, mine blast algorithms. Taking the minimum total cost of the hybrid energy system as the objective function, Ekren et al. [61] adopted simulated annealing (SA) algorithm to optimize the size of a PV/wind/battery HRES. When the optimal calculated results from the SA algorithm were compared with previous research results, it was found that the SA algorithm has a better performance than the traditional response surface methodology. Maleki [62] utilized the discrete simulated annealing algorithm to optimize the size of a solar/wind/fuel cell HRES. Based on the maximum voltage stability index and minimum power loss, Brinda et al. [63] applied the harmony search algorithm to optimize a solar/wind/fuel cell HRES in terms of the size and configuration of the system. With the premise of meeting load requirements, Ahmadi et al. [64] proposed an effective optimization approach based on a hybrid big bang-big crunch (HBB-BC) algorithm to optimize the size of a stand-alone HRES. Compared with the calculated results of the PSO algorithm, the simulation results of the hybrid algorithm showed that the HBB-BC algorithm has access to the optimal size of the system with high accuracy.

7. Conclusion

A review concerning the various aspects of HRESs, including system configurations, energy storage options, simulation and optimization with artificial intelligence, has been presented. Among various renewable energy systems, HRESs are more stable than SRESs for practical applications. By comparing stand-alone and grid-connected HRESs, stand-alone HRESs are suitable for remote areas and must be equipped with energy storage options. Therefore, hydrogen energy storage and battery storage technologies are also highlighted. Different optimization methodologies, including classical, intelligent and hybrid techniques for determining the system components, have also been discussed and summarized. It has been found that AI techniques are suitable to achieve multi-objective optimization with the advantage of relative computational simplicity. The survey shows that the GA and PSO algorithms are the most promising and widely used for optimization. Moreover, combining various algorithms to use the advantages of both seems to be one of the future research directions. This paper would be helpful for scholars to confront and overcome the complexities and challenges in renewable energy-based hybrid system research.

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