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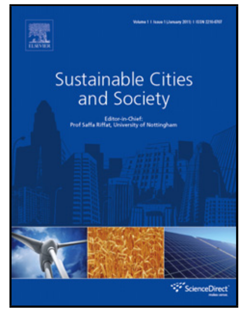

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Authors: Ssennoga Twaha, Makbul A.M. Ramli

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A review of optimization approaches for hybrid distributed energy generation systems: off-grid and grid-connected systems

Ssennoga Twaha[1*] and Makbul A.M. Ramli[2]

[1]Energy and Sustainability Division, Faculty of Engineering, University of Nottingham, NG7 2RD, United Kingdom

[2]Department of Electrical and Computer Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia

* Corresponding author. *E-mails:* mramli@kau.edu.sa (M.A.M. Ramli) ssennogatwaha2007@gmail.com (S. Twaha).

Highlights:

1. Optimization approaches for hybrid distributed generation systems was reviewed.
2. AI techniques are dominating the techniques used for optimization of DEG systems.
3. The objective functions are maximum reliability and optimum operation schedule.
4. Developments are undertaken to improve the operational efficiency in implementation.

Abstract

Distributed generation is a collective term that covers the generation of energy at micro level, distributed in a location near the end user by using renewable and nonrenewable distributed energy generation (DEG) resources including among others, solar, wind, hydro, geothermal and diesel generators. This paper presents a review on the optimization approaches for hybrid DEG systems, considering both stand-alone and grid-connected systems. There are several optimization techniques used on DEG systems, comprising of analytical and artificial intelligent (AI) and hybrid techniques. This work encompasses the selected journal papers published especially in the last five

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years. A brief background of the optimization approaches been highlighted, particularly identifying the most common techniques to give the basis for analysis of the approaches currently applied on hybrid DEG systems. The analysis shows that AI techniques are still dominating the techniques used for optimization of DEG systems, with particle swarm optimization (PSO) recognized as the most used AI method. The objective functions in the optimization of hybrid DEG systems are currently defined to maximize the reliability, to minimize the expected interruption cost, and to optimize operation schedule of DEG resources.

Keywords: Hybrid DEG systems; Optimization techniques; Off-grid systems; grid-connected systems

1. Introduction

Distributed energy generation (DEG) systems have become increasingly popular in the world over the last two decades. DEG systems are a single or mix (hybrid) of both the conventional fossil nonrenewable and renewable resources established near the consumer’s location. However, because of the increasing cost, resultant pollution and probable depletion of fossil fuels, renewable energy sources are being extensively utilized to contribute in meeting the energy demands [1]. It is therefore argued that, exploring the exploitation of local energy sources, especially renewables, it is a matter of economic benefit and security for energy-importing societies [2]. Policy makers in many states around the globe are setting forth renewable energy integration targets to reduce the energy production from conventional sources such as coal, oil and gas, which currently form about 80% of primary energy [3]. A systematic review reported that in North America, climate change is the main driving force for DEG application with job creation or the green economy as the motivating factor [4]. Additionally, the possibility of generating energy on the demand side has many advantages in terms of energy efficiency, as it can reduce the power loss due to network transmission, reserve generation capacity, the network footprint, and the like. However, it is required to optimize the type, size, location and other objective parameters to obtain technical, commercial, environmental and regulatory advantages of DEG systems [5].

Renewable energy resources include among others solar, wind, hydro and geothermal. However, solar energy has gained much more attention due to its long life, inexhaustible nature, low maintenance, zero running costs, availability and pollution free [6]. Nevertheless, to gain the

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maximum benefits from renewable energy, hybridization of the energy resources is necessary so that the challenges faced by some of the energy sources due to their stochastic and intermittent behavior is overcome by the others [7]. For instance, wind has a problem of intermittence, and therefore generates unstable and less energy; in such a moment, other energy resources can compensate the gap left out by the wind energy resource. Alternatively, with microgeneration coupled with a robust and efficient energy storage system within DEG setting, the control of intermittent renewable resources is possible, for example by storing the generated energy and then dispatching it from the storage when called upon to serve the available energy demand later [8]. To perform optimally, appropriate approaches have to be applied to optimize the hybrid DEG systems [9]. A proper site must be selected where all the DEG systems involved can be able to harvest maximum, as well as easy supply of energy to the end users. For example, a geographical information systems (GIS)-based multi-criteria decision analysis is used for site selection of hybrid offshore wind and wave energy systems in Greece [10]. In the study, the unsuitable marine areas for the deployment of the system were identified through the development of a GIS database that produces thematic maps, representing exclusion criteria related to utilization restrictions, considering technical, economic as well as social constraints. Furthermore, as a results of raising electricity prices and greenhouse gas emissions in the building sector, a number of methods are being implemented for energy management in the commercial buildings [11].

Several researches are being conducted on the optimization of both stand alone and hybrid DEG systems. A review of hybrid renewable energy systems was accomplished, covering the feasibility of various controllers like proportional integral controller, microcontroller, fuzzy controller and hysteresis controller [12]. Hybrid renewable energy systems have found application in buildings to improve their energy performance [13]. The status of research on sizing the PV systems is reviewed considering the standalone PV systems, hybrid PV/wind systems, hybrid PV/diesel generator systems, hybrid PV/wind/diesel generator systems and grid connected systems [14]. It is concluded that the numerical methods are the most popularly used techniques. With respect to efficiency and sustainability of hybrid energy systems, Yanine & Sauma [15] reviewed the grid-connected micro-generation systems minus storage. They observe that energy sustainability is fundamentally a system's issue which should be built into a system itself rather than being explained by exogenous factors. Size optimization of stand-alone photovoltaic/wind hybrid system is conducted on the techno-economic point of view to determine a reliable system that has the lowest investment cost [16]. The developed optimization tool gives the optimum size of the PV array and battery bank as well as the desired loss of power supply probability and the minimum

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energy cost consideration. Ramli et al. investigated the performance of support vector machine (SVM) and artificial neural networks (ANN) in predicting solar radiation on a tilted surface with Saudi Arabia as the case study [17]. The results reveals that SVM has significantly higher accuracy, robust during computation and is faster in predicting the radiation on the tilted surfaces in comparison with ANN. Substantial issues affecting the hybrid renewable energy DEG systems are also discussed [18]. Factors considered for designing and implementation of hybrid renewable energy systems including simulation and optimization software packages for making such analyses are assessed.

There are several issues surrounding the incorporation of DEG units within the microgrid network. Several researches of DEG microgrids deserve to be mentioned in this regard. Unamuno and Barrena [19][20] discussed the classification of control strategies and topologies for Hybrid ac/dc microgrids. They observe that more research effort is necessary in terms of management strategies to enable the control of the interface device and the ancillary services by employing for example, the transition between islanded and grid-connected modes of operation and interconnection of microgrids. The impact assessment of optimally placed DEGs with different load models is done using genetic algorithm (GA) in order to achieve the minimum total MVA intake [21]. Different power system performance indicators are evaluated in terms of reduced emissions, reduced economic burden, improved the technical issues and improved system security for renewable energy and gird-connected systems.

