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Review of Researches on Techno-Economic Analysis and Environmental Impact of Hybrid Energy Systems

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Abstract — Hybrid energy systems, which are combinations of two or more renewable and non-renewable energy sources, have been identified as a viable mechanism to address the limitations of a single renewable energy source, utilized for electricity generation. In view of this, several research works have been carried out to determine the optimal mix of different renewable and non-renewable energy resources used for electricity generation. This paper presents a comprehensive review of the optimization approaches proposed and adopted by various authors in the literature for optimal sizing of hybrid energy systems. It is observed that the objective functions - considered by a large percentage of researchers to optimize the sizing of hybrid energy systems - are cost minimization of the generated electricity, system reliability enhancement and environmental pollution reduction. Other factors covered in the literature are equally discussed in this article. Similarly, simulation and optimization software used for the same purpose are covered in the paper. In essence, the main aim of this paper is to provide a scope into the works that have been carried out in the field of hybrid energy systems, used for electricity generation with the view to informing researchers and members of the public alike, on trends in methods applied in optimal sizing of hybrid energy systems. It is believed that the information provided in this paper is very crucial in advancing research in the field.

Keywords — Hybrid energy systems; Electricity generation; Techno-economic analysis; Environmental impact; Cost of energy; Emissions; Optimization algorithms.

Nomenclature

HES	Hybrid energy system
MOEA/D	Multi-objective evolutionary algorithm based on decomposition
PICEA	Preference-inspired co- evolutionary algorithm
DEA	Differential evolutionary algorithm
GA	Genetic algorithm
PSO	Particle swarm optimization
CMIMOPSO	Constrained mixed-integer multi-objective particle swarm optimization
MOGA	Multi objective genetic algorithm
WECS	Wind energy conversion systems
PV	Photovoltaic
DMOPSO	Dynamic multi-objective particle swarm optimization
MOP	Multi-objective optimization
PB	Pareto-based
NPB	Non-pareto-based

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SOP	Single-objective optimization
ACO	Ant Colony Optimization algorithm
$LPS(t)$	Loss of power supply at time t
$E_L(t)$	Load demand at time t
η_B	Efficiency of the battery
$E_{PV}(t)$	Output of PV at time t
$E_B(t-1)$	Battery charge at time $t-1$
$E_{B\min}$	Minimum state of charge of the battery
η_{inv}	Efficiency of the inverter
η_{wire}	Efficiency of the wire
LCC	Life cycle cost
C_{PV}	Cost of PV panel
C_{Batt}	Cost of the batteries
C_{inv}	Cost of the inverter
C_{MO}	Cost of maintenance and operation
$I_{\text{supplied}}(t)$	The current by HRES at hour t
$I_{needed}(t)$	The current required for the load at hour t
n	Number of samples
T	Number of hours considered
$P_{Avail}(t)$	Available power supply at each time step
$P_{load}(t)$	Load demand at each time step
$F_{emissions}$	Fuel emission
F_{cons}	Fuel consumption
Ef	Emission factor
ACS	Annualized cost of the system
C_{ainv}	Annualized investment cost
C_{aom}	Annualized operation and maintenance cost
C_{arep}	Annualized replacement cost
R_{LP}	Ratio of lack of power
P_{LP}	Lack of power
P_{load}	Load demand
$C_{\min}$	Minimum allowable storage of battery
P_G	Total power requirement
C	Storage capacity of the battery
Δt	Time step

1. INTRODUCTION

The global awareness on the speedy depletion of fossil fuel resources has called for a pressing search for alternative energy sources to satisfy the present-day energy demand. Another key reason to reduce reliance on fossil fuels is the increasing evidence of the global warming phenomenon from the global community to reduce reliance on fossil fuels for power generation. In view of this, it is essential to discover alternative green energy sources to satisfy the continuous increase in demand for electrical energy in order to minimize the emissions of CO_2. Renewable energy resources are being considered as promising power generating sources due to their availability for power generations in urban and remote rural areas. However, the major drawback in utilizing these sources of energy is their unstable nature and dependency on weather and climatic conditions. This disadvantage will affect the system's energy performance and also results in rapid replacement of the solar batteries which can result in system over-sizing. This factor in turn could lead to an expensive design. It is a common knowledge that single renewable sources cannot provide a continuous electrical energy supply due to unpredictable weather condition. Luckily, these limitations can be partly or totally overcome by combining two or more renewable and non-renewable energy sources known as HES in a proper and economical manner.

A HES helps to improve the system's reliability and efficiency. It also reduces the capacity of energy storage required as compared to stand-alone systems consisting of only one single renewable energy source. Obviously, with the increased complexity in comparison with single energy systems, the optimum design of a HES becomes complicated through uncertain renewable energy supply and load demand. The non-linear characteristics of the components, high number of variables and parameters that have to be considered for the optimum design, and the fact that the optimum configuration and control strategy of the system must be reliant, are all vitally important. This complexity makes the design and analysis of hybrid systems more difficult [1]. The operation of HES involves optimizing its performance and at the same time satisfying its technical constraints - equality, inequality and integer constraints. Thus, optimization tools, techniques and applications have found recognition to attain these goals [2].

To deploy an optimally efficient HES, it is important to consider an approach that will ensure that the use of renewable resources is properly and economically combined in such a manner to maximize power generation and profit. The optimal sizing approach is required with the purpose of ensuring minimal investment cost, maximal reliability and minimal emissions from the HES. Different sizing approaches, namely, classical optimization methods, simulation and optimization software method and metaheuristic optimization techniques can be used for the technical, economic and environmental analysis of HES. Whatever the sizing and optimization method is used, the utmost goal is to look for optimal combination of the components of the HES with maximum system reliability, minimum system cost and minimum emissions.

This paper presents a comprehensive review of the objective functions considered in the literature for optimal sizing of HES. In addition, different approaches proposed by authors for the optimal sizing of HES are discussed. This work is aimed at exposing the various techniques and system parameters considered in mathematical formulations to the scholars with interest in optimal sizing of HES. The block diagram of typical HES with grid connection is shown in Fig. 1, while a brief overview of the optimization criteria (economic, technical and environmental) for optimal sizing of HES is presented in Section 2. The sizing methods for HES are presented in Section 3 and Section 4 concludes the paper.

