Optimisation Models for Hybrid Energy Systems – A Review

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***Abstract*— Hybrid energy systems are widely utilised as they combine different sources of energy to augment for the shortcomings of each power source. Information regarding the operating performance of the system components plays an essential role in establishing the control strategy for the system. The optimum control allows for proper exchange of energy among system components, thereby enhancing the system's performance at optimum cost. Optimisation models are required for the efficient design of the mix of energy resources. These models can enable efficient management and the distribution of power for reliably satisfying the energy demand. This study presents state-of-the-art assessment of optimisation models for hybrid power systems. As part of research efforts in solving the present energy related problems of developing countries, this study comprehensively reviews the current status and underlying principles of various optimisation modelling technologies. This paper recommends the use hybridised meta-heuristic algorithms for establishing the optimal solutions of hybrid energy systems. Accurate mix of meta-heuristic algorithms can enable the developmental framework for ascertaining the true optimal solution of hybrid energy system in reasonable time.**

Keywords—Hybrid energy system, hybrid optimisation algorithms, optimisation models, reliability analysis, renewable energy, simulation software

I. Introduction

The growing demand for a sustainable electric power supply is motivating worldwide interests in alternative power technologies. Hybrid energy systems are widely utilised as alternative sources of electrical power generation owing to the advances in green energy and power electronics technologies [1]. The utilisation of hybrid energy sources could permit improved power system efficiency and reliability as well as a reduction in the energy storage requirements compared to systems with a renewable source. The mixture of different energy sources depends on the enabling technology. Wind and solar are the most promising renewable source globally, leading other sources in making the surroundings cleaner and more environmentally friendly, creating new jobs and industries, as well as in the combat against water crises – preserving the fresh water resources [2]. The literatures surveyed showed that wind and solar are mainly utilised power sources in recent years, because they are environmentally friendly and technically viable options. Nevertheless, both (wind and solar) resources are irregular in nature [3],[4]. In addition, they depend on site meteorology. To facilitate the economic and efficient utilisation of different power sources for a mixed energy system in a location, it is necessary to apply a suitable optimisation model.

Optimisation models are useful and effective tools for solving problem in the energy sector. These models could enable: investors to decide on the most suitable energy option; and policy makers to set up policies based on a comprehensive evaluation of competing energy technologies and analyses of different scenario [5]. An optimisation model can be defined as a computational method, which establishes the optimum (satisfactory) value of an objective (fitness) function, by subjecting the function variables to a number of constraints, which reflect the resources availability, operation time, environmental conditions, and so on. Practical applications of optimisation models require efficient and powerful computational algorithms, which when run on computers, should numerically solve the computational problems of both medium and large size optimisation models evolving from different disciplines [6].

The overall aim of this review is the state-of-the-art assessment of optimisation models for hybrid energy systems. It indicates in sufficient details shortcomings in the development and utilisation of theories and concepts of optimisation methods for deployment using the hybrid energy system as a case study. The assessment is necessary for efficient design, planning, and management of renewable power system as this could encourage extensive and optimum utilisation of the renewable energy resources in virtually all sectors of the economy. This study considers the energy sector because the world electricity demand is rapidly increasing due to its fast growing population. If the electric power required to cater to the electricity demand in regions without access to electricity were to come from fossil fuels, it could hinder global efforts to reducing global warming. As a result, sustainable energy technology has become a key requirement of the civilised society in alleviating challenges of increased energy demand.

The following section presents the meteorological and load data required for assessment of hybrid energy system. The criteria for optimisation are discussed in section III while the current status of optimisation models are discussed in sections IV. The conclusion of this study is presented in the fifth section.

II. Data for Assessment of Hybrid Energy Systems

The frequently utilised data for evaluating the performance of a hybrid power system are either time-series or statistical [7]. These data can either be minutely, hourly or daily but the hourly data are usually preferred. The main input data sets for optimisation of hybrid energy system include solar irradiation, wind speed, stream flow, temperature and electric load.

In particular, the behaviour of a hybrid energy system can be determined using the hourly time-series data. Gupta *et al.* [8] employed time-series method to study the viability of hybrid energy system designs. A common drawback of this approach is the significant computational effort that is required. Several research efforts strived to either reduce the simulation time or the number of variables utilised in process simulation, or both. In addition, time-series input data are not available for many regions [9].

When the measured data are not available for a specific site, they can be synthetically generated or derived from a nearby site using statistical models. The trendiest technique utilised for data generation was the empirical approach developed by Hall *et al.* [10], which applied the statistical method proposed in [11]. Several studies [12],[13],[14],[15],[16] assessed the performance and viability of various hybrid energy systems using statistical data. The use of statistical (probabilistic) methods is less computationally expensive compared to the time-series approach.

