Multi-Objective Optimal Economic Dispatch of a Fuel Cell and Combined Heat and Power Based Renewable Integrated Grid Tied Micro-grid Using Whale Optimization Algorithm

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Abstract

Micro-grids are practical solution for combining distributed energy resources and combined heat and power units in order to satisfy the system power and heat demands. Nowadays, in order to integrate both renewable and non-renewable energy resources like photovoltaic, wind turbine, combined heat and power systems and fuel-cell unit; micro-grid seems to be a good idea. The aim of this paper is to obtain optimal scheduling of proposed generating units and to reduce the total operational cost and net emission of the system through economic/environmental power dispatch, while considering the impact of grid tied and autonomous mode of operation and satisfying the operational constraints. In this paper, a novel whale optimization algorithm is employed to solve this multi-objective problem. The obtained optimal results through this proposed whale optimization algorithm represents the efficiency, feasibility and capability of handling non-linear optimization problems in

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an efficient way compared to other optimization techniques. The proposed system is studied in a 24-h time horizon. The results obtained from this proposed technique are compared with other techniques which are recently employed.

Keywords: Combined heat and power scheduling, fuel cell, micro-grid, multi-objective, whale optimization algorithm.

1 Introduction

In recent days, micro-grids are effective solution for combining both renewable and non-renewable energy resources and several types of energy sources including CHP [1, 2]. This proposed multi-objective economic /environmental dispatch problem of micro-grid plays an important role for smart grid management or micro-grid central control in which the optimized scheduling of all integrated sources are determined while considering the impact of RES's, CHP and satisfying all operational constraints, to reduce the total operation cost and net emission of MG. Nowadays, the researchers are focused towards the integration of RES with CHP in micro-grid system. Because of the micro-grid as reasonable practical solutions for combining DER's for satisfying heat and power demands of load, either it can be operated in autonomous or grid-connected modes of operation. For taking into account a micro-grid integrating with DER's, such as RES, conventional plants and CHP units, therefore considerable improvements in savings of cost and reduced amount of pollutant gas can be attained [3]. This will shows a significant improvement in cost saving 10–40% [4], and emission reduced by 13–18% [5]. In [6] described a residential energy management operation considering of CHP, energy storage and fuel cell in order to optimized scheduling of the proposed units for satisfying both heat and electrical demands. In reference [7, 8] used renewable sources can reduce the total emission of the power system. The authors was explained short term scheduling of CHP units, it increase total system efficiency [9]. In [10] described economic dispatch of combined heat and power units is a non-convex, non-linear problem, integration of these units with other units are challenging one. In Refs. [11, 12] benders decomposition approach, lagrangian relaxation and branch and bound techniques are used to solve these non-convex problems.

The proposed model of micro-grid studied in this paper consisting of RES's (like photovoltaic system, wind generation systems, fuel cell, power only unit and CHP units are under the operation of grid connected and autonomous mode. The main contribution of this paper is, to optimize the total operation cost and emission of proposed micro-grid in a way that both RES's and CHP's contribute to reduce the total operation cost of micro-grid as well as the emission minimized by integrated CHP units and other system constraints are met. A recently developed whale optimization algorithm (WOA) is used in this paper to solve this proposed multi-objective problem. So this paper is formulated as a multi-objective framework and economic/environmental scheduling of a micro-grid has been solved in this paper.

The remaining of this paper is categorized as follows:

Economic/environmental dispatch problem is formulated in Section 2 and Section 3 includes the brief description of proposed whale optimization algorithm. Section 4 shows the data's utilized in this system. Section 5 presents the simulation results obtained with detailed discussion. Finally, the conclusions are provided in Section 6.

2 Problem Formation

A renewable integrated CHP based MG including photovoltaic system, wind turbine, fuel cell, conventional power generation unit and combined heat and power units. The total operation cost and emission of above mentioned units as formulated as two objectives of this proposed problem can be modeled as below mentioned:

$$Min(F_1) = \sum_{x=1}^{N_p} C_{x,t}^{p} + \sum_{y=1}^{N_c} C_{y,t}^{c} + \sum_{z=1}^{N_{FC}} C_{z,t}^{FC} \tag{1}$$

$$Min(F_2) = \sum_{x=1}^{N_p} E_x(P_{x,t}^{p}) + \sum_{y=1}^{N_c} E_y(p_{y,t}^{c}, H_{y,t}^{c}) + \sum_{z=1}^{N_{FC}} E_z^{FC} \tag{2}$$

where, F_1 – Operation cost of generation units; F_2 – Amount of emission emitted by generation units; x, y, z – Conventional power unit, combined heat and power units and fuel-cell unit indices, respectively; N_p, N_c, N_{FC} – Total number of available conventional power generation unit, CHP and fuel-cell units respectively; $C_{x,t}^{p}$, $C_{y,t}^{c}$, $C_{z,t}^{FC}$ – Cost functions of PO, CHP and FC unit respectively; $E_x(P_{x,t}^{p})$, $E_y(p_{y,t}^{c}, H_{y,t}^{c})$, E_z^{FC} – Emission functions of PO, CHP and FC unit respectively; $P_{x,t}^{P}$, $P_{y,t}^{C}$ – Generated output power of xth conventional power generation unit and yth CHP unit, respectively; $H^{C}_{y,t}$ – Output heat produced by yth CHP unit.