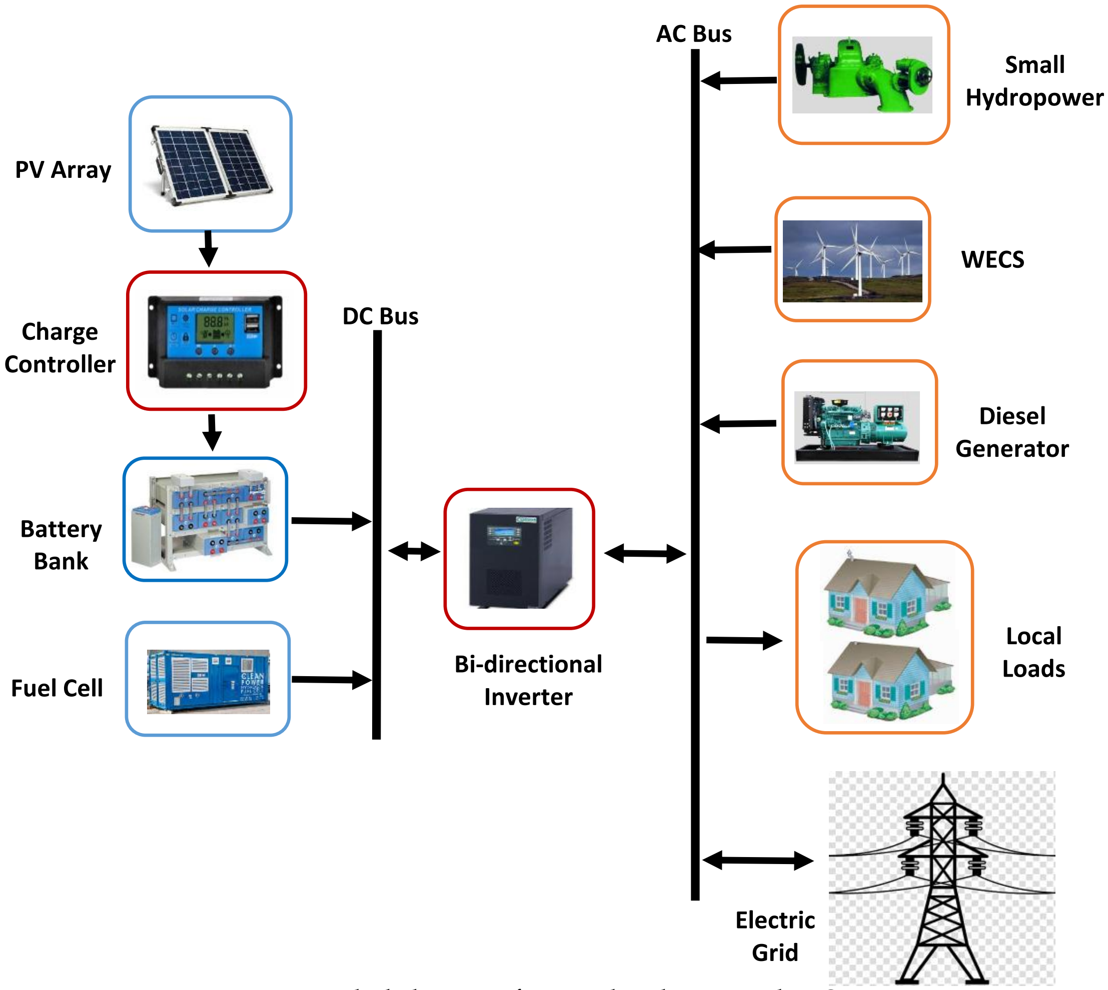

Fig. 1. Block diagram of a typical grid-connected HES.

2. OPTIMIZATION CRITERIA FOR OPTIMAL SIZING OF HYBRID ENERGY SYSTEMS

The various objective functions that are usually considered for optimal sizing of HES can be categorized into economic, technical and environmental. Economic criteria are usually used to minimize costs such as the levelized cost of energy (LCOE), annualized cost of energy, net present cost, life cycle cost (LCC), etc. of the HES. The technical criteria used in the literature include reliability and efficiency to meet up with the load demand at a determined reliability and efficiency values. Environmental criteria are employed to minimize the greenhouse gas emissions like CO_2. These objective functions are further discussed in detail in the following subsections.

2.1. Cost Optimization Analysis

Cost of energy (COE) is one of the most well-known and used indicators of economic profitability of HES [3-4]. Typically expressed in per kilowatt-hour or megawatt-hour, COE includes the initial capital, discount rate, as well as the costs of continuous operation, fuel, and maintenance. This type of calculation assists policymakers, researchers and others to guide discussions and decision making. Other variants include LCOE, life cycle cost, annualized cost of energy, net present cost, etc. Many studies have formulated minimizing LCOE for HES. LCOE can be defined as the ratio of the summation of annualized cost of the HES to the total annual electrical energy, generated by the system. Total net present cost (NPC) of HES includes all the installed capital costs, i.e., the present cost, operation and maintenance costs, and replacement cost within the project lifetime. Different authors have formulated the net present cost with the objective of minimizing it in any HES.

LCC analysis is an economic assessment of the cost for a number of alternatives considering all significant costs over the life span of each alternative, adding each option's costs for every year and discounting them back to a common base (present worth) [5]. Different authors have formulated LCC with the objective of minimizing it in HES. The annualized cost of system is composed of the annualized capital cost, the annualized replacement cost and the annualized maintenance cost [6]. The summary of formulations of related works on cost optimization is presented in Table 1.

Table 1. Formulations of existing works on cost optimization.

Reference	Objective function
[7]	$$\min NPC = NPC_{wg} + NPC_{el} + NPC_{\tan k} + NPC_{fc} + NPC_{reactor} \quad (1)$$ where NPC is total net present cost, and $NPC_{wg}, NPC_{el}, NPC_{\tan k}, NPC_{fc}, NPC_{reactor}$ are net present costs of wind turbine generator, electrolyser, hydrogen tank, fuel cell and reactor. $$NPC_i = N \times \left(\begin{array}{c} \text{capital cost} + \text{replacement cost } \times \text{K} + \\ \text{operation and maintenance cost } \times \dfrac{1}{\text{CRF (ir , R)}} \end{array} \right) \quad (2)$$ where: $$CRF(ir,,R) = \frac{ir(1+ir)^R}{(1+ir)^R - 1} \quad (3)$$ $$K = \sum_{n=1}^{Y} \frac{1}{(1+r)^{L \times n}} \quad (4)$$ $$Y = \left[\frac{R}{L} \right] - 1 \quad \text{if } R \text{ is divisible by } L \quad (5)$$ $$Y = \left[\frac{R}{L} \right] \quad \text{if } R \text{ is not divisible by } L \quad (6)$$ N is the optimal number of each component.

Table 1. Formulations of existing works on cost optimization-Continued(1)

Reference	Objective function
[8]	$$\min NPC = \sum_j \left[C_{I,j} + C_{O\&M,j} \times \frac{1}{CRF(i,T)} + C_{rep,j} \times K_j \right] \times P_j + \begin{bmatrix} C_{elec,b} \times E_{bought} + C_{NG} \times NG_y - C_{elec,s} \\ \times E_{Sold} + C_{Gas} \times Gasoline + Biomass_y \times (C_{b,Col} + C_{b,St} + C_{b,Tr}) \end{bmatrix} \times \frac{1}{CRF(i,T)} \quad (7)$$ where, $C_{I,j}$ states the capital cost of the element j (C$/unit), $C_{O\&M,j}$ is the operation and maintenance cost of the component j (C$/unit), j, $C_{rep,j}$ is replacement cost of the component j (C$/unit). $C_{elec,b}$ is the electricity price bought from the grid (C$/kWh), C_{NG} is the natural gas price (C$/m^3), $C_{elec,s}$ is the electricity price sold to the grid (C$/kWh), and C_{Gas} is the gasoline price (C$/litre). Moreover, biomass collection, storage and transportation costs are defined by $C_{b,Col}, C_{b,St}, C_{b,Tr}$, respectively. *CRF* is the capital recovery factor and *K* is single payment present worth i is interest rate and T is the project life time.
[9]	$$\min COST = \frac{\sum_{i=w,sb}(I_i - S_{Pi} + OM_{Pi})}{N_p} + C_g \quad (8)$$ where w, sb are the wind power, solar power, and battery storage, respectively; I_i, S_{Pi}, OM_{Pi} are the initial cost, present worth of salvage value, and present worth of operation and maintenance cost for equipment i respectively; N_p (year) is the life span of the project; and C_g is the annual cost for purchasing power from the utility grid.
[10]	$$\min LCE = \frac{TAC}{E_{tot}} \quad (9)$$ $$TAC = PVC \times \left[\frac{d(1+d)^n}{(1+d)^n - 1} \right] \quad (10)$$ where PVC is present of value of cost, TAC is total annualized cost, E_{tot} is total annual energy
[11]	$$\min LCE = \frac{C_{acap}(x) + C_{amain}(x) + C_{arep}(x)}{E_{annual}} \quad (11)$$ where E_{annual} is the annual energy consumption (kWh/year), C_{acap} is the levilized capital cost of energy, C_{amain} is the levilized maintenance and operation cost of energy, C_{arep} is the levilized replacement cost of energy
[12]	$$\min LCE = \frac{NPC}{\left\{ \sum_{n=1}^{N} \left[\frac{Q_n}{(1+d)^n} \right] \right\}} \quad (12)$$ where Q_n is energy produced in a year n, d is the annual discount rate, NPC is net present cost