In trying to utilize the available energy resources efficiently, several optimizations approaches have been applied in the modeling and the planning stage of hybrid DEG systems. The main target of using different optimization techniques is to achieve an optimal hybrid DEG system, which is practically, economically, environmentally and socially friendly. The objective of this work is to review the optimization approaches for hybrid DEG systems, considering on-grid and off-grid hybrid DEG systems. The rest of the paper is organized as follow: Section 2 gives a brief introduction to optimization methods. Sections 3 and 4 deals with the optimization techniques for off-grid and-grid connected hybrid DEG systems, respectively. The reviews papers related to hybrid DEG systems are also given due consideration and are discussed in section 5. Some critical analysis of the presented optimization approaches is deliberated in section 6 and section 7 ends with the concluding remarks.

2. Brief introduction to optimization methods.

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Many researchers especially in energy engineering rarely find time to research deeply on the concepts pertaining optimization approaches. They perhaps simply choose one or more working methods and apply it/them to solve the problem at hand. This is the driving force behind giving a brief background about the optimization methods. Engineering design (ED) is defined as a decision-making process to build products that satisfy specified needs. An ED is comprised of complicated objective functions with a large number of decision variables, from which the feasible solutions are the set of all designs characterized by all possible values of the design parameters [22]. Therefore, the optimization method attempts to get the optimal solution from all available feasible solutions. In some applications, it is common to face decision making problems that are determined by their nature multidimensional object. For example, in capital budgeting one could maximize the net present value (NPV) of the selected projects and simultaneously minimize their risks. The same could apply to the hybrid energy system which uses multi-objective problem as to where the output power is maximized while the costs (capital, operation and maintenance) and pollutant emissions could be minimized simultaneously. Multi-objective optimization consists of finding solutions that concurrently maximize several objective functions over a set of feasible solutions [23]. Unlike single-objective optimization, multi-objective optimization leads to a set of non-dominated solutions instead of a single optimal solution.

Optimization methods are majorly divided into two categories: mathematical and metaheuristics methods [24]. On the other hand, optimization techniques can be categorized and compared according to Fig. 1. Heuristic methods are simple procedures that provide satisfactory, but not necessarily optimal, solutions to large instances of complex problems very fast. Meta-heuristics are generalizations of heuristics in the whereby they can be applied to a wide set of problems, requiring few modifications to be adapted to a given case [25].

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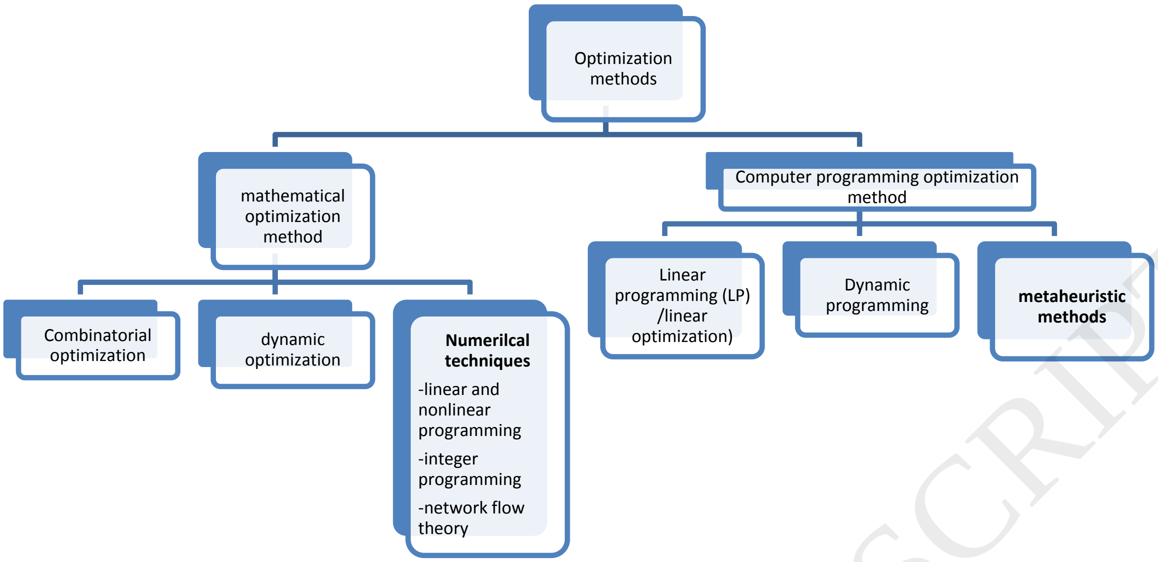

Fig. 1. Classification of optimization methods.

2.1. Mathematical approaches

The mathematical optimization sometimes referred to as deterministic or classical or analytical methods make use of mathematical approaches, such as the gradient information of functions. These methods include among others the steepest decent, Newton, Simplex methods and quasi-Newton [24]. The sub categories of mathematical optimization include numerical techniques such as network flow theory, linear programming, nonlinear programming, integer programming and dynamic programming. On the modeling of the energy systems view point, the mathematical modeling optimization methods have been classified into two broad categories; conventional and new generation approaches whose advantages and disadvantages are discussed by [26]. Accordingly, the conventional techniques include the trade-off Approach, iterative Approach, linear programming (LP) and mixed integer linear programming (MILP). The new generation approaches encompass the conventional mathematical modeling methods applied into the computer technology which include methods that follow under the metaheuristic approaches which are discussed separately.

Probabilistic approaches are also very common by reason of their ability to solve complicated and nonlinear problems. A stochastic method which is very popular is the Monte Carlo Simulation

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(MCS) that is regarded as being a system size independent approach and is used when the system has many uncertain variables [4].

2.2. Artificial intelligent techniques

With the advancement in computer technology, artificial intelligent (AI) methods have become very popular. To solve the problem, AI algorithms are integrated into the computer in the heuristic solvers. Most of the metaheuristic algorithms are nature-inspired [27]. The AI based search methods or metaheuristic methods are divided into three major sub categories including Swarm intelligence (SI), Non-SI, and Physics or chemistry inspired algorithms. The applied methods falling under these categories are illustrated in Fig. 3. It is observed from Fig. 3 that only nature inspired metaheuristic optimization approaches are illustrated for simplicity.