2.1 Renewable Energy Integration

Due to the integration of Renewable energy resources into micro-grid the cost of fuel and amount of emission emitted can be reduced [14]. The inclusion of maximum available renewable generated power reduced the other generating units demand and increase the system efficiency. Because the renewable resources are very clean and inexhaustible power of nature, so it is increase the total system efficiency. It neither incurs any fuel cost and nor does it emits any harmful pollutants in atmosphere. In this proposed work will explain and used wind and solar energy. This can be extended with some other algorithm for further research.

2.2 Conventional Power Generation Unit

Conventional power plant is the overall term applied to the production of electrical energy from coal, oil, or petroleum gas utilizing the delegate of steam. The generator is typically a synchronous machine having small shafts and running at high rates (1500–3600 rpm). The power plant itself should be helpful financially and natural amicable to the general public. The general productivity of energy change from fuel to electrical is extraordinarily impacted by the proficiency of the turbine and condenser. Regular in general effectiveness goes from 30% to 40%. The fundamental elements of these traditional plants are their low capital expense per kilowatt introduced when contrasted with different plants and for all intents and purposes no restriction on their size. The generation cost function of the proposed conventional power generation unit x at time *t* is considered as follows [15]:

$$C_x(P^p_x) = \varphi_x(P^p_{x,t})^3 + \alpha_x(P^p_{x,t})^2 + \beta_x P^p_{x,t} + \gamma_x \qquad (3)$$

where, φ_{x}, α_{x}, β_{x}, γ_{x} – Cost coefficients of xth conventional power generation unit.

2.3 Combined Heat and Power Units

Cogeneration or combined heat and power is the use of a heat engine or power station to produce electricity and useful heat at the same time. Cogeneration is a more efficient use of fuel or heat, because otherwise-wasted heat from electricity generation is put to some productive use. CHP plants recover the wasted thermal energy for heating. This is also called combined heat and power district heating. Small plants are an example of decentralized energy. By-product thermal heat energy at moderate temperatures (100–180°C, 212–356°F) can also be used in absorption refrigeration system for cooling. The supply of high-temperature heat initially drives a gas or steam turbine-powered generator. The resulting low-temperature waste heat is then used for water or space heating. At smaller scales a gas engine or diesel engine may be used. CHP is one of the most cost-efficient methods of reducing carbon emissions from heating systems. CHP plants based on a combined cycle power unit can have thermal efficiencies above 80%. The cost functions of proposed three combined heat and power units are described as follows [15]:

$$C_y(P^c_{y,t}, H^c_{y,t}) = a_y(p^c_{y,t})^2 + b_y p^c_{y,t} + c_y + d_y(H^c_{y,t}) + e_y H^c_{y,t} + f_y p^c_{y,t} H^c_{y,t} \tag{4}$$

2.4 Fuel Cell

Fuel cell is an electrochemical device that produces electrical energy from the conversion process of chemical energy, through a pair of redox reaction. It produces electrical energy, heat energy and water when it's reacted hydrogen with oxygen. For continuous production of electrical energy fuel cell required a continuous source of input fuel and oxygen. For it is continuous operation, usually oxygen taken from air. It produces continuous electricity as long as input fuel and oxygen are provided. Fuel cell is one of the efficient systems for producing electrical energy, compared with other fossil-fuel energy sources.

$$C^{FC}_{z,t} = \sum_{z=1}^{N_{FC}} b_{FC,t} P^{FC}_t \tag{5}$$

where, $b_{FC,i}$ – Cost coefficients of zth fuel-cell unit; $\theta^{FC}_i, \eta^{FC}_i, \psi^{FC}_i$ – Emission coefficients of zth fuel-cell unit.

2.5 Emission Functions

A fundamental issue in regards to the present electrical generation strategies being used today is the critical negative environmental impacts that a considerable lot of the generation processes have like fossil fuels, coal and gas not only discharge carbon dioxide as they combust, yet their extraction from the beginning effects the environment. The corresponding emission functions of the proposed conventional power generation unit, combined heat and power units and fuel-cell unit can be expressed as follows:

$$E_x(P_{x,t}^p) = \alpha_x (P_{x,t}^p)^2 + \beta_x P_{x,t}^p + \gamma_x + \lambda_x \exp(\rho_x P_{x,t}^p) \tag{6}$$

$$E_y(P_{y,t}^c, H_{y,t}^c) = a_y P_{y,t}^c \tag{7}$$

$$E_z^{FC} = \sum_{z=1}^{N_{FC}} (\theta_t^{FC} + \eta_t^{FC} + \psi_t^{FC}) p_t^{FC} \tag{8}$$