Table 1. Formulations of existing works on cost optimization-Continued(2)

Reference	Objective function
[13]	$\min LCC = C_{PV} + C_{Batt} + C_{inv} + C_{MO}$ (13)
[3]	$\min COE(\frac{\$}{kWh}) = \frac{TotalNet\ PresentCost}{\sum_{h=1}^{h=8760} P_{load}} \times CRF$ (14) $CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$ (15)
[14]	$\min LCE = \frac{TLCC \times CRF}{E} \cdot \frac{d(1+d)^n}{(1+d)^n - 1}$ (16) $TLCC$ is total life cycle cost, CRF is capital recovery factor, E is annual energy generation, d is the rate of annual degradation.
[15]	$\min LCE = \frac{\left(\left[\frac{d(1+d)^n}{(1+d)^n - 1} \times ICC\right]\right) + (ANN + [O\&M \times n])}{8760 \times CF_{net}}$ (17) where d is interest rate, n is the operational life span, ICC is installed capacity cost, ANN is the annualized cost, $O\&M$ is the operation and maintenance cost, CF_{net} is net capacity factor.
[16]	$\min LCE = \frac{\left(C + L + \sum_{n=1}^{N} \frac{(OM+1) \times C}{(1+r)^n}\right)}{\left(\sum_{n=1}^{N} \frac{S \times TF \times \eta \times (1-d)^n}{(1+r)^n}\right)}$ (18) where S is solar resource, TF is tracking factor, d is annual degradation rate, η is performance factor, OM maintenance cost, C is cost of the system, L is cost of the required land, r is discount rate
[17]	$\min LPC = \frac{TC}{\sum_{y=1}^{n} AUE_y.(1+r)^{-y}}$ (19) where LPC is levelized production cost, n is the number of years of economic lifetime, AUE is the annual utilized energy during year y, and TC is the discounted present value of the total cost of energy production. $TC = I + \sum_{y=1}^{n} (OM_y + SC_y + RC_y)(1+r)^{-y} - SV(1+r)^{-n}$ (20) where I is the total investment cost, OM represents the operating and maintenance costs during year y, SC is the social cost during year y, RC is the retrofit cost, SV is the salvage value

Table 1. Formulations of existing works on cost optimization-Continued(3)

Reference	Objective function
[18]	$$\min NPC = \frac{(ACC + ARC + AMC)}{\left[\frac{i(1+i)^{j}}{(1+i)^{j}-1}\right]} \quad (21)$$ where is ACC is the annualized capital cost, ARC is annualized replacement cost, AMC is annualized maintenance, i is annual real interest rate, j is the project life span.
[6]	$$\begin{aligned}\mathrm{ACS} = {} & \mathrm{C_{ainv}(PV + WG + Tower + BAT + DG)} + \\ & \mathrm{C_{aom}(PV + WG + Tower + BAT + DG) + C_{arep}(BAT)}\end{aligned} \quad (22)$$
[20]	$$\min NPC = \frac{TAC}{CRF(i,N)} \quad (23)$$ where TAC is the total annualized cost per year, CRF is capital recovery factor, i is annual real interest rate, N is the project life time in year
[21]	$$\min T_c = \min(T_{ic} + T_a + T_{mc}) \quad (24)$$ where T_c is total cost, T_{ic} is initial cost, T_a is operation cost, T_{mc} is maintenance cost $$T_{ic} = S_{ic} + W_{ic} + B_{ic} \quad (25)$$ $$T_a = C_b U_p \quad (26)$$ $$T_{mc} = M_s + M_w + M_b \quad (27)$$ where S_{ic}, W_{ic}, B_{ic} are the initial cost of PV panels, wind turbines, and batteries, respectively; C_b, U_p are the electricity bill per kilowatt-hour and electric power bought to the utility, respectively; and M_s, M_w, M_b are the maintenance cost of PV panels, turbine generators, and batteries, respectively
[22]	$$\min Cost = \sum_k \left[\left(C_{I,k} + C_{O,k} \times \frac{1}{CRF} + C_{R,k} \times R_k\right) \times P_k\right] \quad (28)$$ $$T_{\cos t} = Cost - C_{ex} \times \frac{1}{CRF} \quad (29)$$ $$C_{ex} = \mathrm{Pr}_s \sum E_{SP} - \mathrm{Pr}_P \sum E_{GP} \quad (30)$$ where, k is the component indicator, C_I, C_O, C_R are the initial, operation, replacement per unit costs ($/kW), respectively. C_{ex} is the net grid interaction cost. R_k and CRF are single payment present worth and capital recovery factor, Pr_s and Pr_P are the selling and purchasing prices of electricity respectively. $$R_k = \sum_{n=1}^{N} \frac{1}{(1+i)^{L \times n}} \quad (31)$$ where, i is the real interest rate, N is the number replacements of the component k and L is its lifetime.

Table 1. Formulations of existing works on cost optimization-Continued(4)

Reference	Objective function
[19]	$$\min C_c = \sum_{h=1}^{N_h} C_h + \sum_{w=1}^{N_w} C_w + \sum_{s=1}^{N_S} C_s + \sum_{g=1}^{N_g} C_g + \sum_{b=1}^{N_b} C_b \quad (32)$$ where N_h, N_w, N_s, N_g, N_b are the total number of micro-hydro, wind, solar PV, diesel generator and battery units, respectively, and C_h, C_w, C_s, C_g, C_b are the corresponding capital costs. C_c is the total capital cost.
[23]	$$\min ACS = C_{cap} \cdot \left[\frac{i(1+i)^{Y_{proj}}}{(1+i)^{Y_{pproj}} - 1} \right] (PV + Wind + Bat + Tower) + C_{rep} \left[\frac{i}{(1+i)^{Y_{rep}} - 1} \right] (Bat) + C_{amain}(PV + Wind + Bat + Tower) \quad (33)$$ where ACS is annualized cost of the system, C_{cap} is initial capital cost of each component, Y_{proj} is the component life span, C_{amain} is annualized maintenance cost, Y_{rep} is the battery life span, C_{rep} is the replacement cost of the battery, i is the annual interest rate.
[24]	$$\min COE = \frac{TNPC \times CRF}{\sum_{t=1}^{8760} E_{Gen(t)}} \quad (34)$$ where: $$\mathrm{CRF(d, n)} = \frac{\mathrm{di}\,(1+\mathrm{di})^{\mathrm{n}}}{(1+\mathrm{di})^{\mathrm{n}}} - 1 \quad (35)$$ where COE is the cost of energy, $TNPC$ is the total net present cost, $E_{Gen(t)}$ is the total generated energy over a period, CRF is the capital recovery factor, di is discount rate, n is the life span of the plant [year].
[25]	$$\min LUEC = \frac{LCC \times CRF}{\sum_{t=1}^{8760} E_{Gen(t)}} \quad (36)$$ $LUEC$ is levelized unit electricity cost, $E_{Gen(t)}$ is total electricity generated over a period, LCC is life cycle cost of the hybrid system, CRF is capital recovery factor.
[26]	$$\min CC = \alpha . N_{PV} + \beta . N_{batt} + C_O \quad (37)$$ CC is the capital cost of the hybrid system, α is the cost of the PV module, β is the cost of battery, N_{PV} is the number of PV modules, N_{batt} is the number of storage batteries, C_O is the total constant cost such as installation cost, design cost e.t.c.