III. Criteria for Hybrid Energy System's Optimisation

The design of optimum configurations for hybrid green energy systems that could satisfy the electric load demand is accomplished based on the life-cycle cost, quality and reliability of the power system, irrespective of the sizing and optimisation technique utilised. Moreover, studies the mechanical performance of various energy components could significantly impact the optimum cost of such power systems [17].

Although, the structural performance and the anticipated reliability from hybrid power system are essential in the optimisation, the monetary cost of the hybrid power system is the decisive factor, except there is an unrestricted budget [18]. A hybrid renewable energy system can attain an optimum solution when there is a good compromise between these criteria (system reliability and cost). Conversely, when assessing hybrid power systems incorporating conventional energy sources such as a diesel generator or a utility grid reduction in pollutant emissions is another essential factor, typically considered.

A. Reliability Analysis

The reliability analysis is an essential part in the process design of hybrid systems since the irregular nature of energy sources (wind speed and solar radiation, and perhaps, the utility grid for some developing regions) can highly influence the power generation from such systems [19]. There are different techniques utilised to estimate the reliability of the mixed power systems. Among the technical methods used for the evaluation of power system reliability, the Loss of Power Supply Probability (LPSP) is the mostly utilised [7]. The LPSP can be expressed mathematically as follows:

$$LPSP = \sum_{\tau=1}^{N} P_{def}(\tau).\Delta\tau \,/\, (\sum_{\tau=1}^{N} P_d(\tau).\Delta\tau) \quad (1)$$

$P_d(\tau)$ is the load power, $P_{def}(\tau)$ is the deficit in load power, τ is the simulation time interval while N is the operation time.

This method specifies the probability of a deficient supply. The two techniques available for hybrid power system are chronological simulations and probabilistic methods. The former method is computationally expensive while the later method integrates the random nature of the energy sources and the electric load, thereby getting rid of the need for time-series data.

B. Cost Analysis

There are different monetary criteria for evaluating the viability of hybrid energy systems. The net present cost is expressed as the overall present value of a time-series of cash flows by means of the initial, replacement and operation/maintenance costs of components, which occur within the project lifespan [18]. The HOMER computer-based model utilises the overall net present cost to determine the entire cost of a power system. A detailed explanation of the computation is available in the literature [7].

The theory of levelised cost of energy is widely utilised to assess the performance of power system designs. The levelised concept can be mathematically expressed as (2). $COI_{ann,sys}$ is the system annualised cost, $E_{ann,sys}$ (kWh/y) is the system energy output per annum and TPV is present value of actual cost of the system components while CRF is the capital recovery factor, expressed by the (3) and (4) respectively, where pC_j is the present cost of component j in system life, r_i is the yearly interest rate and L_N (y) is the lifespan of the system [14].

$$LCE = COI_{ann,sys} / E_{ann,sys} = TPV \times CRF / E_{ann,sys} \quad (2)$$

$$TPV = \sum_{j=1}^{j} pC_j, \quad (3)$$

$$CRF = r_i(1+r_i)^{L_N} / [r_i(1+r_i)^{L_N} - 1], \quad (4)$$

Nafeh [14] defined the annualised cost of investment of a hybrid system in terms of the Present worth (PW) as (5).

$$COI_{ann,sys} = 1/L_N \left(\sum_{j=1}^{j} (COI_{j,ini} + COI_{j,ini(PW)} + COI_{j,om(PW)} - COI_{j,sal(PW)} \right) \quad (5)$$

where, COI_{ini} is the total initial Cost of Investment, $COI_{rep\,(PW)}$ is the total present worth of replacement cost, $COI_{OM\,(PW)}$ is the total present worth of annual Operation and Maintenance (OM) cost, $COI_{sal\,(PW)}$ is the present worth of all salvage value, and j is the aggregate number of hybrid system's component unit.

Other economic methods, for instance, the cost of energy and life-cycle cost are extensively utilised in various studies. The cost of energy indicates the total cost of electric power generation, which can be expressed as the ratio of the overall annualised cost of investment of the hybrid system to the yearly electric power supplied by the hybrid system [7],[20]. The life-cycle cost considers the sum total of recurring and non-recurring costs over the power system's useful lifespan. Gonzalez *et al*. [21] utilised the life-cycle cost concept, measured in terms of the net present value, to ascertain the optimum cost of a grid-linked hybrid PV–wind–biomass power system. Other factors that could impact the cost analysis of hybrid power systems are discussed in [22].