2.6 Constraints

In this formulation the total summation of produced electrical and heat energy should be satisfy the electrical and heat demand constraints as in (9) and (10) respectively.

$$\sum_{x=1}^{N_p} P_{x,t}^p + \sum_{y=1}^{N_c} P_{y,t}^c + P_{PV,t} + P_{W,t} + P_{FC,t} = P_{D,t} \forall\, t \tag{9}$$

$$\sum_{y=1}^{N_c} H_{y,t}^c = H_{D,t} \forall\, t \tag{10}$$

P_t^{PV}, P_t^{WT} and P_t^{FC} – Generated output power of photovoltaic, wind turbine and fuel cell unit at time *t; $P_{D,t}$, $H_{D,t}$* – Total load demand and heat demand of the system in time *t*. The minimum and maximum limit functions of electrical and heat energy related to conventional power generation unit, photovoltaic system, wind turbine, fuel cell and combined heat and power units should be considered as follows:

$$P_t^{pv,\min} \leq P_t^{pv} \leq P_t^{pv,\max} \tag{11}$$

$$P_t^{wt,\min} \leq P_t^{wt} \leq P_t^{wt,\max} \tag{12}$$

$$P_x^{p,\min} \leq P_{x,t}^p \leq P_x^{p,\max} \tag{13}$$

$$P_y^{c,\min}(H_{y,t}^c) \leq P_{y,t}^c \leq P_y^{c,\max}(H_{y,t}^c) \tag{14}$$

$$H_{y,t}^{c,\min}(P_{y,t}^c) \leq H_{y,t}^c \leq H_{y,t}^{c,\max}(P_{y,t}^c) \tag{15}$$

$$P_z^{FC,\min} \leq P_{z,t}^{FC} \leq P_z^{FC,\max} \tag{16}$$

Where, $P_x^{P,min}$, $P_x^{P,max}$, $P_y^{c,min}$, $P_y^{c,max}$, $P_t^{PV,min}$, $P_t^{PV,max}$, $P_t^{WT,min}$, $P_t^{WT,max}$ and $P_z^{FC,max}$, $P_z^{FC,min}$ Minimum and maximum power output of xth conventional power generation unit, yth CHP unit, photovoltaic, wind turbine and zth fuel cell unit respectively; $H_y^{c,min}$, $H_y^{c,max}$ – Minimum and maximum amount of heat produced by yth CHP unit.

3 Implementation of Whale Optimization Algorithm

In this proposed nature inspired algorithm are used to solve the non-linear optimization problem by physical phenomenon of humpback whales [13]. In this present work explains a recently proposed algorithm, named as WOA. The proposed nature inspired algorithm characteristics are depend upon the behavior of hunting approach of whales. The most interesting characteristics of humpback whales are special way of hunting the prey.

3.1 Encircling Prey

The nature that has the whales to locate the place of targeting prey and surrounds the prey. Hence the placement of the feasible output is in given solution is unknown priori. So the proposed WOA is consider the present suitable carrier solution as achievement prey, otherwise it is very nearer to optimal solution. After the suitable carrier is identified, the remaining all other carrier will become tries to upgrade myself in such a way of that suitable carrier. The below equations are represents the strategy stated here,

$$D = |B \cdot Y * (t) - Y(t)| \tag{17}$$

$$Y(t+1) = Y * (t) - A.D \tag{18}$$

where *t* indicates present iteration; *A* and *C* are coefficients; Y^* location of the better solution obtained so far; *Y* is the present position of whale. Therefore *A* and *C* values are obtained from:

$$A = 2a \cdot r - a \tag{19}$$

$$C = 2 \cdot r \tag{20}$$

3.2 Bubble-net Attacking Method

The bubble-net attacking strategy inspires this proposed optimization procedures. This is the special interesting hunting strategy of humpback whales.

school of krill or tiny fishes nearer the place is selected by whales to be hunted, where it seems to be created a circle shape or nine shaped route. This is an unique way for treatment assess by whales. This proposed technique is based on this strategy is summarized as below as follows. There are two ways are used to represents the model of air bubble net treatment of whales is mentioned here below:

3.2.1 Shrinking encircling mechanism

Equation (19) simply represents this proposed concept. The value of A should be reduced from 2 to 0. According the above value of *A*, the change in value of *A* is to be reduced. The values are randomly selected between [−a, a]. These intervals and between [−1, 1] the better location of search agent has to be selected.