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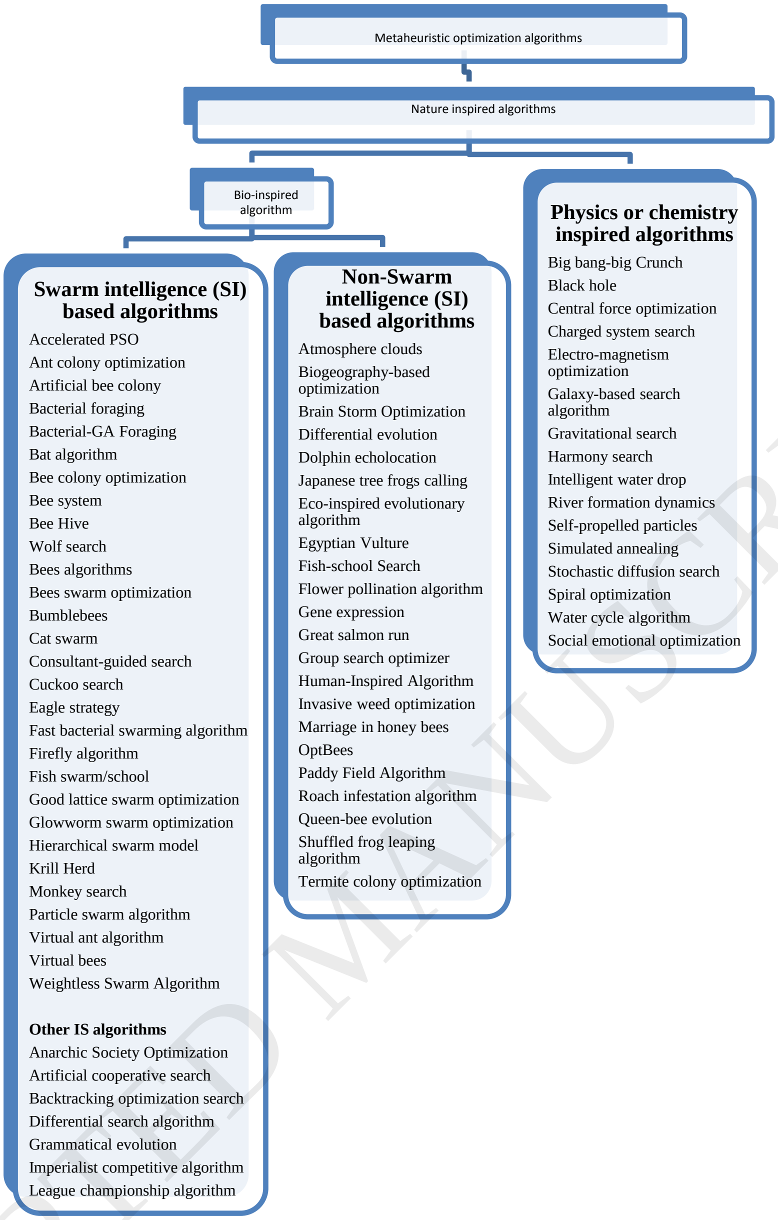

Fig. 2. Metaheuristic optimization algorithms: Modified from [28]

Although metaheuristic optimization algorithms are classified as indicated in Fig. 2, there are other ways in which the summarized methods can be grouped. For instance, an iterative search algorithm that uses a stochastic procedure to generate the next iterate is referred to as a stochastic search algorithm [29]. Instance-based algorithms maintain a single solution or population of candidate solutions. Evolutionary algorithms (EAs), simulated annealing and Tabu search (TS) are the common members of this category.

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Dr. Eberhart and Dr. Kennedy, inspired by social behavior of bird flocking or fish

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schooling. PSO shares many similarities with evolutionary computation techniques such as Genetic Algorithms (GA) [30]. A research work presented the analysis of AI methods for optimization of renewable energy systems indicates that GA, PSO and SA are the most commonly used algorithms whereas ant colony and algorithm of the Artificial Immune System (AIS) are the most promising methods for sizing hybrid DEG systems in the future [31].

Hybrid Intelligent Algorithms are also being applied in the optimization of hybrid energy systems including hybrid GA/TS, GA/SA, GA/PSO, PSO/Gravitational Search Algorithm, etc. [29]. Sedghi et al. compared the performance of different algorithms used in the network distribution network planning, which is not far from hybrid DEG system optimization, giving their advantages and disadvantages [32]. Elsewhere, while reviewing the optimal allocation DEG systems, the researchers listed the pros and cons of classical approaches, intelligent methods and the hybrid systems [33].

With the above discussion in mind, it is a little bit clear what are algorithms are currently being used in modeling and analysis of engineering designs, mainly energy systems. In the following two sections, the optimization techniques used in hybrid DEG systems are classified into two major categories; those applied on hybrid off-grid and those on grid connected DEG systems.

3. Optimization techniques for off-grid hybrid DEG systems

The optimization techniques for off-grid DEG systems are grouped into single AI based techniques, analytical and hybrid optimization approaches.

3.1 Single AI based techniques for off-grid hybrid DEG systems

The PSO algorithm is employed to simultaneously minimize the load probability loss, total cost and CO_2 emission of the PV/Diesel/Battery hybrid DEG system [34]. The analysis revealed the role of battery banks and PV systems to reduce the cost of energy by cutting the amount of diesel used in addition to minimizing the overall hybrid system cost under non-existence or unmet load condition. After initialization of the first population, the target of simulation is specified to determine the annual fuel consumption of DEG component, annual unmet load and the CO_2 emission.

Askarzadeh [1] developed a discrete harmony search (HS) algorithm for optimization of the size of wind/PV hybrid energy system. The algorithm is simple in terms of implementation and can efficiently handle the discrete problem quickly to find the optimal solution. Implementation of

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the proposed discrete HS algorithm for finding the optimum size of a hybrid wind/PV system is done by the following steps.

Step 1: N_h feasible solutions are generated where each one is named harmony. Each harmony consists of two integer values. The first one denotes number of wind turbines and the second specifies number of solar panels. The harmonies are memorized in the harmony memory (HM).

Step 2: For each harmony, the value of the total annual cost is calculated.

Step 3: The algorithm's adjustable parameters are set.

Step 4: A new harmony is produced by the following pseudocode:

Step 5: If the improvised harmony is a feasible solution with better quality than the worst harmony memorized in the HM, it is included in the HM and the existing worst harmony is excluded from the HM.

Step 6: Steps 3–5 are repeated until the stopping criterion is reached.

Step 7: The values corresponding to the HM best harmony are returned as the optimum number of wind turbines and solar panels.

Likewise, Askarzadeh & dos Santos Coelho [35] presented an optimization model to determine the best size of a stand-alone hybrid renewable energy system for electrification of a remote area using PSO. Three decision variables are chosen and used to build the model, incorporating the total area occupied by the set of PV panels, total swept area by the rotating turbines' blades and the number of batteries as the system components. In addition to the original PSO, its variants are also applied including; PSO with adaptive inertia weight to prevent the problem of premature convergence; PSO with constriction factor to make PSO more stable and converge faster; and PSO with repulsion factor, to encourage a particle to modify its search direction as well as moving towards a region ignored by the population. To vary the inertia weight from a large value to a small one, in case of PSO with adaptive inertia weight, the inertia weight is defined as;

$$\omega_{iter} = \omega_{max} - \frac{\omega_{max}-\omega_{min}}{iter_{max}} * iter \tag{1}$$

where ω_{min} and ω_{max} are the final and the initial inertia weights, respectively.