C. Mechanical/Structural Performance

Structural optimisation can be expressed in terms of the system topology or component structure [23]. Several factors such as tip deflection, shell and airfoil characteristics, stress and natural frequency are usually considered when optimising the performance of wind turbine energy systems. Vital design factors for optimising the airfoil shape of HAWTs include: high-pitched lift-to-drag ratio, elevated lift coefficient, satisfactory operation throughout the stochastic wind flow, and low sensitivity to leading-edge roughness [17], [24], [25]. Different methods have been applied in the literature [26] to optimise the mechanical performance (structural weight, lattice tower support structures and thickness and diameter) wind turbine energy system. Mohammed *et al*. [27] specified the optimum size of hybrid power systems in terms of the optimum selection/positioning of component types/units and the optimum size configuration of the power generation units to efficiently supply the electric load requirements, provided the physical and operational constraints are satisfied.

D. Environmental Impact Analysis

The reduction of pollutant emissions in hybrid power systems that consists of a mixture of power sources (renewable and conventional) imposes additional constraints on the system design architecture. In practice, the design of such hybrid energy system, considers at least two objectives simultaneously, which includes costs and either reliability or pollutant emissions. The task of simultaneously minimising cost and emissions is considered to be in conflict, since reducing the costs of the hybrid renewable power system design would lead to an increase in pollutant emissions and vice versa as reported in [18],[28]. The assertion that the monetary cost of the conventional energy is lesser than that of renewable energy is consensus of these literatures. In other words, a reduction in renewable energy can lead to a corresponding rise in the conventional energy in attaining optimum configuration. However, [29] has shown that the objective of minimising the cost of energy does not conflict with that of emission reduction for emerging cities with unreliable utility grids as it is generally accepted in literatures. The deviation from the general norm was justified due to the relatively expensive grid electricity as compared to renewable sources and the high unreliability index that characterised grid electricity system in Nigeria [30]. It is worthy of mention that the monetary cost of renewable energy has significantly reduced in recent times due to improvement in renewable technologies.

Nevertheless, the task of attaining satisfactory results is complicated in a multi-objective problem where simultaneous minimisation of the objective function parameters conflict each other. The solution to such multi-objective problems can be computationally as large number of variables could be applied to such models. In addition, it may not be capable of considering all the features associated to the given problem [4],[5],[26]. The multi-objective system design usually search for either the configuration or the control, or both parameters that gives the least total cost of energy through the valuable life span of the project while pollutant emissions are considered after establishing the design configuration, which minimises monetary costs. Other multi-objective systems design utilised in literatures [28],[31] included the ecological issues associated with such installations during the design process by economically evaluating and including them as part of the monetary cost function. These designs simplify the task by reducing the problem to a single fitness function. The mapping of monetary costs to pollutant emission is subjective but impacts the optimum capacity allocation of the energy system. Also, other methods including the multi-objective evolutionary and strength Pareto evolutionary algorithms were utilised in the designs reported in [7],[18],[32].

IV. Optimisation Models for Hybrid Energy Systems

There has been an outstanding interest in the optimum capacity allocation of hybrid power systems, but the non-linear nature of the energy sources, electric load demands and other system components usually complicate the design process. In addition, the complete assessment of hybrid energy systems, which include conventional and non-conventional energy sources depends on several factors, such as the technical (e.g., power system quality and reliability), economic (e.g., energy costs) and environmental (e.g., pollutant emissions) objectives. Optimisation modelling has enabled researchers to establish satisfactory solutions, with relative ease, to complex problems associated with hybrid energy system. The optimum sizing of hybrid power systems are, usually, achieved using optimisation methods. The various optimum sizing methods for hybrid power systems are broadly categorised into two, viz. simulation program/software and optimisation methods – conventional and advanced.

A. Utilisation of Software-Based-Packages

Various researchers around the globe have made different attempts to solving the problems of hybrid energy systems using different simulations and optimisation software. The commonly used tools include Hybrid power system simulation model (Hybrid2), Hybrids, Hybrid Optimisation by Genetic Algorithms (HOGA) and Hybrid Optimisation Model for Electric Renewable (HOMER) [7], [30].

1) Hybrid2: Hybrid2 is a software model developed by a research team of the University of Massachusetts for hybrid power systems design and operation simulation. The software uses a combined time series/probabilistic method to account for long-term/short-term predictions. The probabilistic approach used is based on probability density functions (pdf), such as the Normal, Gaussian and the Weibull distribution. These functions are used in each time step to find the expected values (minimum and maximum), the fraction of time in which those values may be within a certain range, and the amount of energy that may be required or available in the range.

Barley *et al*. [33] applied the Hybrid2 simulation software in combination with a fundamental time-series paradigm in the assessment of a hybrid wind-photovoltaic system that could supply electric power to roughly one-third of the isolated households in Inner Mongolia. The system configuration was established on the basis of a subjective compromise between the system's monetary cost and the deficit load fraction. The result showed that the inclusion of solar photovoltaic array to the wind-only system, in addition with an increase in battery capacity, reduced the deficit load by over 75%, with a cost increase of only 22%. Hybrid2 simulates hybrid energy systems with remarkably high accuracy computations, but the software does not optimise the system [7].