3.2.2 Spiral updating position

The distance between the humpback whales and the prey located is (X, Y) and (X^*, Y^*) respectively. The position between the whale and prey represents the spiral path. This is shown in below Equation (21).

$$Y(t+1) = D' \cdot e^{bl} \cdot \cos(2\pi l) + Y*(t) \tag{21}$$

where, b is a constant for represent the position of the logarithmic spiral, l denotes a random value between [−1,1]. There is a 50% probability is assumed to select the two approaches as are shown below:

$$Y(t+1) = \begin{cases} Y*(t) - A \cdot D & \text{if } p \leq 0.5 \\ D'e^{bl} \cdot COS(2\pi l) + Y*(t) & \text{if } p \geq 0.5 \end{cases} \tag{22}$$

where, the random number of p is between [0, 1]. In sum of this bubble-net method, whales are randomly found out for their prey.

3.3 Searching for Prey

Humpback whales pursue their preys without any definite aim, as per the place of each other's. The difference of the value of vector A is -1 or less than 1 it makes the search agents to move away from reference whale. The location of search agent has been upgraded in the investigation stage as per a randomly picked search agent rather than the better pursuit agent discovered in this way. This scheme and $|\mathrm{A}| > 1$ highlight investigation and tolerate the WOA calculation to perform a global pursuit.

$$D = |B \cdot Y\, rand - Y| \tag{23}$$

$$Y(t+1) = Y\, rand - A \cdot D \tag{24}$$

The flowchart describing various computational steps involved in WOA for environmental based economic dispatch of typical MG arrangements are shown in Figure 1.

4 Case Study

The proposed test system of this paper is including photovoltaic system, wind turbine, fuel cell, conventional power generation unit and combined heat and power units. Data's utilized in conventional power generation unit, power and heat limits, coefficients of the proposed combined heat and power units and data's utilized in fuel cell unit is presented in Table 1. The day ahead forecasted output data of photovoltaic and wind systems are from [16]. The cost of upstream power from utility grid is presented in Table 2. Finally, the electrical and heat demand of renewable integrated combined heat and power based MG system is presented in Table 3.

5 Simulation Results

In this section, the numerical simulation results obtained in combined economic/environmental dispatch of renewable integrated CHP based MG test system have been presented. In this paper, three case studies are investigated, namely operation of renewable integrated CHP based MG in connected mode is presented in case 1, operation of renewable integrated CHP based MG in autonomous mode is presented in case 2 and operation of renewable integrated CHP based MG in autonomous mode of operation with weighting factor is presented in case 3. To solve the proposed problem, MATLAB environment has been used and installed in a personal computer with 2.53 GHz core i7 processor 5th generation and 8 GB of RAM in addition with 250 GB of SSD. The program is run with 100 iterations for 30 repeated trials and the same will do for all the other technique used.