For the PSO with constriction factor, the velocity equation is defined as;

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$$vel_j(iter+1) = K * \begin{bmatrix} vel_j(iter) + c_1 * r_1 \left(pbest_j(iter) - x_j(iter)\right) \\ +c_2 * r_2(gbest(iter) - x_j(iter)) \end{bmatrix} \quad (2)$$

where

$$K = \frac{2}{2-\emptyset-\sqrt{\emptyset^2-4\emptyset}}, \qquad \emptyset = c_1 + c_2 \quad (3)$$

With PSO with repulsion factor, the position of each particle is updated as follows:

$$x_j(iter+1) = Sign_j(iter) * vel_j(iter+1) + x_j(iter) \quad (4)$$

where the sign is expressed as;

$$Sign = \begin{cases} -1 \; if \; r \le P_f \\ +1 \; if \; r \ge P_f \end{cases} \quad (5)$$

A stand-alone hybrid PV/Wind/Diesel system with different battery technologies is optimized using GA technique [36]. The component sizes and the model settings are varied while the system is re-examined to minimize the overall costs. The results indicated that the use of batteries in conjunction with renewables is economic and ecological.

An interactive operation management approach for a micro-grid with multiple distributed generations is developed by applying a uniform water cycle algorithm (WCA) [37]. The WCA is a single objective optimization algorithm inspired from hydrologic cycle. The objective is to minimize both operation cost and emission of the system. A complementary condition called extremes' distance is also introduced to compensate for the deficiency in comparing the multi-objective optimization algorithms by two commonly used criteria i.e. generational distance and spacing.

To address the problem associated with stochastic nature of renewable resources backed by excessive renewable energy penetration, a systematic PSO based approach was developed to determinate the optimal configuration of DEG resources for a selected autonomous hybrid power system (AHPS) [38]. The model is tested for different DEG resource configurations to decide the optimal component sizes based on levelized cost of the electricity (LCOE) as the decision variable. Similarly, an optimum design of a microgrid connected hybrid PV/Concentrated Solar Power (CSP)/LPG is carried out using PSO to achieve lower computational cost [39].

In the meantime, a PSO-simulation based approach for optimization of hybrid renewable energy system is presented where the ε-constraint method is applied to minimize the total cost of the system, fuel emissions and the unmet load [40]. The method is tested on the hybrid DEG system

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that is consisting of PV panels, wind turbine, diesel generator, fuel cell, batteries, hydrogen tank and electrolyzer whose simulation procedure. The sensitivity analysis reveals that the total cost of the system is more sensitive to the allowable level of CO_2 emission compared to other parameters. However, if the interest rate and life time of the batteries are reduced, the total cost increases. Similarly, a network-independent pattern is employed to optimize a hybrid PV/wind/Battery system with high reliability in terms of reduced production total costs over the life of the system using multifarious PSO method [41]. Variants of PSO algorithm i.e. a modified PSO (MPSO), PSO based on repulsion factor (PSO-RF), PSO with constriction factor (PSO-CF), and PSO with adaptive inertia weight (PSO-W) are applied to optimize the size of a hybrid PV/wind/Battery system and their performance analyzed. The analysis shows that PSO-CF outperforms other algorithms including simulated annealing (SA), TS and HS in terms of mean, standard deviation, worst and best total annual cost. In the same line, PSO technique is applied to HRES to minimize only the LCOE Cost [42].

Another work comprised of the optimal design and management strategy of a trigeneration system consisting a diesel combined heat and power (CHP) engine, a PV plant, a boiler and a reversible heat pump is presented [30]. The study combined both system component sizing and optimization of the operation strategies of the hybrid system using PSO algorithm. The target of the study is to minimize the overall costs subject to the fulfillment of end user's energy needs in terms of heat, cooling, electricity and drinking water.

Likewise, Pirkandi et al. [43] assessed a multi-objective optimization technique for a CHP system integrated with low-energy buildings. The objective is to maximize the net power output and exergetic efficiency. It is concluded that a slight increase in the exergetic efficiency leads to a significant increase in the total cost rate.

In another development, the biogeography-based optimization (BBO) algorithm are applied on a small autonomous hybrid system (SAHS) including solar radiation and wind speed forecasting [44]. The results demonstrate the usefulness of incorporating wind speed and solar radiation forecasting in a SAHS optimization problem.

Table 1 shows a summary of the described single AI based techniques. It is observed that PSO technique and its variants is currently the most applied method on off-grid hybrid DEG systems. Variants of PSO are applied for different purposes as well as to achieve various objectives on different hybrid DEG system configurations.

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Table 1. Artificial intelligence optimization approaches based on single technique applied to off-grid DEG systems

Metaheuristic approaches	Objective /Purpose	Hybrid energy system
Discrete harmony search (DHS) [1]	Optimize size of wind–PV hybrid energy system	Wind/PV
1. PSO algorithm [34] 2. PSO with adaptive inertia weight, constriction factor, repulsion factor and with velocity control [35] 3. PSO based model 4. Systematic approach based on PSO algorithm [38] 5. PSO based algorithm [39] 6. PSO with ε-constraint method [40] 7. Multifarious PSO method	1. Minimize the loss of load probability (LLP), total system cost, CO_2 emission 2. Size of a stand-alone hybrid 3. Minimization of the overall costs 4. Minimize component sizes, Minimize LCOE for different hybrid DEG configurations 5. Minimize propane consumption, minimize propane consumption as secondary objective 6. Minimize the total cost of the system, fuel emission and the unmet load 7. Optimize size of the system	1. PV-Diesel-Battery 2. PV/Wind/battery 3. Trigeneration system consisting a diesel CHP engine, a PV plant, a boiler and a reversible heat pump 4. Diesel generator /PV/wind/battery 5. PV/Concentrated Solar Power (CSP)/LPG microgrid 6. Diesel generator /PV/wind/fuel cell/batteries/hydrogen tank/electrolyzer 7. PV/wind/battery
1. GA algorithm [36] 2. GA algorithm [43]	1. Minimize the overall costs 2. Maximize the net power output and exergetic efficiency	1. PV/Wind/Diesel 2. CHP system integrated with low-energy buildings
Uniform water cycle algorithm [37]	Minimize both operation cost and pollutant emissions (sum of SO_2, CO_2 and NO_X)	Micro-grid (Micro water turbine/fuel cell/PV/Wind/battery)
Biogeography-based optimization (BBO) algorithm [44]	Wind speed and solar radiation forecasting	Solar/wind

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3.2 Hybrid techniques for off-grid hybrid DEG systems

A model is used to optimize the operation of a battery/PV/fuel cell/grid hybrid energy system using fuzzy satisfying approach as well as the weighted sum technique [45]. In this approach, the model is operated in such a way that the system is optimized while making sure that the energy system load is responsibly managed within acceptable limits. The main objective of the model is to minimize the total cost of the hybrid system and the CO_2 emissions. The amount of emitted CO_2 due to gas consumption is a product of the carbon intensity of the city gas and the gas from the fuel cell as well as the backup burner for one year, given as:

$$CO^{gas} = \sum_m \sum_h \left(\frac{E^{fc}_{m,h,load} + E^{fc}_{m,h,charge}}{Eff^{fc}_e} + \frac{H^{ab}_{m,h}}{Eff^{bb}} \right) * D.CI^{gas} \quad (6)$$

where $E^{fc}_{m,h,load}$ is the power generated by the fuel cell to supply the load; $E^{fc}_{m,h,charge}$ is the electrical power from the fuel cell to charge the battery; $H^{ab}_{m,h}$ is the generated heat by the backup burner; Eff^{bb} is the efficiency of the backup burner; Eff^{fc}_e is the electrical efficiency of the fuel cell; h is the index of the hour; D represents the days considered in each month. Other equations can be accessed here [45].