2) Hybrids: The Hybrids are spreadsheet-based renewable power system design and evaluation application developed by Solaris Homes. This model can only simulate a single configuration at a time. In addition, it does not provide an optimised configuration for the system. However, the model could improve the optimum design configuration obtained from HOMER, when the design output from HOMER is used as design input for the Hybrid2 [30].

3) HOGA: HOGA was produced in Spain by the University of Zaragoza. It is a hybrid system optimisation program that applies the genetic algorithms to design the sizing and management of hybrid energy systems. HOGA could perform an assessment of all possible combinations, including components and control strategies. Dufo-Lopez *et al*. [34] applied HOGA program to develop the optimal management control of solar-diesel hybrid systems. The optimum structure was described accurately as the type/number of photovoltaic generators, battery, inverter and the capacity of the diesel generator. The computational results demonstrated the economic benefits of the photovoltaic-diesel hybrid system. Nevertheless, this approach is, usually, not realistic, because the number of variables could be large, thus resulting in computation times of the order of months, or even years. In addition, the ecological issues associated to the design comprising diesel generator were not considered during the design process. The omission has a significant effect on the optimum design configuration.

4) HOMER: The National Renewable Energy Laboratory produced HOMER for optimisation of hybrid power systems due to the shortcomings of the Transient energy System simulation tool [30]. The model could help in the design and assessment of hybrid systems and can aid comparison of different power options. The software does not optimise the battery state of charge set point. In addition, it requires excessively high computation time when the number of design parameters is reasonably large. HOMER computer-based model is the most extensively utilised software for sizing hybrid power systems in the literature. Several authors [13],[15],[35],[36],[37],[38],[39] used HOMER for planning and sizing of energy systems and determined the optimum configurations for different combination of off-grid hybrid power systems. Unlike other simulation software, HOMER permits comparison with several design alternatives based on economic and technical advantages, consequently, different studies including [12],[40],[41],[42],[43] have used this software for capacity allocation of grid-linked hybrid system.

System components sizing with HOMER assumed many simplifications and analysis entails information on power sources, financial constraints and control techniques. For instance, in grid-connected applications it considered reliable and steady grid supply, and established grid electricity purchased as the sum of net energy generation (the difference between energy produced and load demand) during periods when energy generated is less than the amount demanded. This assumption could significantly impact the accuracy of results deduced from HOMER, especially within the emerging world where grid electricity is not reliable. To account for some of these shortcomings, a recent release (HOMER Pro 3.9.1) introduced random outages to account for unreliable grids based on three variables - mean failure frequency, mean repair time in hours, and repair time variability as a percent. Nevertheless, more research is needed for improving the performance of hybrid energy systems, by establishing methods for precisely predicting the power system output and reliably integrating the utility grid with non-conventional energy sources. Alternative methods are essential, to facilitate comparison, which could help to determine the applicability of different techniques.

Table I shows a comparison of the software-based-packages widely used in the literature. It is important to note that these software packages are implementations of algorithmic/ mathematical routines. No single software tool is completely adequate. The choice of tool depends on the hybrid energy system architecture and the requisite degree of accuracy.

B. Utilisation of conventional optimisation techniques

Several researchers have utilised various traditional optimisation techniques for optimum sizing of hybrid power systems worldwide. The commonly used techniques are probabilistic, iterative techniques and linear programming. Probabilistic method can permit multiple results with changing degrees of certainty/uncertainty of occurrence. Tina *et al.* [44] applied probabilistic sizing method to assess the impacts of solar irradiation and the variability of wind speed on hybrid system design. Although, this method was utilised by different authors for optimisation of mixed energy systems, the dynamic performance of the power system could not be considered.

Iterative methods were used in [45],[46] to calculate the optimum sizes of different hybrid energy systems including wind turbines, solar panels and batteries subject to different constraints. Yang *et al.* [47] utilised the iterative optimisation model for the minimisation of a mixed energy system cost either by linearly varying the decision variables values or by applying linear programming. The iterative optimisation tool, however, is computationally expensive. In addition, the method does not optimise the tilt angle of the photovoltaic array as well as the tower height of the turbine as the resulting energy output and monetary cost of the system are highly affected by these parameters in studies reported.

Gupta *et al.* [48] recommended mixed integer-linear computational program to verify the optimal capacity of a hybrid system, as well as the evaluation of the economic benefits of the photovoltaic generator. The method adopted incorporated a fixed cost of each anticipated power source (biomass, small hydro, wind turbine, photovoltaic and diesel generators) in the fitness function. Hence, components with lower unit costs share a larger proportion of the overall energy demand. A linear programming framework was proposed in [49] for minimising the out sourced power supply and storage capacity of hybrid energy systems with different power system losses. Nogueira *et al*. [50] determined the sizing configuration of a power system with photovoltaic generator, wind and battery with high reliability and minimal cost using linear programming techniques. On the other hand, Khatib [51] utilised a similar technique to optimise a grid photovoltaic-wind hybrid system for in Nablus, Palestine. The mixed-integer linear programming techniques was also used in [52],[53] to solve energy related issues in recent time.