Table 1. Formulations of existing works on cost optimization-Continued(5)

Reference	Objective function
[27]	$\min EC = EC_{pv} \times P_{pv} + n_{sto} \times EC_{sto} \times C_{nom} + n_{inv} \times EC_{inv} \times S_{inv}$ (38) where EC is energetic cost, P_{pv} is peak power of PV array, C_{nom} is the nominal capacity of the storage, S_{inv} is the apparent power of inverter, n_{sto} is number of lead acid battery replacement, n_{inv} number of inverter over the life cycle of the system, $EC_{pv}, EC_{sto}, EC_{inv}$ are energetic parameter of PV, battery and inverter.
[28]	$\min TC = Cost_{fuel} + Cost_{PV} \times CRF_{PV} + Cost_{ESS} \times CRF_{ESS}$ (39) $Cost_{fuel} = \sum_{s=1}^{4} \sum_{t=1}^{960} Price_{fuel}.(a.P_{d(s,t)} + b.P_d^{rated})$ $Cost_{PV} = (C_{capitall}^{PV} + C_{replacement}^{PV}).P_{PV}$ $Cost_{ESS} = C_{capital}^{ESS} + C_{replacement}^{ESS}).E_{ess}$ where $Price_{fuel}$ is the fuel price); $C_{capitall}^{PV}$, $C_{replacement}^{PV}$, $C_{capital}^{ESS}$ and $C_{replacement}^{ESS}$ denote the installation and replacement prices for PV and the battery; P_{PV} is the size of PV (kW) and E_{ess} is the capacity of the battery.
[31]	$J = {}_{x}^{\min} \left\{ \sum_i NPC_i + NPC_{Loss} \right\}$ (40) where J is the objective function of the optimization problem $NPC_i = N_i \times \left(CC_i + RC_i \times K_i + MRC_i \times PWA(ir, R) \right)$ (41) N is the number of units or unit capacity (kW), CC is capital investment cost in ($/unit), RC is replacement cost ($/unit), K is single payment present worth, MRC is maintenance and repair cost ($/unit –*yr*), PWA is annual payment present worth, ir is real interest rate, R is the project life time (*yr*). $K_i = \sum_{n=1}^{y_i} \frac{1}{(1+iR)^{n \times L_i}}$ (42) $PWA(ir, R) = \frac{(1+ir)^R - 1}{ir(1+ir)^R}$ (43) y and L are the total number of replacements and the lifetime of a particular device, respectively. $NPC_{Loss} = LOEE \times C_{Loss} \times PWA$ (44) C_{Loss} is the equivalent cost of load curtailment per kWh ($/kWh), $LOEE$ is loss of energy expectation.

Table 1. Formulations of existing works on cost optimization-Continued(6)

Reference	Objective function
[29]	$$\min C = IC + MC + FC + VC - RV \quad (45)$$ $$IC = IC_{ss}(1-\gamma_{ss}) + IC_{wt}(1-\gamma_{wt}) + IC_{pv}(1-\gamma_{pv}) + IC_{de}$$ $$= (C_{se}E_{ss} + C_{sp}P_{ss})(1-\gamma_{ss}) + C_{wt}P_{wt}(1-\gamma_{pt}) + C_{pv}P_{pv}(1-\gamma_{pv}) + C_{de}P_{de}$$ $$= \left[\left(C_{se}\frac{d_o}{\eta_{ss}D_oD_L} + C_{sp}\right)(1-\gamma_{ss})\xi_{ss} + C_{wt}(1-\gamma_{wt})\xi_{wt} + C_{pv}(1-\gamma_{pv})\xi_{pv} + C_{de}\xi_{de}\right]P_{pl}$$ $$MC = (IC_{ss}m_{ss} + IC_{wt}m_{wt} + IC_{pv}m_{pv})\sum_{j=1}^{j=n}\left(\frac{1+i_{mc}}{1+i}\right)^j + \sum_{j=1}^{j=n}(IC_{de}m_{de} + c_{om}E_{de,j})\left(\frac{1+i_{mc}}{1+i}\right)^j \quad (46)$$ $$FC = \sum_{j=1}^{j=n}\left[c_f\sum_{h=1}^{h=8760}\eta_{de}(P_{de,j,h})\right]\left(\frac{1+i_{fc}}{1+i}\right)^j \quad (47)$$ $$VC = IC_{ss}\sum_{k}^{k=k_o} r_k\left\{\sum_{l=0}^{l=l_k}\left(\frac{(1+i_{k1})(1-i_{k2})}{(1+i)}\right)^{\ln_k}\right\} \quad (48)$$ $$RV = \frac{RV_{ss} + RV_{wt} + RV_{pv} + RV_{de}}{(1+i)^n} \quad (49)$$ $$c_o = \frac{C}{E_{tot}\sum_{j=1}^{j=n}\left(\frac{1+i_o}{1+i}\right)^j} \quad (50)$$ where C is the total life cycle cost, IC is the initial investment cost, MC is the maintenance and operation cost, FC is the fuel consumption cost, VC is the replacement cost, RV is the residual value, c_o is the present value of energy generation cost ¥/kWh, E_{tot} is the total energy generation over a certain period, $\eta_{de}(P_{de,j,h})$ is a function of fuel consumption with a quadratic term, D_oD_L is depth of discharge (%), c_f is price of fuel (¥/L), C_{se}, C_{sp} are initial cost of battery storage in ¥/kWh, ¥/kW); C_{wt}, C_{pv}, C_{de} are initial coefficient costs of wind turbine generator, PV and diesel generator; c_{om} is the maintenance and operation cost of diesel generator per unit energy (¥/kWh), E_{ss} is storage capacity of battery (kWh), $E_{de,j}$ is total annual generation of diesel generator (kWh), $\gamma_{ss}, \gamma_{wt}, \gamma_{pv}$ are subsidy percentages of battery, wind turbine and PV; ξ_{ss}, ξ_{wt} ξ_{pv}, ξ_{de} are capacity penetration of battery, wind turbine, PV, diesel generator; η_{de} is conversion efficiency of diesel generator, i is discount rate(%), $RV_{ss}, RV_{wt}, RV_{pv}, RV_{de}$ are residual values of battery, wind turbine, PV and diesel generator, n is the expected lifetime of the system, P_{ss}, P_{wt}, P_{pv}, P_{de} are the nominal power of storage battery, wind turbine, PV and diesel generator; P_{pl} is the peak load kW, n_k is the expected life time of part *k*.