Another hybrid Flower Pollination Algorithm (FPA) and Simulated Annealing (FPA/SA) algorithm with computational fluid dynamics (CFD) simulation was used to optimize the stand-alone PV/Wind/Battery system [46]. A hybrid FPA/SA algorithm is employed to minimize system's costs and maximize system's reliability. On the other hand, the influence of PV panels' tilt angle on the wind speed is studied by using CFD simulation. The Payback time and Loss of Power Supply Probability are taken as the objective functions whereas the tilt angle of the PV panel, number of batteries and number of PV panels are designated as the decision variables.

A comparative study has also covered the sizing of a hydrogen-based stand-alone PV/wind system using AI techniques [47]. The work is aiming at assessing the performance of different AI techniques for optimum sizing of the hybrid PV/wind/battery system to satisfy the load demand with the minimal total annual cost. The hybrid PV/wind/battery system is compared with a PV/wind/FC system. Four well known heuristic algorithms including, TS, PSO, HS and simulated annealing (SA) are applied to the system. The analysis shows that PSO is the most robust as well as more promising than other techniques.

A hybrid optimization method with fuzzy programming is employed to study an energy management system (EMS) strategy for CHP systems [48]. The optimal range for boiler and CHP

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capacities are derived using a hybrid optimization method involving PSO and the linear programming algorithms. The viability of the proposed method is demonstrated by analyzing the decision to construct a CHP system for a typical hospital. The system architecture for the CHP system.

Nevertheless, the optimum design of a stand-alone hybrid desalination scheme is determined and investigated [49]. The work involved weather forecasting to realize the optimization of a hybrid solar/wind system using a novel optimizer approach. The optimized parameters include minimizing the life cycle cost and not exceeding the maximum allowable loss of power supply probability by employing HS and a combination of HS with chaotic search algorithm. HS algorithm is used because it is easy to implement and can escape from local optima. A set of the studied hybrid systems.

A summary of hybrid AI optimization approaches is given in Table 2. It can be observed that different AI techniques have been hybridized to optimize different parameters of the hybrid DEG systems, where it is evident that HS algorithm is one the popular method in this category.

Table 2. Hybrid AI optimization approaches applied to off-grid hybrid DEG systems

Hybrid approaches	Objective /Purpose	hybrid energy system
Fuzzy satisfying approach and weighted sum method [45]	Minimize total cost, CO_2 emissions	Battery/PV/fuel cell/grid
Flower Pollination Algorithm (FPA) and Simulated Annealing (SA) [46]	Minimize system's costs, maximize system's reliability	PV/Wind/Battery
TS, PSO, harmony search (HS) and simulated annealing (SA) [47]	System sizing, minimize total annual cost.	PV/wind/battery
PSO and the linear programming algorithms [48]	Optimize the boiler and CHP capacities	Boiler and combined heat and power (CHP) systems
Hybrid of a self-adapted evolutionary strategy and	Minimize the annual operational and investment costs of the system	Wind/energy storage

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the Fischer–Burmeister algorithm [50]		
Hybrid Harmony search-based chaotic search (HSBCS) [49]	Minimizing the life cycle cost	Solar/wind/battery with reverse osmosis

3.3. Analytical approaches for off-grid hybrid DEG systems

A decision-support tool in the form of a linear program is established to determine the optimal investment and operating decisions for residential energy systems consisting of a heat pump, fuel cell, PV panels, a boiler, solar thermal collectors, including battery and hot water tank as storage [51]. Under specific conditions, cost reductions between 5% and 60% are achieved, whereas emissions can be reduced by 45–90%. The analysis focuses on meteorological data because radiation and temperature data can both be obtained from satellite measurements and are readily available, whereas it is more complicated to find multi-year measurements of residential electricity and hot water consumption.

During the stochastic program, the number of decision variables in the second stage is proportional to the number of weather scenarios expressed as;

$$minimize\ c_x^T x + c_y^T y + \frac{1}{N}\sum_{n=1}^{N} \Delta t \sum_t c_{op} x^+ t, n \tag{7}$$

where N is the number of years considered in the stochastic program.

The optimal sizing of a hybrid DEG system with wind/energy storage is performed using combined algorithms composed of a self-adapted evolutionary strategy and the Fischer–Burmeister algorithm [50]. The objective is to minimize the annual operational and investment costs of the system.

Bortolini et al. [52] presented an economic and environmental bi-objective design of an off-grid PV/diesel generator/battery hybrid energy system. The purpose is to identify the rated power of PV, the capacity of the battery and the technical configuration which can reduce the LCOE and the carbon footprint of energy (CFOE). It is observed that the most effective trade-off between environmental and economic performance results to the decrease in CFOE of about 48% and a slight reduction in the economic performance (-2%).

An analysis of the operation mode of energy storage (ES) is presented in which it is aimed to ensure the operation stability and efficiency of DEG system [53]. The performance analysis is

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carried out by employing a mixed integer linear programming (MILP) model programmed through the General Algebraic Modelling System (GAMS). The daily mode (DM) and weekly mode (WM) of ES are compared in terms of their operation and costs. It is recommended to operate the ES in a DM mode due to the high capital cost of ES. The objective function for cost minimization is given as;

$$Minimize\ F = \underbrace{ESE * ESEC * M}_{Energy\ stirage\ Energy\ related\ Cost} + \underbrace{ESP * ESPC * M}_{Energy\ stirage\ Power\ related\ Cost} + \underbrace{ESP * ESF}_{Energy\ stirage\ Operation\ cost} + \underbrace{I * IC * M}_{Inverter\ Capital\ Cost} + \underbrace{\sum_{c,d,t} G^{B}_{cdt} * V}_{Biomass\ Operation\ cost} \quad (8)$$

where ESE is the ES energy related capacity; ESEC is the ES energy related capital cost; ESP is the ES power related capacity; ESPC is the ES power related capital cost; ESF is the ES fixed operating and maintenance cost; I is the inverter capacity; IC is the inverter capital cost; G^{B}_{cdt} is the total amount of biomass power generation; V is the variable O&M of the biomass power generator; and M is the yearly amortized factor with monthly payment over a period of 30 years at an interest rate of 7%.

Energy management strategy (EMS) for a stand-alone battery/PV/diesel system is assessed based on grid frequency modulation. The EMS is configured in such a way that when power reduction is required, the battery inverter increases the grid frequency. Correspondingly, the PV is automated to detect the action of the battery to continuously reduce the PV inverter power in order to prevent the battery from over-current or overcharge [54]. The efficiency of the hybrid system is optimized as well as the operating life of the diesel generator. The hybrid DEG system.

A statistical approach for hybrid energy storage system sizing is presented based on capacity distributions in an autonomous PV/Wind power generation system [55]. This hybridization, of both slow and fast dynamics, aims to eliminate the power peaks caused by the load consumption. The obtained results prove that the integration of supercapacitors takes advantage of the complementary characteristics of the batteries, improves the exchanged power flow, extends the battery life cycle and affects storage system sizing by accommodating the fast power fluctuations.