The conventional optimisation methods widely used are compared in Table II. In general, the conventional optimisation methods are derivative-based techniques. These traditional methods, although are reliable and have proven to be effective in solving many categories of optimisation problems, could encounter technical hitches such as being trapped in local minimum and not being able to solve certain types of objective functions – NP-hard problems.

C. Utilisation of advanced optimisation techniques

Advanced methods, such as artificial intelligence, are a rapidly evolving paradigm that can overcome the shortcomings of the derivative-based techniques. Moreover, they possess the capability of enhancing the optimisation process in hybrid systems [54]. Artificial intelligence depicts the computational ability of a system to carry out similar kinds of functions, which characterise human thought. There are several global optimisation algorithms, which applies artificial intelligence tools for sizing hybrid energy systems. These algorithms are, usually, population-based heuristics due to their applicability to a broad range of problems.

Several authors used the meta-heuristic methods to tackle the optimal mix problems by taking into consideration not only the energy resources, but the technological characterisation, economic parameters (such as installed and maintenance costs) and incentives as well. Standard global optimisation algorithms include the tabu search, ant colony optimisation, pattern search algorithms, genetic algorithms and particle swarm optimisation. Other methods commonly applied for optimisation of hybrid energy systems includes the fuzzy logic and artificial neural network [55].

1) Tabu Search Algorithms: The tabu search algorithms [56] use the "move" operation to determine the region of any given solution. The capability of the algorithm to avert the local optimum in addition to cycles that typically cause the simple descent algorithms to stop functioning characterises its operation. Katsigiannis & Georgilarkis [57] utilised the tabu search algorithms for sizing a small, remote hybrid power system (with a peak yearly electric load of 100kW) using computer codes developed in MATLAB for Chania region, Greece. Though the implementation of the tabu search algorithms was advantageous in terms of its simplicity, the execution time of over 42 minutes was a considerable disadvantage: the convergence time was considerably high.

2) Ant Colony Optimisation: The ant colony optimisation algorithm is a swarm-inspired probabilistic method for solving computational problems [58]. The essential characteristics of the ant colony optimisation algorithms include distributed computation, positive feedback and incremental construction of solutions. The ant colony optimisation algorithms inspired

TABLE I. COMPARISON OF SOFTWARE-BASED-PACKAGES FOR OPTIMISATION OF HYBRID ENERGY SYSTEMS

Models	Highlights/Features	Merits	Demerits	Remarks
Hybrid2	It is a user friendly tool. It combines time series/probabilistic method to account for long-term/short-term predictions	It simulates hybrid systems with remarkably high degree of accuracy, widely available.	It cannot adequately optimise the system	Software packages are implementations of algorithmic/ mathematical routines. No single software tool is completely adequate. The choice of tool depends on the hybrid energy system architecture and the requisite degree of accuracy.
Hybrids	A spreadsheet-based application used to simulates a single power system architecture at a time	It could improve the optimum design configuration obtained from HOMER	It cannot provide an optimised system configuration.	
HOGA	Program developed in C++ and applies the genetic algorithms for sizing and management control of hybrid systems	It is freely available, allows optimum economic analysis of hybrid energy systems	Technical accuracy is low.	
HOMER	A computer-based simulation tool with a robust user interface for hybrid system sizing with detail sensitivity analysis	Simplicity of its operation and use Allows comparison with several design options based on techno-economic merits.	Software is not freely available to users. Components sizing assume many simplifications; hence, technical accuracy is low.	

TABLE II. COMPARISON OF CONVENTIONAL OPTIMISATION TECHNIQUES FOR HYBRID ENERGY SYSTEMS

Models	Highlights/Features	Merits	Demerits	Remarks
Probabilistic	Stochastic method that exhibits varying degrees of certainty/ uncertainty of occurrence of a system	Easy to comprehend Computationally less expensive	Cannot adequately model the dynamic nature of the hybrid system	They encounter difficulties (e.g., modality, multi-dimensionality and differentiability) when solving large-scale problems. Linear programming is flexible and can solve more complicated problems than other methods; however, it could be trapped in local minimum
Iterative	It is a recursive process that terminates when a satisfactory solution is attained based on the design specifications	It is easy to comprehend and can detect faulty solutions at early stages	It is computationally expensive.	
Linear programming	It is designed based on a numerical model specified in terms of linear relationships	It is flexible and can be applied for solving broad range of problems.	Assumptions/simplifications are not realistic; hence, encounters hitches especially when applied to nonlinear problems.	

researchers to solve to a variety of optimisation problems discussed in [58],[59],[60]. Several problems have emerged from diversifying the original idea to solve a broad range of NP-hard problems, drawing on different features of the behaviour of ants. Although, convergence is guaranteed by iteratively changing the probability distribution, the order of random decisions and the time to convergence is indefinite.