Table 1. Formulations of existing works on cost optimization-Continued(7)

Reference	Objective function
[30]	$\min C_{total} = C_{DEC} + C_{EWC} - C_{HPC}$ (51) Where C_{DEC} is the composition of investment costs (C_{INV}), operation and maintenance (O&M) costs ($C_{O\&M}$) and replacement costs (C_{REP}), $C_{DEC} = (C_{INV} + C_{O\&M} + C_{REP})/T_{Sys}$ (52) $C_{INV} = C_{PV} \times N_{PV} + C_{WT} \times N_{WT} + C_{Bat} + C_{EL} + C_{FC} + C_{HY} \times N_{HY} + C_{Inv}$ Where C_{PV}, C_{WT}, C_{Bat}, C_{EL}, C_{FC}, C_{HY}, C_{Inv} are the price of the PV, wind turbine, battery, electrolyzer, FC, hydrogen tank and inverter, respectively. N_x is the number of component *x*, $C_{O\&M} = \alpha \times C_{INV} \times T_{Ssy}$ Where α is a coefficient, T_{Ssy} is the operating time of the hybrid system (20 year) $C_{REP} = C_{Bat} \times N_{Bat} \times \sum_{n}^{T_{Sys}/T_{Bat}} \frac{1}{(1+i)^{n\times T_{Bat}}} + C_{EL} \times N_{EL} \times \sum_{n}^{T_{Sys}/T_{EL}} \frac{1}{(1+i)^{n\times T_{EL}}} + C_{FC} \times N_{FC} \times \sum_{n}^{T_{Sys}/T_{FC}} \frac{1}{(1+i)^{n\times T_{FC}}}$ (53) where i is the interest rate and T_{Bat} (two years), T_{EL} (five years) and T_{FC} (five years) are the lifetime of the battery, electrolyzer and Fuel Cell, respectively. $C_{EWC} = \sum \frac{C_{DEC}}{E_{out-annual}} \times (P_{gen}(t) - P_L(t) - P_{stor}(t))$ (54) where $E_{out-annual}$ is the average output of the generation unit every year. $P_{gen}(t)$, $P_L(t)$, $P_{stor}(t))$ are the energy generated, consumed and stored at time t respectively. $C_{HPC} = \sum \frac{C_{DEC}}{E_{out-annual}} \times \frac{E_{HY}(i)}{\eta_{el}}$ (55) $E_{HY}(i)$ is the energy stored in hydrogen tanks at the end of each season, $E_{out-annual}$ is the average output of the generation unit every year.

2.2. System Reliability Optimization

The intermittent nature of renewable energy resources can highly influence the expected output energy from the HES. In view of this, power reliability index is used as an important criterion in the optimal design of HES. To evaluate the reliability of the system, the indices considered in the literature include Loss of Power Supply Probability (LPSP), Loss of Load Probability (LOLP), Loss of Load Expectation (LOLE), Expected Energy Not Served (EENS) System Performance Level (SPL), Loss of Load Hours (LOLH), and Equivalent Loss Factor (ELF).

LPSP is a statistical parameter, which indicates the probability of power supply failure either due to low renewable resource or technical failure to meet the demand [3]. There are two methods of calculating LPSP for the optimal design of HES. They are chronological simulation and probabilistic techniques [3]. The former technique uses time-series data in a given period and is computationally burdensome, which requires the availability of data spanning a certain period of time [1]. The latter is based on the energy accumulative effect of the energy storage system [3] and uses probabilistic techniques to incorporate the fluctuating nature of the resource and the load, thus eliminating the need for time-series data [1]. Details and examples can be found in [3, 6, 30, 32- 35].

LOLE is an index used to measure the average time (hours or days) the capacity of available generation is likely to drop below the load demand. The weakness of this index is that it cannot identify the level of capacity shortage. On the other hand, the LOLP is a measure of the probability that a system demand will exceed the system's power supply capacity in a given time period, often expressed as the estimated number of days over a long period [1]. The weakness of LOLP index is that it cannot identify the level of capacity shortage

The SPL is defined as the probability that the load demand cannot be satisfied [1]. ELF is defined as the ratio of actual load outage hours to the total number of hours [36]. An example can be found in [37]. EENS can be defined as the amount of load demand expected not to be served by generation in a specified year. It is due to those events when the load goes beyond the accessible generation. It represents an index which could be used to quantify security of energy supply and also to establish a reliability standard. Examples can be found in [38-42]. The summary of formulations of related works on power reliability optimization is presented in Table 2.

Table 2. Formulations of existing works on system reliability optimization.

Reference	Objective function
[13]	$$\min LPSP = \frac{\sum_{t=1}^{t=\max} LPS(t)}{\sum_{t=1}^{t=\max} E_L(t)} \quad (56)$$ $$LPS(t) = E_L(t) - (\eta_B \times E_{PV}(t) + E_B(t-1) - E_{B\min})(\eta_{inv}\eta_{wire}) \quad (57)$$
[6]	$$\min LPSP = \frac{\sum_{t=0}^{T} T(P_{Avail}(t) < P_{load}(t))}{T} \quad (58)$$
[27]	$$\min LPSP = \frac{\sum_{t=1}^{t_{sim}} LPS(t)}{\sum_{t=1}^{t_{sim}} E_{Ld}(t)} \quad (59)$$ $$LPS(t) = E_{Ld}(t) - E_{Lc}(t)$$ $LPS(t)$ is the deficit known as loss of power supply, $E_{Ld}(t)$ is the sum of energy demand during the year, $E_{Lc}(t)$ is the energy consumed by the load at time t.

Table 2. Formulations of existing works on system reliability optimization-Continued

Reference	Objective function
[43]	$$\min LOLP = \frac{\sum_{t=1}^{n} hours(I_{supplied}(t) < I_{needed}(t))}{n} \quad (60)$$
[44-46]	$$\min LLP = \frac{\sum_{t=1}^{8760} shortage(t)}{\sum_{t=1}^{8760} D(t)} \quad (61)$$ where LLP is loss of load probability, $D(t)$ is the demand for electricity, $shortage$ is the unmet load during time period t.
[47]	$$\min R_{LP} = \frac{\sum_{t=1}^{T} P_{LP}(t)}{\sum_{t=1}^{T} P_{load}(t)} \quad (62)$$ $$P_{LP}(t) = P_{load}(t)\Delta t - (P_G(t)\Delta t + C(t-1) - C_{\min})\eta_{inv} \quad (63)$$
[22]	$$\min GPAP = \frac{\sum_{t=1}^{T} E_{GP}(t)}{\sum_{t=1}^{T} D(t)} \quad (64)$$ where $GPAP$ is grid power absorption probability, T is the operating time (T=8760 h) for one-year analysis), $E_{GP}(t)$ is the purchased electricity over period T, $D(t)$ is the total load required over period T
[30]	$$\min LPSP = \frac{\sum Time(if\ P_{avai}(t) < P_L(t))}{T} \quad (65)$$ where T is the number of hours in the study, $$P_{avai}(t) = P_{PV}(t) + P_{WT}(t) + P_{Bat}(t) + P_{HY}(t) \quad (66)$$
[31, 36, 48-59]	$$\min ELF = \frac{I}{N}\sum_{t=1}^{N}\frac{Q(t)}{D(t)} \quad (67)$$ where $Q(t)$ and $D(t)$ are the total load loss and the total load demand at i^{th} step-time, respectively, N is the total number of step-times. $$LOLE = \sum_{i}^{N} E[LOL(t)] \quad (68)$$ $$LOEE = \sum_{i}^{N} E[LOE(t)] \quad (69)$$ $$LPSP = \frac{LOEE}{\sum_{i}^{N} D(t)} \quad (70)$$ where $E[LOL(t)]$ is Mathematical expectation of loss of load at step-time t, $E[LOE(t)]$ is mathematical expectation of loss of energy at step-time t, $LOLE$ is Loss of load expectation, $LOEE$ is loss of energy expectation.