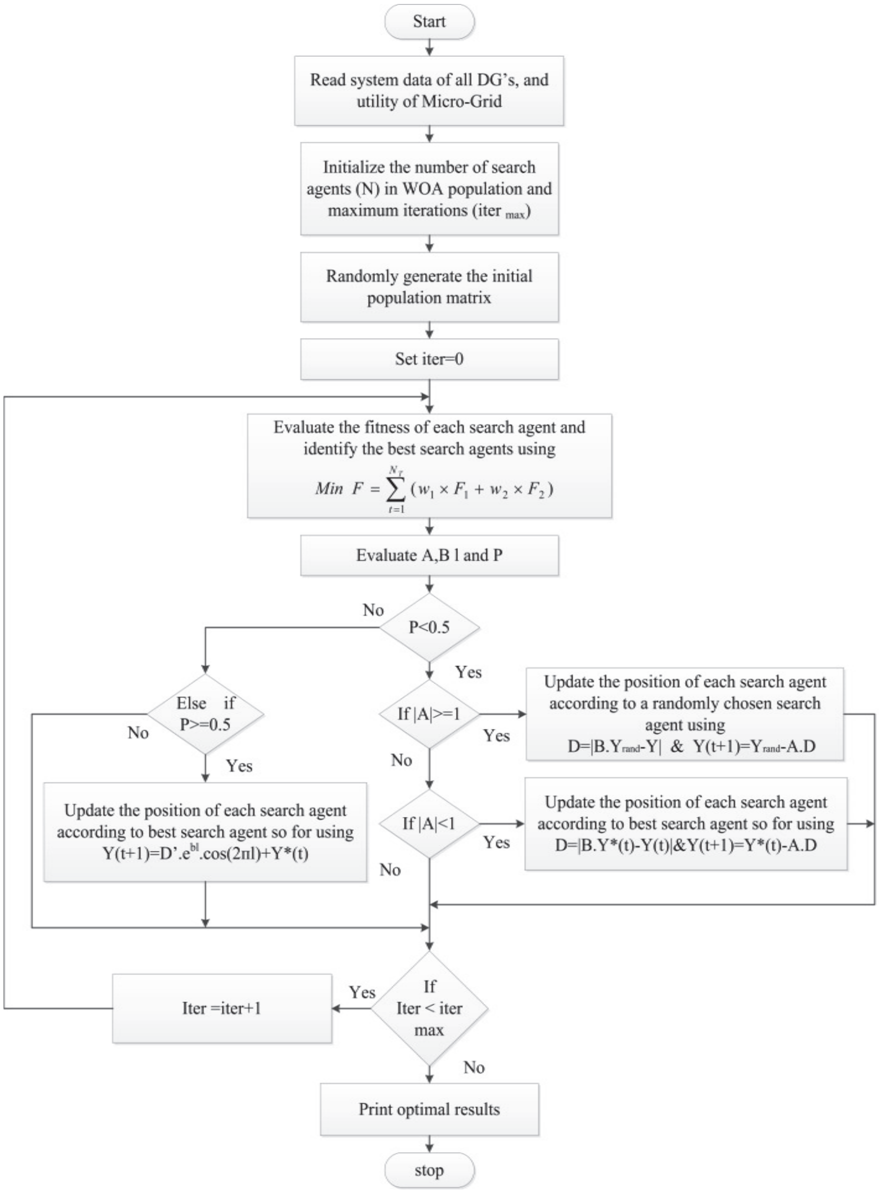

Figure 1 Flowchart for proposed whale optimization algorithm.

Table 1 Parameters of installed DG sources

Power Only Units						
Unit	ϕ_x ($\$/MW^3$)	α_x ($\$/MW^2$)	β_x ($\$/MW$)	γ_x ($\$$)	$P_{min}(MW)$	$P_{max}(MW)$
1	0.000115	0.00172	7.6997	2.5489	35	135
CHP Units						
	a_y	b_y	c_y	d_y	e_y	f_y
2	0.0435	36	1250	0.027	0.6	0.011
3	0.1035	34.5	2650	0.025	2.203	0.051
4	0.072	20	1565	0.02	2.3	0.04
Fuel Cell						
	$b_{FC,z}$(*$/MWh*)	θ_z^{FC}	η_z^{FC}	ψ_z^{FC}	P_{min} *(MW)*	P_{max} *(MW)*
5	0.0848	0.000001814	0.000004536	0.393264585	0	6

Table 2 The real-time market prices

Time(h)	1	2	3	4	5	6	7	8
($/hr)	78	90	92	94	99	96	94	94
Time(h)	9	10	11	12	13	14	15	16
($/hr)	92	91	90.5	95	96	120	96	95
Time(h)	17	18	19	20	21	22	23	24
($/hr)	90.5	78	77	90.5	76	90.5	76	75

Table 3 Power and heat demand of micro-grid

Time (h)	Power Demand (MW)	Heat Demand (MWth)
1	260	78
2	250	90
3	250	92
4	255	94
5	280	99
6	315	96
7	350	94
8	375	94
9	380	92
10	400	91
11	300	90.5
12	370	95
13	360	96
14	360	120
15	380	96
16	400	95
17	350	90.5

(*Continued*)

Table 3 Continued

Time (h)	Power Demand (MW)	Heat Demand (MWth)
18	400	78
19	400	77
20	400	90.5
21	390	76
22	355	90.5
23	325	76
24	280	75

5.1 Case 1

In case 1 of operation discusses the renewable integrated CHP based microgrid in grid tied mode. In this mode of operation consists photovoltaic systems, wind turbines, fuel cell, conventional power generation unit, CHP units and electrical power provided by the grid network, this can be used to satisfy the electrical and heat demand of the proposed test system. The operation cost and total emission of the renewable integrated combined heat and power based MG of this mode is 318733.35$/day and 324.51kg/day respectively. It includes 32516.63$ cost of generating power from power only unit, 286054.01$ cost of generating heat and power by combined heat and power units, 80.59$ cost of electrical energy produced by fuel cell unit and 82.10$ cost of purchased power from utility grid.

The output power of utility grid, photovoltaic system, wind turbines, fuel cell, conventional power generation unit and combined heat and power units; and the output heat energy produced by proposed combined heat and power units and its corresponding cost and emissions is presented in Tables 4, 5 and 6, 7 respectively. The dispatch results of RES are presented in Table 8.

Table 4 Multi-objective economic/environmental dispatch using WOA (case 1: Total cost = 318733.35 $/day, Total emission = 324.51 kg/day)

	DG Units					
	Output power(MW)					
Time(h)	PO	CHP1	CHP2	CHP3	Grid	FC
1	135	42	18	62.702	0	0.6
2	134.98	47.643	19.142	38.69	0	1.0441
3	135	41.6	18	45.531	0	0.6
4	135	44	18	40.741	0	0.6
5	135	44	18	75.182	0	0.6
6	135	63.262	17.997	93.203	0	0.6

(*Continued*)