Suhane & Rangnekar [61] used the ant colony technique for the optimisation of a solar-wind-battery mixed system. An improved ant colony optimisation algorithm based on sorting was applied in [62] to verify the optimal size of an off-grid hybrid energy system with photovoltaic array, wind turbine, and a battery-hydrogen hybrid storage system for an island of Zhejiang, China. A similar method was used in [63] to assess the reliability index of micro-grid consisting of wind-solar with hydrogen storage for Ardebil Province (Iran).

3) Pattern Search Algorithms: The pattern search algorithms are an evolutionary method capable to solving a category of optimisation problem, which are outside the range of the normal optimisation methods. Unlike genetic algorithms, pattern search algorithms possess a well-balanced and flexible operator, which enhances, adapts and fine tune the local search to attain the global optimum. The pattern search algorithm was used to solve the formulated non-linear constrained optimisation problems for different system architectures [64],[65], while an enhanced version of the algorithm was used for optimum capacity allocation of wind energy system in another study [66].

4) Simulated Annealing: The algorithm utilises a random search technique comparable to iterative enhancement approach, but could accept inferior solutions due to its stochastic nature. Ekren & Ekren [67] utilised the simulated annealing algorithm in optimising a wind-photovoltaic-battery hybrid system. The aim was to validate the optimum size of the hybrid energy system with minimum runtime as compared to the response surface methodology. The study utilised historical hourly average data and random measurement of the mobile base transceiver station load situated on the campus area in Turkey. Simulation results indicated that the heuristic tool converges in a reasonable runtime and the hybrid system can effectively power a BTS site. However, the study neglected the seasonal change of the energy demand, which is an essential factor for accurate determination of the optimum size of the power system. The simulated annealing algorithms have been applied to the optimal sizing problems of different energy system options [68],[69].

5) Genetic Algorithms: The genetic algorithm follows the principles of natural genetics and selection for the determination of the search and optimisation procedures, which operates based on survival of the fittest. The genetic algorithm (GA), unlike strict numerical methods, has the ability to adapt to non-linearity and discontinuities in hybrid power systems. The genetic algorithms make use of three operators – selection, crossover and mutation [7]. The extensive use of the algorithm for solving complex-design optimisation problems is due to its potential in solving both continuous/ discrete variables and non-linear fitness and constraints functions, without the need for gradient information. The ability is traceable to its sensitivity and the ability to solving real, non-linear and mixed-integer optimisation problems. In contrast, its expensive computational cost is a major drawback.

Several authors have used the GA for optimal sizing of green energy applications. Koutroulis *et al*. [70] developed a model to calculate the size of system components to ensure optimum operation of the system at minimal cost, provided the electric load requirements were fully satisfied with a no load rejection ratio. The primary objective was the minimisation function, which was implemented using genetic algorithms. The viability of a wind-solar micro-grid for a remote telecom site in China was assessed in [71] using the genetic algorithm. The design considered energy consumptions of 1.3kW ($24V_{ac}$) and 0.2kW ($24V_{dc}$) for microwave communication for standard operation of the RBS2206 mobile base station. The study reported based on an annual time-series field data studied that an optimum configuration consisting of 120kWh (5000Ah, 24V) battery capacity, 12kW wind turbine, and 7.8kW PV array inclined at 29.5^o enabled good system behaviours and satisfactory performance. Ould *et al*. [72] recommended a multi-objective GA for size optimisation of a wind-solar-battery mixed system with the primary aim of minimising the annualised system cost and the unmet electric load. The results of [70],[71],[72] showed the robustness of the genetic algorithms in finding global optimum solutions. A comparative performance of the teaching learning based-optimisation and the genetic algorithm techniques for optimising a micro-grid was assessed in [73]. The result showed that the genetic algorithm out shines teaching learning based-optimisation technique. Ko *et al*. [32] used a modified GA to compute the optimum specifications of a micro-grid operating under full-load (solar photovoltaic and collector, fossil fuel, chiller, boiler and heat pumps – ground and air sources) conditions at Gimpo, South Korea. The algorithm resolved the multi-objective function by simultaneously maximising the renewable energy penetration and minimising the life cycle cost and the pollutant emissions. Campana *et al*. [74] developed a multi-objective (cost/reliability) optimisation model using genetic algorithm for optimal energy harvest that could satisfy the energy needs of a residential consumer. The simulation result showed that the developed multi-objective genetic-algorithm-based model minimised the life cycle cost of the hybrid energy with increased reliability.