2.3. Environmental Pollution Optimization

The diesel generator is the major component of the HES that generates and emits pollutants (NO_x, SO_2, CO_2, CO, *HC* and *soot*) to the atmosphere. In view of this, it is encouraged to optimize the use of diesel generator at highest efficiency and reduce the number of hours of operation, so as to minimize emissions. In contrast, additional energy generation obtained from the diesel generator usually increases the magnitude of emissions. Authors in the literature have formulated different objective functions for minimization of the pollutant emissions for the optimal sizing of microgrids. The summary of the formulations of related works on this is illustrated in Table 3.

Table 3. Summary of the formulations of existing works on emissions minimization.

Reference	Objective function
[44-46]	$\min F_{emissions} = \sum_{t=1}^{T} F_{cons}(t).Ef$ (71)
[8]	$\min CO_2 = Gasoline \times EF_{Gas} + NG_y + EF_{NG} + E_{bought} \times EF_E$ (72) where, EF_{Gas} is the emission factor of gasoline, EF_{NG} is emission factor of natural gas, and EF_E is CO_2 emission produced by consumption of 1 kWh electricity.
[60]	$\min C_{co_2} = CP_{co_2}(E_i \times R_{i,co_2})$ (73) where, C_{co_2} is the gravimetric cost penalty for carbon emissions, CP_{co_2} is monetary cost of CO_2, E_i is the annual system component power consumption/utilization, R_{i,co_2} is specific CO_2 emission rate
[61]	$\min emission_i = \sum_{s=1}^{4}\sum_{t=1}^{960} E_{CO_x}(P_{Gj}) = \sum_{s=1}^{4}\sum_{t=1}^{960} Em_{fuel}.(a.P_{d(s,t)} + b.P_d^{rated})$ (74) where P_d^{rated} is the rated power; P_d is the output power of the diesel generator, and a = 0.246 (L/h) and b = 0.0845 (L/h) are the coefficients of the consumption curve
[29]	$\min Q_{de} = \sum_{j=1}^{j=n}\left[\sum_{h=1}^{h=8760}(w_1\zeta SO_2 + w_2\zeta NO_x + +w_3\zeta CO_2 + w_4\zeta CO + w_5\zeta Dust)P_{de,j,h}\right]$ (75) Where Q_{de} is pollutant emissions, w_1, w_2, w_3, w_4, w_5 are weights of pollution emissions; $\zeta SO_2, \zeta NO_x, \zeta CO_2, \zeta CO, \zeta Dust$ are airborne pollution emissions per unit energy (kg/L)

2.4. Other Factors

In order to further improve the reliability of the HES, other criteria such as renewable energy ratio and power losses, among others, have been formulated by different authors in the literature. The summary of formulation of related work on other criteria is presented in Table 4.

Table 4. Summary of formulation of related work on other criteria.

Reference	Objective function
[62]	$$F = \min\left[120\sum_{j=1}^{NY}\sum_{t=1}^{24}(P_{LOSS,sum}+P_{LOSS,mon}+P_{LOSS,win}\right] \quad (76)$$ where, $P_{LOSS,sum}, P_{LOSS,mon}, P_{LOSS,win}$ are losses of summer, monsoon and winter seasons. $$P_{LOSS} = \sum_{i=0}^{n-1} I_i^2 r_i \quad (77)$$ where, I_i *i* and r_i gives the gives the branch current and resistance respectively
[8]	$$\max RER = \frac{\text{Re}\, newbleEnergy}{\text{Pr}\, imaryEnergy} \quad (78)$$ RER is renewable energy ratio
[29]	$$\max \lambda_{re} = \frac{\sum_{j=1}^{j=n} E_{re,j}}{n.E_{tot}} = \frac{\sum_{j=1}^{j=n} E_{wt,j} + E_{pv,j}}{n.E_{tot}} \quad (79)$$ where λ_{re} is renewable energy penetration level, $E_{wt,j}$ is total annual energy generation of wind turbine, $E_{pv,j}$ is total annual energy generation of PV

3. OPTIMUM SIZING METHODS FOR HYBRID ENERGY SYSTEMS

Several research works have been carried out over the years on optimal sizing of HES using different approaches. The approaches used by authors in this research area are discussed in this section. The summary of the literature reviewed on optimum sizing of HES is presented in Table 5.

3.1. Classical Optimization Algorithm

In classical optimization algorithms, the differential calculus are often used to find optimum solutions for functions that are differentiable and continuous, since they have restricted abilities for functions with non-differentiable or non-continuous objective functions. Several classical optimization techniques have been used by different authors for sizing of microgrid/HES. Examples of classical optimization algorithms that have been popularly used by authors for optimal sizing of HESs/microgrid in the literature are: linear programming model (LPM), dynamic programming (DP) and non-linear programming (NLP) [63].

An optimization method for a system of linear objective functions and constraints is called linear programming. The purpose of linear programming is to obtain the values of the variables that maximize or minimize the linear objective function subject to linear constraints (equality and inequality). Examples of such method can be found in [64- 67]. In NLP, it is either both the objective functions and constraints or one of them constitutes the nonlinear segment, of which a few examples can be found in [19, 68]. DP is a technique based on division of the optimization problem into minor sub-problems. In other words, it is a technique for dealing with a complex problem by splitting it into a group of easier sub-problems, working out each of the sub-problems once, and loading their solutions. Example can be found in [69-71].

Table 5. Summary of objective functions, HES components and approaches reported in the literature.

Author	MOP/SOP	PB/NPB	Objective function(s)	Components of HES	Optimization technique(s)	Remarks
[90]	SOP	NPB	Minimization of the total net present cost of the system.	PV, Diesel, Battery	GA	Application to real-life is limited since only one objective function and static load model were considered.
[7]	SOP	NPB	Minimization of total net present cost of the system	Fuel cell, WECS Electrolyzer, Reformer, anaerobic reactor, Hydrogen tank	PSO	The results are impressive as the excess energy is converted to hydrogen. However, application to real-life scenarios is limited since only one objective function and static load model were considered.
[3]	MOP	NPB	Minimization of levelized cost of energy, and loss of power supply probability.	PV, WECS, Diesel, Battery	PSO	The design is complex though results show that the MOPSO optimization model produce appropriate sizing of the components for each location.
[21]	SOP	NPB	Minimization of the system life cycle cost	PV, WECS	GA	Application to real-life scenarios is limited since only one objective was considered.
[91]	MOP	PB	Minimization of the system life cycle cost, pollutant emissions, and maximization of quality of load serve	PV, WECS, Battery,	PSO	Good results are delivered though only static load model was considered.
[92]	SOP	NPB	Minimization of the system life cycle cost	PV, WECS	GA	Application to real-life is limited since only one objective function and static load model were considered.
[46]	MOP	NPB	Minimization of system total cost, unmet load, and fuel emissions	WECS, PV, fuel cells, electrolyzers, diesel generators, hydrogen tanks, and batteries	DEA/Fuzzy technique	Good results are delivered though only static load model was considered.