A Distributed Energy Resources Customer Adoption Model (DER-CAM) is used to determine the optimal size and type of DEG resources and their operating schedules for a hybrid renewable energy system for microgrid application [56]. The assessment of DER-CAM model provides information on the optimal type, size and operational schedules for DEG application based on the total annual CO_2 emissions and total annual energy costs.

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Another unique method is called ontology which is applied to optimize a multi-source renewable DEG system [57]. The study combines size optimization techniques and ontology domain, where it is noted that the introduction of ontology in renewable energy systems allows the shared knowledge representation of a common area of a unit, including the conceptualization of knowledge that can be updated without changing the system goals. On the other hand, mathematical programming techniques are used for optimization of the structure of a DEG System [58].

To analyze the dynamic and probabilistic behavior of the hybrid energy systems, another study proposed a model that combines the autoregressive moving average (ARMA) and Fourier series to characterize the historical weather measurements and to generate synthetic weather data e.g. for wind speed [59]. The generated synthetic wind speed data is utilized to perform probabilistic analysis of a hybrid energy system configuration, which consists of nuclear power plant, wind farm, battery storage, natural gas boiler, and a chemical plant. The study mainly aims at analyzing economic and environmental impact on a hybrid DEG system as well as the impact of deploying different sizes of batteries for smoothing renewable variability.

An approach for connecting renewable energy sources to a utility mini-grid is developed considering the practical and economical aspects for hybridization of small off-grid system consisting of solar PV, micro-hydro and wind sources [60]. The two hybridization techniques use the battery charger and a grid tie inverter (GTI). The PV and wind generators are hybridized using a hybrid charge controller (HCC) whereas the power output from the HCC is fed into the battery bank to charge the batteries. A GTI sometimes referred to as 'grid-interactive inverter' or 'synchronous inverter' is a power inverter that converts direct DC to AC voltage and feeds it into the grid by synchronizing its frequency to 50 or 60 Hz. The results verified that the systems can be hybridized by using a GTI, HCC with a suitable electronic load controller.

Table 3 summarizes the analytical approaches applied to off-grid hybrid DEG systems. It can be observed that the analytical approaches not only consist of linear and nonlinear mathematical programming techniques, but also statistical and other computer based deterministic methods.

Table 3. Analytical optimization approaches applied to off-grid hybrid DEG systems

Classical/Analytical approaches	Objective /Purpose	Hybrid energy system

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Stochastically model and sequential Monte Carlo simulation [50]	Optimal sizing	Wind/energy storage
Bi-objective design model [52]	Minimize levelized cost of the electricity (LCOE) and the carbon footprint of energy (CFOE)	PV/battery/diesel generator
1. Linear programming (MILP) model programmed through the General Algebraic Modelling System (GAMS) [53] 2. Linear programing [51]	1. Determine operation mode of the storage system for hybrid DEG system 2. Minimize cost and emissions	1. DEG system with battery storage 2. Heat pump, fuel cell, PV, a boiler, solar thermal collectors, with battery and hot water tank storage
Energy management strategy (EMS) based on grid frequency modulation [54]	Maximize system efficiency, maximize operating life of the diesel generator	Stand-alone battery/PV/diesel system
Statistical approach based on capacity distributions [55]	Storage system sizing	PV/wind/battery/supercapacitor
Distributed Energy Resources Customer Adoption Model (DER-CAM) [56]	Optimize size and type of DEG resource, operating schedules Reduce the annual costs, the CO2 emissions	Microgrid/PV/ diesel generator/battery
Ontology method [57]	Optimize size of DEG resource	Multi-source renewable DEG system
Hybrid of autoregressive moving average (ARMA) and Fourier series [59]	Analyzing economic and environmental impact on hybrid DEG system	Hybrid energy systems including Wind

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Grid tie inverter (GTI) and hybrid charge controller based approach [60]	Optimize system reliability	PV/Wind/micro hydro

4. DEG connected to the grid

There are several works related to planning, optimal location, sizing, emissions reduction and configuration of hybrid DEG systems connected to the distribution networks or to the national grid systems. However, in this section only grid connected hybrid DEG systems with the aim of achieving optimal location, size, and emissions reduction are discussed, mainly highlighting the objective functions and performance of the systems and the optimization methods applied. The power flow and load flow methodologies are not discussed in this work, but some issues occur in power systems like systems voltage profile and losses are reported as part of the auxiliary benefits of hybrid DEG systems' optimization.

4.1 Single AI based optimization methods for grid-connected hybrid DEG systems

A grid-connected hybrid PV/wind energy system size optimization through the use of cuckoo search (CS) algorithm is examined [61].The CS method has faster convergence, less computation time and better accuracy compared to the PSO method. A Multi-objective Shuffled Bat algorithm is used to determine the optimal location and sizing of several DEG resources with different load models [62]. The algorithm is analyzed by considering the system loss diminution, DEG cost minimization and voltage profile improvement as objective functions.

Another study is about the use of a Pareto optimal approach for allocation of distributed generators in radial distribution systems by applying improved differential search algorithm [63]. The objective is to determine the locations and optimal sizes for DEGs in a radial distribution system to reduce the operating cost, losses and improve the voltage profile.

In another study, PSO with constriction factor approach is applied to determine the optimum size and location of multiple DEG units in a distribution power system network [64]. It is observed that the penetration of multiple number of DEG units in distribution system results in a significant improvement in numerous distribution system parameters such as active and reactive power loss, total cost of energy, purchased cost of energy and voltage deviation in the distribution system.

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A multi-objective optimal reconfiguration and DEG power allocation technique for distribution networks is studied using Big Bang-Big Crunch (BB–BC) algorithm considering load uncertainty [65]. The BB–BC algorithm was proposed by Erol & Eksin [66] based on the theory of evolution of the universe i.e. the BB–BC Theory. The objective is to minimize the operation cost, power losses, and emissions in addition to maximizing the voltage stability index. Based on the analysis, it is proved that the used method renders into more diversified Pareto solutions, indicating that a better exploration capability is realized even with higher fitness. Furthermore, GA technique is applied to optimize the DEG system within the distribution power system so that the real and reactive power losses can be minimized, in addition to reducing the short circuit current and improvement of the voltage profile [67].

A summary of single AI based optimization approaches applied to grid-connected hybrid DEG systems is given in Table 4.

Table 4. Single AI based optimization approaches applied to grid-connected hybrid DEG systems

Single AI based approaches	Objective /Purpose	Hybrid energy system
Cuckoo search (CS) algorithm [61]	Optimal sizing	PV/wind
Shuffled Bat algorithm [62]	Optimal location, sizing, cost minimization, voltage profile improvement	PV, wind, Fuel cells, And micro hydro turbines
Improved differential search algorithm [63]	Locations and optimal sizes, minimize operating cost, minimize losses, voltage profile improvement	DEGs in radial distribution systems (not specified)
PSO with constriction factor approach [64]	Optimum size and location	Multiple wind turbines
Big Bang-Big Crunch algorithm [65]	Minimize operation cost, power losses, and emissions, maximizing the voltage stability index	PV/wind/FC
GA technique [67]	Minimization of real and reactive power losses	PV, micro turbines, FC, bio-gas, wind, diesel generator

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4.2. Analytical optimization approaches for grid-connected hybrid DEG systems

In [68], an optimization framework based on centralized decision-making scheme is developed for analyzing the operation of a small-scale natural gas grid fueled by hybrid DEG units, in which their capability to minimize the peak demand of the area being served is assessed. The study indicates that there is a substantial increase in natural gas consumption near consumers for all scenarios considered, resulting into the control challenges for the natural gas grid. It is however suggested that it is important to have a centralized decision-making scheme when multiple distributed generation resources are present as well as optimally sizing the DEG units.