6) Particle Swarm Optimisation: The particle swarm algorithms are population-based stochastic optimisation approach, which fit into the group of evolutionary computation for solving global optimisation problems. It can provide an efficient optimisation of complex multi-dimensional search spaces. The algorithm was initiated as an optimisation model [75]. It applies virtually to any problem expressed in terms of an objective function. A recent survey on the state-of-art in the particle swarm algorithm showed that the algorithm has gained significant interest from the computing research community

[76]. The application of the algorithm to a broad range of search and optimisation problems exist in the literature. Ref. [77] demonstrated the ability of the particle swarm algorithms in optimising the total cost of an off-grid mixed energy system for south-east of Iran. The result showed that the imposed constraints of the problem were satisfied at optimal cost.

The main drawbacks of this algorithm are the problem-dependent performance, premature character, high computational complexity and slow convergence. The dependence commonly caused by parameters setting, could result in high-variation of the performance of the algorithm. The premature nature could lead to convergence at a local minimum. Typically, the algorithm experiences premature convergence when optimising large multi-modal problems. In addition, the algorithms are unable to provide the optimum results in real-time scheduling problems. To solve these problems, different modifications as well as hybridisation with other meta-heuristic algorithms as described in [76],[78] are suggested. A standard approach to resolve premature nature is through the use of self-adaptive parameters.

Tudu *et al*. [79] introduced an enhanced edition of particle swarm optimisation technique for optimum sizing analysis of an isolated hybrid power system for India considering the real load and meteorological data. The result proved that the improved method can efficiently solve complex non-linear optimisation problems moderately. Borhanazad *et al*. [80] introduced a control framework for multi-objective function based on particle swarm optimisation for hybrid energy systems in different operation modes. Mohamed *et al*. [81] applied particle swarm optimisation algorithms to estimate the optimum size of an off-grid hybrid energy system with photovoltaic and wind turbine generators, storage batteries and diesel generator, with a smart-grid based load management for some isolated parts of Saudi Arabia. The study also verified that parallel execution of the particle swarm optimisation algorithm is faster compared to serial computing.

7) Hybrid Optimisation Algorithms: The search for a global optimum method for hybrid energy systems with relative computational simplicity has led to the use of advanced artificial intelligence or hybrid search (combination of different heuristics) techniques. Cai *et al*. [82] introduced a technique for community scale renewable power management. The authors applied the two-stage, interval-linear and superiority-inferiority based fuzzy-stochastic programming techniques for power system planning for different communities. The results could inform decision making for effective policy framework under different techno-economic constraints. Abedi *et al*. [83] proposed the use of a hybrid method (differential evolution and fuzzy techniques), to reduce the overall monetary cost, deficit load and pollutant emissions of a mixed-integer non-linear multi-objective optimisation problem of a hybrid power system. This method was implemented on a system with some commonly utilised generators in isolated systems, including photovoltaic modules, wind turbines, fuel cells, electrolysers, hydrogen storage tanks, diesel generators and storage batteries. In order to achieve an effective power utilisation from renewable energy sources, the optimal monthly tilt angles of the photovoltaic modules and the optimal installation height of the wind turbines were computed. The results demonstrated the ability of the proposed architecture for optimisation of hybrid energy systems

Naama *et al.* [84] proposed a hybrid genetic algorithm-tabu search optimisation model to resolve the economic dispatch problems with hybrid energy systems. Compared with the individual algorithms, the proposed hybrid method has the best capability of finding the global optimum solution within reasonable computing time. Katsigiannis *et al.* [85] developed a hybrid (genetic algorithm-tabu search) optimisation software for sizing hybrid energy systems, either connected to the grid or operated separately, with a variety of components (photovoltaic modules, wind turbines, diesel generators, micro-turbines, biogas generators, batteries, converters and dump loads). The authors in [20],[30] utilised the hybrid Genetic-Algorithm/Pattern Search (h-GAPS) technique for assessing the impacts of unreliable grid network and developed a framework for the inclusion of an index term to account for power outages in the analysis of grid-linked hybrid energy systems. The results showed that the h-GAPS technique has the highest technical accuracy for optimum sizing of mixed energy systems compared to the standard pattern search and genetic algorithms. Bustos & Watts [86] introduced a three-stage framework (genetic algorithm/robust optimisation/mixed integer linear programming) for optimal sizing of isolated micro-grid. The system capacity was deduced by the genetic algorithm while the robust optimisation and mixed-integer linear programming paradigms were utilised to ascertain the optimal operation strategy of the micro-grid. A variety of hybrid algorithms comprising of a combination of the meta-heuristic (particle swarm, simulated annealing, ant colony, genetic algorithms, etc.) techniques were used to establish the optimal mix of resources of hybrid energy systems in recent time [87],[88], [89]. The numerical results of these studies showed that hybridisation of meta-heuristic algorithms can be used to deduce more satisfactory optimal solutions within realistic runtime compared to a single meta-heuristic method. Table III shows a comparison of the advanced optimisation methods widely used in the literature.