Table 5. Summary of objective functions, HES components and approaches reported in the literature-Continued(1)

Author	MOP/SOP	PB/NPB	Objective function(s)	Components of HES	Optimization technique(s)	Remarks
[93]	MOP	PB	Minimization of loss of power supply probability, system life cycle cost, system embodied energy	PV, WECS, Battery	GA	Good results are delivered.
[94]	MOP	PB	Minimization of system life cycle cost, and maximization of availability of the generated electricity	PV, WECS, Battery	MOGA	Energy demand-supply match was not considered as a criterion to maximize the reliability of the system in order to satisfy a given demand.
[95]	MOP	PB	Minimization of total system cost, and maximization of system reliability	WECS, PV and Storage batteries	CMIMOPSO	Good results are delivered.
[96]	MOP	PB	Minimization of cost of energy, and total GHG emissions	WECS, PV, FC, Diesel generator and Storage batteries	NSGA	Good results are delivered.
[97]	MOP	PB	Minimization of fuel cost, and pollutant emissions	WECS, Diesel generator	MOGA	Good results are delivered.
[98]	MOP	NPB	Minimization of operation cost, CO_2, and maximization of energy saving	PV, Solar collector, Diesel generator	Simulation	Good results are delivered.
[8]	MOP	PB	Minimization of total NPC, CO_2 emission, and maximization of renewable energy ratio	Heat pump, biomass boiler, WECS, Solar heat collectors, PV, heat storage tank.	DMOPSO	Good results are delivered.

Table 5. Summary of objective functions, HES components and approaches reported in the literature-Continued(2)

Author	MOP/SOP	PB/NPB	Objective function(s)	Components of HES	Optimization technique(s)	Remarks
[99]	MOP	NPB	Minimization of total NPC, greenhouse gases emissions, and maximization of renewable energy ratio	PV, WECS, batteries, and diesel generator	Simulation	Hourly load data was not considered in the model though good results are delivered.
[61]	MOP	NPB	Minimization of the investment cost, fuel cost, and CO_2 emissions	PV, diesel generator	PSO	Good results are delivered.
[100]	MOP	PB	Minimization of cost, fuel emissions, and maximization of reliability/renewable ability	PV, WECS, batteries, and diesel generator	MOEA/D	Good results are delivered though energy demand-supply match was not considered as a criterion to maximize the reliability of the system to satisfy a given demand.
[101]	MOP	NPB	Minimization of cost of energy Minimization of dummy load Maximization of reliability	PV, WECS, batteries, and diesel generator	Iterative	Good results are delivered though energy demand-supply match was not considered as a criterion to maximize the reliability of the system in to satisfy a given demand.
[102]	MOP	NP	Minimization of overall annual cost, and of pollutant emissions	PV, WECS, batteries, and diesel generator	Clonal Selection Algorithm and Genetic Algorithm	Good results are delivered though the system reliability was not considered.
[103]	MOP	PB	Minimization of annualized cost of system, loss of power supply probability, and fuel emissions	PV, WECS, batteries, and diesel generator	PICEA	Good optimal sizing performance is found by the proposed method, which results in high performance despite its simplicity.
[6]	MOP	NPB	Minimization of annualized cost of system, and loss of power supply probability	PV, WECS, batteries	GA	Good optimization performance is found.

Table 5. Summary of objective functions, HES components and approaches reported in the literature-Continued(3)

Author	MOP/SOP	PB/NPB	Objective function(s)	Components of HES	Optimization technique(s)	Remarks
[104]	SOP	NPB	Minimization of total annualized cost	PV, WECS, batteries	Grey Wolf Optimizer	Application to real-life scenarios is limited since only one objective was considered.
[105]	MOP	NPB	Minimization of cost of energy, and maximization of power availability	PV, WECS, batteries	Simulation	The analysis was done in MATLAB to simulate the model performance.
[106]	SOP	NPB	Minimization of cost of energy	WECS, Hydropower Systems	Simulation	Application to real-life is limited since only one objective function and static load model were considered
[107]	MOP	PB	Minimization of: Cost of network upgrading, Cost of power losses, Cost of energy not supplied, Cost of energy required by the served customers	Sizing and Siting of Distributed Generation	GA and ε-constrained	Promising results were delivered
[108]	SOP	NPB	Minimization of the network real power losses	Sizing and Siting of Distributed Generation	ACO	Application to real-life is limited since only one objective function and static load model were considered
[22]	MOP	PB	Minimization of grid power absorption probability (GPAP), and total cost of the grid connected hybrid system	PV, WECS, batteries	cuckoo search	Good results were delivered
[29]	MOP	NPB	Minimization of life cycle cost, maximization of renewable energy source penetration, and minimization of pollutant emissions	PV, WECS, batteries, and diesel generator	GA	Promising results were delivered Energy demand-supply match was not considered as a criterion to maximize the reliability of the system in to satisfy a given demand.
[30]	MOP	NPB	Minimization of annual system cost and loss of power supply probability	PV, WECS, batteries, Hydrogen system	ACO	A promising result was delivered by utilizing the excess power.Life span of the selected battery is too short.

3.2. Simulation and Optimization Software

The available simulation programs that are commonly used for optimal sizing of HES are Hybrid Optimization Model for Electric Renewable (HOMER), RETScreen, HYBRID2, Hybrid Optimization by Genetic Algorithms (HOGA) and HYBRIDS.

3.2.1. HOMER

The HOMER software produced by National Renewable Energy Laboratory (NREL) is a micro power optimization model that can evaluate a range of equipment options over varying constraints to optimize small power systems. It is the most-popular simulation and optimization software for HESs.

HOMER can simulate the operation of thousands of different system designs, with and without a backup generator. It is one of the most preferred commercially available optimization tools in the open literature. It uses hourly load and environmental data for arriving at optimum target. It identifies the least cost system as a function of load size and other variables. HOMER has been used extensively for optimal sizing of standalone HES. Although simulations can take a longer time, depending on the number of variables used, its operation is simple and straightforward. The program's limitation is that it does not enable the user to intuitively select the appropriate components for a system, as algorithms and calculations are not visible or accessible [1]. Case study examples can be found in [72- 85].

3.2.2. HYBRID2

The HYBRID2 is the hybrid power simulation model software that was jointly developed by the researchers from the NREL and the University of Massachusetts (UMass). It is a time-series/probabilistic model that uses time-series resource and load information, combined with statistical analysis, and manufacturer's data for hybrid system equipment to accurately predict the performance and cost of hybrid power systems [86]. It is a user-friendly tool that allows for the direct comparison of many different renewable and non-renewable power system designs. NREL recommends using Hybrid2 to improve the optimal results of HOMER. The simulation time step range between 10 min and 1 hour. Hybrid2 can study a wide variety of hybrid power systems which may include three types of electrical loads, multiple wind turbines of different types, photovoltaics, multiple diesel generators, battery storage and four types of power conversion devices. Moreover, the systems can be modeled either on the AC or DC, or both buses [86].

3.2.3. HOGA

HOGA software was developed in C++ by researchers of the University of Zaragoza, Spain for the simulation and optimization of HES. The software can model systems with DC or AC electrical energy consumption and Hydrogen. The sizing components considered in the package include photovoltaic generator, wind turbines, hydroelectric turbine generator, auxiliary generator, diesel generator, inverter, batteries (lead acid or lithium), charger, batteries charge controller, components of hydrogen, among others. It can simulate and optimize systems of any size that is either connected to the grid or stand alone. The optimization is carried out by means of GA, and can be mono-objective or multi-objective [1]. The simulation is carried out using 1-h intervals, during which all of the parameters remained constant [1]. HOGA makes use of advanced models to calculate the lifetime of the batteries, which are considered the most costly and most frequent replacements component.