Furthermore, demand response and operational optimization of hybrid renewable energy systems are analyzed [69]. A receding horizon optimization (RHO) strategy is applied, in which a certain cost function is minimized over a moving time-horizon to determine the optimal power references for the various energy generation subsystems. RHO is used as the first layer of Model Predictive Control (MPC), which is a mature technology widely used in process systems engineering. During operational optimization, at each time step in RHO, the cost function is minimized, subject to certain constraints, over a time horizon of a finite length. The horizon length is discretized into a number of time intervals [70]. System sizing with consideration of energy flows is done to obtain the optimal combination of PV panels and wind turbines. From the perspective of the generation-side and demand-side, the energy management strategies are designed to form the objectives of meeting the electricity demand in addition to minimizing the overall environmental and operating costs. The design optimization is made based on the dynamic simulation by incorporating the power demand, the generation, energy loss and storage.

In an effort to analyze the stability and losses of the power system when the DEG systems are installed, a study is carried out on locating and sizing the DEG units by employing a separately-optimized algorithm and dynamic programming search technique, considering voltage stability and power losses while observing the voltage-related constraints [71]. Many DEG units are installed to keep the system voltage profile within permissible security limits. The optimal sizes of DEG units are determined by employing the dynamic programming search method. It is revealed that when the reactive limits of DEG unit is considered, different voltage stability bifurcations appear, and this affects the optimal location, size, and number of DGs.

Theo et al. [72] presented a mixed-integer linear programming (MILP) model for cost-optimal planning of a grid-connected hybrid system for an eco-industrial park . The model aims to

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minimize the net present value (NPV) of the overall electricity generation cost and determination of the optimal energy storage technology. The optimal energy storage is identified as the lead-acid battery technology due to its low investment requirement. Stochastic optimization of hybrid renewable energy systems is analyzed by applying sampling average method, incorporate the uncertainties associated with renewable energy resources and the system load in sizing the hybrid DEG system [73]. The objective is to increase renewable energy ratio as large as possible, minimize the total NPC and fuel emission while satisfying a desirable level of loss of load probability. The generated Pareto front (PF) by the stochastic approach is compared to a deterministic PF using the popular performance metrics, where it is indicated that a higher NPC is observed in the stochastic case. Worth still, the outcome of the employed performance metric demonstrates that the quality of the generated PF in the deterministic case is better than the stochastic one. The energy flow of the hybrid renewable energy system.

The discounted cash flow analysis and real options analysis are used to evaluate a hybrid natural gas and renewable electricity (NG-RE) systems in distributed applications [74]. The results consistently suggest that a hybrid NG-RE DEG system is a more favorable investment in the applications studied in relation to the single- technology alternatives when incentives for renewables are available.

Similarly, analytical expressions are designed to capture the optimal power factor of each DEG unit for reducing energy losses and enhancing voltage stability [75]. The expressions are based on the derivation of a multi-objective index, which is formulated as a combination of active and reactive power loss indices. The optimal size, location and number of DEG units are decided based on the benefit–cost analysis.

To determine the optimal energy technology allocation for DEG systems, a two-stage multi-objective strategic technology-policy framework which puts into consideration the technical, environmental economic objectives is designed [76]. The first stage is based on a production frontier estimation model and is used by each end user to evaluate the performance of each energy technology based on the three objectives. The bottleneck multi-criteria decision model in the second stage uses outputs for the first stage as the inputs, i.e. factor efficiencies, dispatchability, capacity limitations and renewable penetration for each technology as well as demand for each end use, to provide the Pareto-optimal energy resource allocation for each end-use. This framework is proved to avoid the need to subjectively specify weights associated with the individual objectives. The model can be used by the stakeholders i.e. DEG developers, users, and

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policy makers, to determine the optimal energy technology allocation and to develop regulatory policy based on the model outputs.

The summary of analytical optimization approaches for grid-connected hybrid DEG systems is presented in Table 5.

Table 5. Summary of analytical optimization approaches applied to grid-connected hybrid DEG systems

Analytical approaches	Objective /Purpose	Hybrid energy system
Optimization framework based on centralized decision-making scheme [68]	Optimal sizing	Small-scale natural gas fueled DEG units
A receding horizon optimization (RHO) strategy [69]	System sizing, minimizing the overall environmental and operating costs	PV/wind
Separately-optimized algorithm and dynamic programming search technique [71]	Locating and sizing	Two DEGs including PV
Mixed-integer linear programming (MILP) [72]	Minimum net present value (NPV), optimize energy storage technology	PV/Wind/Battery
Stochastic sampling average method [73]	Maximize renewable energy ratio, minimize the total NPC and fuel emission	PV/Wind/solar collector/Biomass/Natural gas/
Discounted cash flow analysis and real options analysis [74]	Optimize systems costs, optimize incentives	Natural gas micro turbines and PV
Analytical expressions based on derivation of a multi-objective index (IMO) [75]	Optimal location, sizing, optimal power factor	Gas turbine engine-based DEG units

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A two-stage multi-objective strategic technology-policy framework [76]	Optimal energy technology allocation, optimal DEG allocation	PV/Wind/FC/Biodiesel/ Gas microturbine CHP/ Solar thermal collector, Geothermal etc.

4.3. Hybrid techniques for grid-connected hybrid DEG systems

A hybrid technique comprising of ant colony optimization (ACO) and artificial bee colony (ABC) algorithm is presented for probabilistic sizing and optimal placement of DEG resources [77]. The objectives include minimizing power losses, total electrical energy cost, total emissions produced by the substation and resources, besides improving the voltage stability. The analysis demonstrates the potential and effectiveness of the multi-objective algorithm in comparison with other evolutionary optimization methods.

In addition, ACO method for continuous domains based on integer programming is also applied for sizing a hybrid PV/wind DEG system with the total design cost (capital and maintenance cost) as the objective function for minimization [78]. The results are compared with other AI methods including ABC and GA and a conventional optimization B&B method in which ACO demonstrates exceptional performance.

A multi-objective framework is also proposed for optimizing the network reconfiguration and DEG power allocation through the application of a hybrid BB–BC algorithm with the incorporation of fuzzy based mutation operator to improve the exploration capability [79]. The objective functions include the DEG cost, power losses, greenhouse gas emissions and voltage stability which are optimized subject to system technical and operational constraints.

A method which employs a Modified Teaching–Learning Based Optimization (MTLBO) algorithm is presented to determine the optimal location and sizing of DEG units in distribution systems [80]. The optimal sizing and locating of DEG is modeled as a mixed integer nonlinear programming problem because of the independence of this method from the type of the objective function and constraints. The comparison between the MTLBO algorithm and a brute force method indicates that the studied algorithm’s performance is better and more effective than brute force and many other methods.