Table 4 Continued

	DG Units					
	Output power(MW)					
Time(h)	PO	CHP1	CHP2	CHP3	Grid	FC
7	135	95.146	14.808	78.114	0.00122	6
8	134.99	75.725	38.599	77.95	0	5.9931
9	134.38	68.237	23.95	102.97	0	5.8364
10	135	79.609	21.901	100.26	0.017885	5.9984
11	133.93	59.986	17	68.278	0	0.6
12	134.95	96.891	25.984	83.935	0	5.9402
13	134.92	47.362	31.44	99.011	0	0.9807
14	135	66.15	29.198	91.893	0.000299	0.6003
15	134.93	84.895	46.525	89.51	0	5.797
16	134.97	98.485	42.818	98.806	0	5.9074
17	134.59	86.637	31.129	81.341	0.0234	3.2729
18	135	117.38	46.5	90	0.94	6
19	135	111.47	53.784	93	0.000724	6
20	135	104.33	57	97.5	0.002701	6
21	135	109.04	46.953	92.851	0.011304	5.9954
22	135	72.675	46.5	94.507	0.007322	6
23	135	75.783	19.053	88.054	0.040356	6
24	134.98	60.132	16.619	61.693	0	5.9927

Table 5 Output heat scheduling of combined heat and power units

	DG Units		
	Output Heat (MWth)		
Time(h)	CHP1	CHP2	CHP3
1	40	0	0
2	45	0	0
3	42	0	0
4	0	0	50
5	8.0411	0	56.959
6	50.301	6.1983	13.5007
7	5.4263	23.125	46.448
8	17.585	12.447	59.968
9	78.496	6.8306	6.6737
10	29.435	1.9053	63.6596
11	74.889	8.1274	16.9838
12	83.524	2.8126	5.6635
13	90	0	0
14	88	0	0
15	9.8326	33.824	46.34

(*Continued*)

Table 5 Continued

	DG Units		
	Output Heat (MWth)		
Time(h)	CHP1	CHP2	CHP3
16	59.11	0	35.89
17	19.584	24.814	65.6
18	3.2048	48.007	63.788
19	19.778	27.412	64.81
20	48.733	15.836	30.431
21	22.251	24.381	43.369
22	14.658	47.012	23.33
23	70.583	1.4724	2.9448
24	3.6491	39.879	26.472

Table 6 Cost values of economic/environmental dispatch for 24 hrs using WOA

	DG Units					
	Cost ($/MW)					
Time(h)	PO	CHP1	CHP2	CHP3	Grid	FC
1	1356.3	2924.4	3304.5	3102.1	0	0.5202
2	1356	3169.1	3348.3	2446.6	0	0.90527
3	1356.3	2914.9	3304.5	2624.9	0	0.5202
4	1356.3	2918.2	3304.5	2499.3	0	0.5202
5	1356.3	2928.7	3304.5	3475.6	0	0.5202
6	1356.3	3835	3324.7	4094.5	0	0.5202
7	1356.3	5078.8	3265.4	3727	0.11463	5.202
8	1356.2	4259.1	4191.7	3731.3	0	5.196
9	1347.3	4181.5	3560.2	4413.3	0	5.0602
10	1356.3	4458.4	3461.7	4319.6	1.6276	5.2006
11	1340.8	3811.8	3293	3310.1	0	0.5202
12	1355.6	5473.9	3626.4	3767	0	5.1502
13	1355.1	3372.2	3837	4251.1	0	0.85026
14	1356.3	4147.6	3745.6	4010.8	0.035853	0.52046
15	1355.3	4637.4	4662.5	3932.1	0	5.026
16	1355.9	5411.2	4317	4244	0	5.1217
17	1350.3	4736.2	3933.7	3703.1	2.1177	2.8376
18	1356.3	6081.4	4755.3	4135.3	73.32	5.202
19	1356.3	5849.9	4959.3	4181.6	0.055732	5.202
20	1356.3	5628.5	5040	4298.1	0.24443	5.202
21	1356.2	5746.3	4625	4186.4	0.85911	5.198
22	1356.3	4122.4	4748.4	4177.3	0.66261	5.202
23	1356.3	4463.7	3349.6	3893	3.067	5.202
24	1356.1	3577	3413.4	3125.9	0	5.1957