V. DISCUSSION

The dynamic interaction between the various power resources and electric load demand could cause power system instability and this could reduce the reliability and quality of the power system. Thus energy control strategy is important in the optimal design for a cost-effective utilisation of hybrid power systems. Moreover, the control strategy can influence the available power supply and the overall lifetime of the system components. Correct system sizing of in terms of monetary cost, the technology and energy requirements is critical. Therefore, finding the optimum system configuration involves deciding on the mixture of energy resources and the technological impacts, the quality or size of all components and the operation strategy the system should utilise, with the minimum monetary and socio-technical costs.

TABLE III. COMPARISON OF ADVANCED OPTIMISATION TECHNIQUES FOR HYBRID ENERGY SYSTEMS

Models	Highlights/Features	Merits	Demerits
Tabu search	Meta-heuristic search tool, which uses local search methods for numerical optimisation	Algorithm is simple, fast computation time, boosts local search scheme	Inadequate optimising tool
Ant colony optimisation	A swarm-inspired probabilistic method with distributed computation, positive feedback and incremental construction of solutions	It has some merits in global search; can solve a number of optimisation problems	It can accept inferior solutions due to its stochastic nature
Pattern search	Numerical tool that can resolve continuous and differentiable functions; possess a well-balanced and flexible operator	It can enhance, adapt and fine tune the local search to attain the global optimal; available in MATLAB toolbox	It can converge to non-stationary points in some cases
Simulated annealing	Mimics the annealing process of a crystalline structure	Can resolve unconstrained, bound-constrained optimisation problems; robust and flexible; available in MATLAB toolbox.	Can accept inferior solutions; modifications required for different constraints.
Genetic algorithm	Operates on the principles of survival of the fittest on the basis of three operators (selection, crossover and mutation).	Can adapt to non-linearity; solve complex tasks especially when search space is computationally imposible; available in MATLAB toolbox	Computational cost is expensive; convergence depends on initial population and genetic operators.
Particle swarm optimisation	Mimics birdand fish movementbehaviour	Faster computation speed compared to genetic algorithms	The performance is problem-dependent; encounters partial optimality
Hybrid optimisation algorithms	A combination of two or more algorithms	Better performance than any single method	High complexity

The applicability of an optimisation model is dependent on its performance (convergence speed, computational ease, technical accuracy, etc.) and this could vary with the formulated optimisation problem. Different software packages have been introduced for sizing hybrid power systems. The accuracy of the software packages depends on the precision of the algorithmic implementations. In addition, the user may not intuitively adjust/select the suitable parameters/component units for a system, because the developed codes and computations are neither visible nor accessible. The conventional optimisation models could be applied in handling many classes of optimisation problems but may not attain satisfactory solution in reasonable runtimes for certain categories of fitness functions.

Consequently, approximate models based on heuristics approaches were developed to solve the problems of the conventional optimisation techniques. Meta-heuristic is a sub-group of the heuristics algorithms, inspired by nature and biological behaviours. The heuristic approaches can speedily provide satisfactory solutions to significant cases of complex problems while the meta-heuristics-based techniques are capable of producing high-quality solutions using robust iterative generation processes for exploring and exploiting the search space efficiently but require few modifications to be adapted for specified application. Although, no single optimisation model is completely adequate on its own, accurate mix of meta-heuristic algorithms can enable the developmental framework for finding the true optimal solution of hybrid energy system in reasonable time. It is important to note that research is ongoing for enhancing the efficiency of hybrid energy systems, establishing methods for precisely optimising the operation of the system components and accurately estimating the input data, reliably interfacing the grid with alternative power sources and for proper management of the mix of energy resources.

VI. CONCLUSION

This paper presents the state-of-the-art assessment of optimisation models for hybrid energy systems. The hybridisation of different algorithms can achieve better results than any single models. This is because the hybridised tool combines the different paradigms to maximise each algorithm's strength while compensating for the other's drawbacks. This paper recommends the use hybridised meta-heuristic algorithms for establishing the optimal solutions of hybrid energy systems. The choice of the hybrid algorithmic mix depends on the hybrid energy system architecture as well as the requisite degree of accuracy, which can vary with user constraints. But, when the complexity of hybrid method is computationally expensive, the parallel computing techniques could be applied to obtaining robust solutions in reasonable runtimes when the optimisation model is computationally expensive.

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