When the DEG units are connected to the grid, the reliability aspect in the operation of the whole grid network needs to be considered. Therefore, a multistage framework for reliability-based distribution expansion planning considering DEG system is assessed using a hybrid Self-

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adaptive Global-based HS Algorithm (SGHSA) as well as a fuzzy satisfying method to obtain the final optimal solution. [81]. The objective functions of the optimization problem include the investment cost, operation cost, maintenance cost and expected customer interruption cost.

A summary of the hybrid optimization approaches applied to grid-connected hybrid DEG systems is indicated in Table 6.

Table 6. Hybrid optimization approaches applied to grid-connected hybrid DEG systems

Hybrid approaches	Objective /Purpose	Hybrid energy system
Ant colony optimization (ACO) and artificial bee colony (ABC) algorithm [77]	Sizing and location, minimizing power losses, total electrical energy cost, total emissions	Gas turbine, fuel cell and wind
ACO method for continuous domains based integer programming [78]	Minimize total design cost,	PV/wind
Hybrid BB–BC algorithm with the incorporation of fuzzy based mutation operator [79]	Systems sizing, optimal location, System costs, power losses, GHG emissions, voltage stability	PV/Wind/Fuel cell
Modified Teaching–Learning Based Optimization (MTLBO) algorithm based on mixed integer nonlinear programming [80]	Optimal placement and sizing	PV, wind, micro turbines, fuel cells, diesel generator, mini hydro turbines
Hybrid Self- adaptive Global-based Harmony Search Algorithm (SGHSA) as well as fuzzy satisfying method [81],	Minimize investment cost, operation costs, maintenance cost and expected customer interruption cost.	Multiple DEG units (not specified)

5. Other reviews about DEG systems

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A review of optimum DEG placement for voltage stability enhancement of distribution system was conducted [82]. In this work, the authors discussed the optimum location of DEG units considering minimization of power losses, voltage stability improvement, and voltage profile enhancement. Mahmud and Zahedi [83] carried out a review on control strategies for voltage regulation of the smart distribution network with high penetration of renewable DEG systems. The research mainly addressed the direct effects of increased integration of renewable DEG systems on the distribution network operation and the evaluation of research status on voltage control strategies. A review on DEG planning based on power system performances is also carried out taxonomically [84]. Chehouri et al. [85] reviewed the performance optimization techniques applied to wind turbines. The authors observe that for 30 years, the objective function evolved from the maximized metric of the power coefficient to the maximization of the annual energy production. It is noticed that such information is of much relevancy to the optimization of DEG systems. Different approaches for optimal planning of renewable generation are reviewed including among others, analytical methods, 2/3 rule, nonlinear programming, optimal power flow and mixed integer programming [86]. The methodologies for sizing, control and configurations of hybrid energy systems are discussed purposely to set the required suitable design constraints for implementation of the same systems for off-grid and grid-connected topologies according the system requirements and standards [87]. A comparative review is performed on mathematical and numerical modeling methods for planning and optimization of DEG systems [26]. The review provides research gaps, guidelines and recommendations for developing an excellent DEG system planning and optimization tool. Meanwhile, a related study not only highlighted the planning and configurations, but also combined both modeling and optimization techniques for hybrid renewable energy systems for off-grid applications [88]. Similarly, a review of objectives, techniques and technology for proper planning of grid integrated DEG systems is done [89]. This work reveals that researchers have concentrated more on conventional DEGs than renewable DEG systems. Another research combined both siting or placement and sizing techniques for DEG systems in distribution systems, in which the meta-heuristic and analytical (classical) techniques are compared [90].

On a different frontline, another review paper concentrates on optimization algorithms for integration of wind energy to the grid, elaborating the pros and cons of optimization techniques in light of their application to the wind farm [91]. A critical review is made on the solar hydrogen hybrid energy systems for off-grid electricity supply with a survey of demonstration projects

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presented in literature [92]. The need for authoritative system modeling is explained as well, for sizing the system components to achieve the minimum cost at a nominal availability of supply.

Colmenar-Santos et al. [93] tackled the analysis of factors that can facilitate the scenario of DEG units embedded in the new distribution networks. Their article includes aspects such as new information and communications technologies for smart grids, microgeneration and storage technologies, active management networks, regulatory issues and multi-objective planning as an optimization tool for selection of sites and sizing of DEG systems. Soft computing techniques, resources, configurations for power management and control of PV/wind hybrid system are explained by Indragandhi et al. [94]. The successful PV/wind system projects, important challenges facing the general deployment of PV/wind integrated system techniques and the future vision of an integrated power generation are also clarified. Additionally, optimization of microgrids with hybrid energy systems are reviewed emphasizing the framework of various objectives [95], whereas computational optimization for microgrid is analyzed with new planning approaches [96].

6. Some critical analysis of the methods presented

From Table 1 to 6, it can be observed that many DEG units such as PV, wind, diesel generator, fuel, CHP system, micro water turbine, CSP, LPG, hydrogen tank, electrolyzer, etc., have been hybridized into various configurations either interconnected through microgrids or dc/ac bus systems. However, it is clearly noted that so far PV and wind are the most commonly integrated DEG units and in most cases, they are connected together to form a hybrid PV/wind/battery system.

According to the findings in this study, in the last five years, the objective functions have shifted mainly from minimization of systems costs (investment, operation, maintenance costs) and pollutant emissions to maximizing system's reliability, minimizing expected customer interruption cost as well as optimizing operation schedule of DEG resources. Such developments are more likely to improve the operation efficiency, in addition to improve acceptance and implementation of hybrid DEG systems.

Considering the methods depicted in Fig. 3 as a benchmark for comparison of the AI methods discussed in this review, it can be observed that very few metaheuristic techniques have been utilized in the optimization of hybrid DEG systems. The PSO algorithm and its variants is the most widely applied method, followed by GA and HS algorithms, within the period considered in this

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work. On the other hand, for analytical methods, linear and nonlinear programing methods are the most widely used optimization methods on both off-grid and grid connected hybrid DEG systems.

7. Conclusion

This work has presented a review on the optimization approaches for hybrid DEG systems, considering both off-grid and grid-connected systems. The articles from selected journal papers mainly published in the last five years have been reviewed. The optimization approaches used in engineering designs has been briefly discussed to provide the foundation for assessing the optimization approaches of hybrid DEG systems. It has been noted that AI techniques are still dominating the techniques used for optimization of DEG systems, with PSO identified as the most common utilized AI method. The PV and wind resources are reported as the most popular hybridized DEG units, mainly integrated with battery. However, during the optimization of hybrid DEG systems, is has been observed that the objective functions have shifted mainly from minimization of system costs (investment, operation, maintenance costs) and pollutant emissions to maximizing system's reliability, minimizing expected customer interruption cost as well as optimizing operation schedule of DEG resources in the studied period. Such developments are more likely to improve the operational efficiency as well as enhancement of acceptance and implementation of hybrid DEG systems.

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