Table 7 Emission values of economic/environmental dispatch for 24 hrs using WOA

	DG Units				
	Emission (Kg/MW)				
Time(h)	PO	CHP1	CHP2	CHP3	FC
1	11.913	0.0693	0.0396	0.068972	0.20881
2	11.909	0.078611	0.042113	0.042559	0.36337
3	11.913	0.06864	0.0396	0.050084	0.20881
4	11.913	0.0726	0.0396	0.044815	0.20881
5	11.913	0.0726	0.0396	0.0827	0.20881
6	11.912	0.10438	0.039594	0.10252	0.20881
7	11.913	0.15699	0.032578	0.085925	2.0881
8	11.912	0.12495	0.084919	0.085745	2.0857
9	11.804	0.11259	0.052691	0.11327	2.0311
10	11.913	0.13135	0.048183	0.11028	2.0875
11	11.725	0.098977	0.0374	0.075106	0.20881
12	11.904	0.15987	0.057164	0.092329	2.0672
13	11.898	0.078148	0.069167	0.10891	0.34129
14	11.913	0.10915	0.064235	0.10108	0.20891
15	11.901	0.14008	0.10236	0.098461	2.0174
16	11.908	0.1625	0.094199	0.10869	2.0558
17	11.84	0.14295	0.068484	0.089476	1.139
18	11.913	0.19368	0.1023	0.099	2.0881
19	11.913	0.18392	0.11833	0.1023	2.0881
20	11.913	0.17214	0.1254	0.10725	2.0881
21	11.912	0.17992	0.1033	0.10214	2.0864
22	11.913	0.11991	0.1023	0.10396	2.0881
23	11.913	0.12504	0.041916	0.09686	2.0881
24	11.91	0.099217	0.036562	0.067862	2.0855

Table 8 Dispatch results of WT and PV

Time(h)	1	2	3	4	5	6	7	8
PV (MW)	0	0	0	0	0	0.03	6.27	16.18
WT(MW)	1.7	8.5	9.27	16.66	7.22	4.91	14.66	25.56
Time(h)	9	10	11	12	13	14	15	16
PV (MW)	24.05	39.37	7.41	3.65	31.94	26.81	10.08	5.3
WT (MW)	20.58	17.85	12.8	18.65	14.35	10.35	8.26	13.71
Time(h)	17	18	19	20	21	22	23	24
PV (MW)	9.57	2.31	0	0	0	0	0	0
WT (MW)	3.44	1.87	0.75	0.17	0.15	0.31	1.07	0.58

5.2 Case 2

In this case 2 of operation discuss the renewable integrated combined heat and power based MG in autonomous mode of operation. In autonomous mode of operation consists photovoltaic systems, wind turbines, conventional power generation unit, combined heat and power generation units and fuel cell unit, this can be used to satisfy the electrical and heat demand of the proposed test system.

The total operation cost and net emission of the renewable integrated CHP based MG of this mode is 313952.75$/day and 339.35 kg/day respectively. It includes 32550.53$ cost of generating power from power only units, 281285.58$ cost of generating heat and power by combined heat and power units, 116.64$ cost of electrical energy produced by fuel cell unit.

The output power of photovoltaic system, wind turbines, conventional power generation unit, combined heat and power units, fuel cell unit and the output heat energy produced by proposed CHP units and its corresponding cost values are presented in Tables 9, 10 and 11 respectively. Table 12 shows the emission values of corresponding units. In autonomous mode of operation the proposed test system electrical demand are satisfied without considering the support of utility grid. From the obtained results of autonomous mode of operation the total cost and emission of renewable integrated CHP based MG is reduced 313952.75$ which is compared to connected mode of operation. It is mainly, the system operated in autonomous mode of operation. In this mode of operation the electrical energy are satisfied by renewable units. Due to fuel free and zero emission operation renewables are produced more power and considered as maximum utilization mode.

Table 9 Multi-objective economic/environmental dispatch using WOA (case 2: Total cost = 313952.75 \$/day, Total emission = 339.35 kg/day)

	DG Units				
	Output power(MW)				
Time(h)	PO	CHP1	CHP2	CHP3	FC
1	135	44.202	22.783	50.316	6
2	134.98	41.602	18	45.681	1.2323
3	134.97	44.006	18.006	42.443	1.304
4	135	44.07	13.041	40.229	6
5	135	42.54	20.131	69.109	6
6	135	40.915	51.65	76.495	6
7	135	55.926	34.688	97.456	6

(*Continued*)

Table 9 Continued

	DG Units				
	Output power(MW)				
Time(h)	PO	CHP1	CHP2	CHP3	FC
8	135	58.316	28.944	105	6
9	135	44.229	53.964	96.177	6
10	135	54.375	51.891	95.514	6
11	135	41.201	18.859	78.73	6
12	135	46.667	55.267	104.77	6
13	135	54.712	27.998	90	6
14	135	52.755	24.085	105	6
15	135	67.907	47.753	105	6
16	135	86.756	48.234	105	6
17	135	56.316	40.674	99	6
18	135	94.32	55.5	105	6
19	135	99.25	54	105	6
20	135	103.22	50.613	105	6
21	135	83.85	60	105	6
22	135	56.19	57	100.5	6
23	135	45.216	37.366	100.35	6
24	135	43.215	23.556	71.649	6

Table 10 Output heat scheduling of combined heat and power units

	DG Units		
	Output Heat (MWth)		
Time(h)	CHP1	CHP2	CHP3
1	5.2798	24.328	10.3921
2	45	0	0
3	0	0	42
4	1.4198	28.013	20.5676
5	36.735	9.6703	18.595
6	55.516	4.8154	9.6688
7	13.515	11.747	49.738
8	35.294	27.057	27.64833
9	15.019	16.637	60.344
10	44.645	5.2642	45.091
11	68.178	11.146	20.6763
12	47.375	0.00002397	44.625
13	19.176	11.604	59.22
14	41.392	38.977	7.63147
15	43.843	0.63059	45.52559
16	47.248	2.2543	45.4977