3.2.4. RETScreen

RETScreen, a Clean Energy Project Analysis Software, is a decision support tool which was originally developed by Natural Resources Canada in 1996 with relevant input from government, university researchers and industries. The software can be used to evaluate the energy generation and savings, energy costs, CO_2 emissions reduction, economic viability and risk for various types of Renewable-energy and Energy-efficient Technologies (RETs). RETScreen is not interested in the total costs, but contrarily, the costs of the proposed case that are in surplus of those for the base case. Here, the energy benefits are the same for both the base case and the proposed case.

For instance, if a proposed on-grid solar park generates 100,000 MWh annually, is compared to 100,000 MWh of electrical energy from conventional sources available through the grid, the cost of a unit of energy cannot be the same for the two cases. In most cases, the proposed case will have higher initial but lower annual operation and maintenance costs. Consequently, RETScreen's analysis is to check if the balance of costs and savings over the life span of the project makes a financially interesting proposition. RETScreen software can analyze more than 40-year time-horizon by using monthly or yearly time-steps. Examples can be found in [87-88].

3.2.5. HYBRIDS

HYBRIDS is a commercially available application that was produced by Solaris Homes. It assesses the technical potential of a renewable energy system for a given configuration and determines the potential renewable fraction. It is also used to evaluate the economic viability using the Net Present Cost analysis [1]. HYBRIDS is a Microsoft Excel spreadsheet-based renewable energy system assessment application and design tool, requiring daily-average load and environmental data estimated for each month of the year [1]. Because HYBRIDS is not designed to produce an optimised configuration like HOMER, it can only simulate one configuration at each time step. Notwithstanding, it is comprehensive in terms of renewable energy system variables and the level of detail required. For this reason, HYBRIDS requires a higher level of knowledge of renewable energy system configurations than HOMER. It is designed so that the user enriches his/her renewable energy system design skills through its application.

3.3. Modern Optimization Algorithms

An optimization algorithm is generally used to solve optimization problems. It is a technique that is executed repetitively by likening different kinds of solutions until an optimum solution is found. Optimization algorithm is required in order to properly and economically harness the potential of renewable energy resources. In order to guarantee the minimum system investment costs, a good optimization algorithm is required. Meanwhile, the sufficiency of the algorithm is a function of the formulation and formulation procedure also depends on the chosen algorithm itself. As the number of optimization variables increases, so also is the number of simulations exponentially, with a consequent increase in time and the effort required. It, therefore, becomes imperative for system designers to find a feasible optimization technique that can select the optimum system configurations quickly and accurately [1]. Generally, optimization algorithms are divided into two main types which are Deterministic and Probabilistic Algorithms [89]. Classification of optimization algorithms based on operation method is presented in Fig. 2. However, it should be noted that the classification here is not exhaustive.

Fig. 2. Classification of optimization algorithms based on operating principles.

3.3.1. Deterministic Algorithm

A deterministic algorithm is an algorithm that behaves expectedly. In simple terms, it is an algorithm whose behavior can be completely predicted from the input. In a deterministic algorithm, there must be a maximum of one way to advance for each implementation step. Contrary to this, it means the algorithm has come to an end. One of the advantages of deterministic algorithms is that they can run efficiently on real machines. By this virtue, they are the most practical and most studied kind of algorithm.

3.3.2. *Probabilistic Algorithm*

Probabilistic algorithms are stochastic in nature. These algorithms have added advantages over deterministic algorithms because of certain features which deterministic algorithms lack. If for instance, the correlation between the solution candidate and its fitness is complex, then they cannot be carried out using deterministic algorithm. To solve such problems, stochastic algorithms which use some types of randomness are recommended [89]. A probabilistic algorithm consists – minimum - of one instruction that operates based on random numbers that are the constraint of deterministic algorithm and disregarded in probabilistic algorithm. A good example of probabilistic algorithms is genetic algorithm where solutions in the program will be dissimilar at each time step the program is run. In terms of performance, the probabilistic algorithms run speedily than any best deterministic algorithm. Also, in terms of simplicity, the probabilistic algorithms are easier in description and implementation than deterministic algorithms of analogous performance. However, their finishing outcome does not have much variation.

Majorly, there are two categories of probabilistic algorithms Las Vegas versus Monte Carlo algorithms and heuristic versus metaheuristic.

a) Las Vegas Algorithms: These are randomized algorithms that may not return a solution whatsoever, and if they do, the solution is always guaranteed to be true. In other words, these algorithms can never return an incorrect result; instead they will fail to proceed. Since they normally have an anticipated execution time, their termination cannot be guaranteed. Las Vegas algorithm can be converted to a Monte Carlo algorithm through early termination by applying Markov's inequality. However, the solution may not be correct with a small probability.
b) Monte Carlo algorithms: These are randomized algorithms whose answer may not be exact with a small probability. In other words, they may return an answer that is not exact. The name "Monte Carlo" refers to the grand casino in the Principality of Monaco at Monte Carlo, which is popularly-known globally as a portrait of gambling. It was introduced first in the year 1947 by Nicholas Metropolis. As it is possible in Las Vegas algorithm, it is not likely for a Monte Carlo algorithm to be changed to a Las Vegas algorithm even if at all there is a method to confirm that the result generated by the algorithm is truly correct. Generally, Monte Carlo algorithms can be used to deal with problems with probabilistic analysis.
c) Heuristic algorithms: A heuristic algorithm is a method that is designed to deal with problems more rapidly when classic methods are too gentle. It is used to determine the near optimal solution when a classic technique is unsuccessful in finding any precise solution. Generally, it can be regarded as a shortcut. They can also be described as an

algorithm to find out solution by trial and error. A relevant example is the travelling salesman problem.

d) Metaheuristic algorithms: A metaheuristic is also a heuristic, but a great one, because of the presence of the procedure to prevent it from being stuck in a local minimum. In another way a metaheuristic is a technique used to solve broad classes of problems. It combines heuristic or objective functions in a synopsis and effective way, normally, without making use of profounder comprehension into their structure. Invariably, a metaheuristic algorithm addresses problems like a black-box event. They plan to explore a search space and find a best solution. Ant colony algorithm, particle swarm optimization, hill climbing, tabu search, simulated annealing, genetic algorithms are examples of metaheuristic algorithms.

4. CONCLUSIONS

This paper has presented a critical review of various objective functions (economic, technical, environmental and other) as well as different methods used for optimal sizing of HES. The approaches proposed by different authors for the optimal sizing of HES were extensively discussed. The optimum sizing techniques have been categorized as single-objective versus multi-objective optimization technique, and Pareto-based versus non-Pareto-based optimization techniques. Optimum sizing methods for HES were classified into classical, simulation and optimization software, and modern optimization methods. As a constrained optimization problem, HES may be sized with classical optimization algorithms such as Linear Programming, Non-Linear Programming, and Dynamic Programming.

However, due to the intermit nature of renewable energy sources and nonlinearity of electrical energy demand, it can be concluded that the classical optimization techniques failed the accuracy test. By considering nonlinear algorithms and integer variables, the running time will be much longer, even as the algorithm becomes less robust. In contrast, the modern algorithms such as PSO, EA, ACO, GA can give good solutions and address the integer variable issue perfectly. The exact sizing of HES can greatly help to determine the required initial capital investment in addition to maintaining the system's reliability at a reduced cost. Parameters considered in the study included cost of energy, system's reliability, and greenhouse gas emissions reduction.

By way of recommendation, the authors of the present work are of the opinion that the most promising economical criterion that could be considered in conjunction with the appropriate reliability and environmental factors for optimal sizing of HES for future research works is the levelized cost of energy. This is a quick means by which the profit of power distribution utilities could be determined while it satisfies system constraints.

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