(*Continued*)

Table 10 Continued

	DG Units		
	Output Heat (MWth)		
Time(h)	CHP1	CHP2	CHP3
17	30.382	8.2905	71.327
18	33.36	19.465	62.1741
19	24.353	26.393	61.2545
20	12.75	22.233	60.01751
21	45.674	0.15014	44.17614
22	9.6587	12.031	63.3104
23	35.974	7.9379	31.088
24	25.002	12.876	32.121

Table 11 Corresponding cost values of economic/environmental dispatch for 24 hrs using WOA

	DG Units				
	Cost ($/MW)				
Time (h)	PO	CHP1	CHP2	CHP3	FC
1	1356.3	2932.7	3586.4	2776.7	5.202
2	1356.1	2925.2	3304.5	2628.9	1.0684
3	1355.9	2918.4	3304.7	2543.5	1.1305
4	1356.3	2922.6	3217.5	2491.7	5.202
5	1356.3	2935.8	3420	3337.5	5.202
6	1356.3	2937.3	4731.9	3542.5	5.202
7	1356.3	3420.7	4021.4	4283.7	5.202
8	1356.3	3574.8	3853.1	4458.9	5.202
9	1356.3	2949.8	4902.5	4232.8	5.202
10	1356.3	3443.4	4745.2	4240.4	5.202
11	1356.3	3004.4	3375.8	3637.5	5.202
12	1356.3	3138.1	4872.8	4450.6	5.202
13	1356.3	3382.8	3742.6	4123.9	5.202
14	1356.3	3365.4	3712.7	4460.4	5.202
15	1356.3	4006.2	4536.4	4462.9	5.202
16	1356.3	4834.3	4565.5	4472.7	5.202
17	1356.3	3477.3	4261.7	4324.1	5.202
18	1356.3	5117.2	4991	4474.1	5.202
19	1356.3	5308.7	4963	4467.3	5.202
20	1356.3	5455.8	4780	4458.9	5.202
21	1356.3	4700.3	5093.4	4459.8	5.202
22	1356.3	3424.5	5017.9	4363	5.202
23	1356.3	3041.1	4117.8	4312.4	5.202
24	1356.3	2930.7	3568.1	3447.6	5.202

Table 12 Corresponding emission values of economic/environmental dispatch for 24 hrs using WOA

	DG Units				
	Emission (Kg/MW)				
Time (h)	PO	CHP1	CHP2	CHP3	FC
1	11.913	0.072933	0.050122	0.055348	2.0881
2	11.91	0.068644	0.0396	0.050249	0.42885
3	11.908	0.072609	0.039612	0.046687	0.45379
4	11.913	0.072716	0.02869	0.044252	2.0881
5	11.913	0.070192	0.044288	0.07602	2.0881
6	11.913	0.06751	0.11363	0.084144	2.0881
7	11.913	0.092278	0.076315	0.1072	2.0881
8	11.913	0.096222	0.063677	0.1155	2.0881
9	11.913	0.072978	0.11872	0.10579	2.0881
10	11.913	0.089718	0.11416	0.10507	2.0881
11	11.913	0.067981	0.04149	0.086603	2.0881
12	11.913	0.077	0.12159	0.11524	2.0881
13	11.913	0.090275	0.061596	0.099	2.0881
14	11.913	0.087046	0.052986	0.1155	2.0881
15	11.913	0.11205	0.10506	0.1155	2.0881
16	11.913	0.14315	0.10612	0.1155	2.0881
17	11.913	0.092921	0.089483	0.1089	2.0881
18	11.913	0.15563	0.1221	0.1155	2.0881
19	11.913	0.16376	0.1188	0.1155	2.0881
20	11.913	0.17031	0.11135	0.1155	2.0881
21	11.913	0.13835	0.132	0.1155	2.0881
22	11.913	0.092713	0.1254	0.11055	2.0881
23	11.913	0.074607	0.082206	0.11038	2.0881
24	11.913	0.071304	0.051823	0.078814	2.0881

5.3 Case 3

The scope of this case is to obtain the impact of reduction in operation cost and net emission of proposed multi objective problem of RES integrated combined heat and power based MG using weighted sum method. In this mode of operation the obtained total operation cost and emission are 312712.51$/day and 341.82 kg/day respectively. Figure 2 show the convergence characteristics of three different cases. Table 13 shows the optimal results of power and heat obtained using weighting factors. Also, the Tables 14 and 15 show the cost and emission obtaining after 30 trials. The best trade off obtained between the two objective functions, while considering $W1 = 0.5$

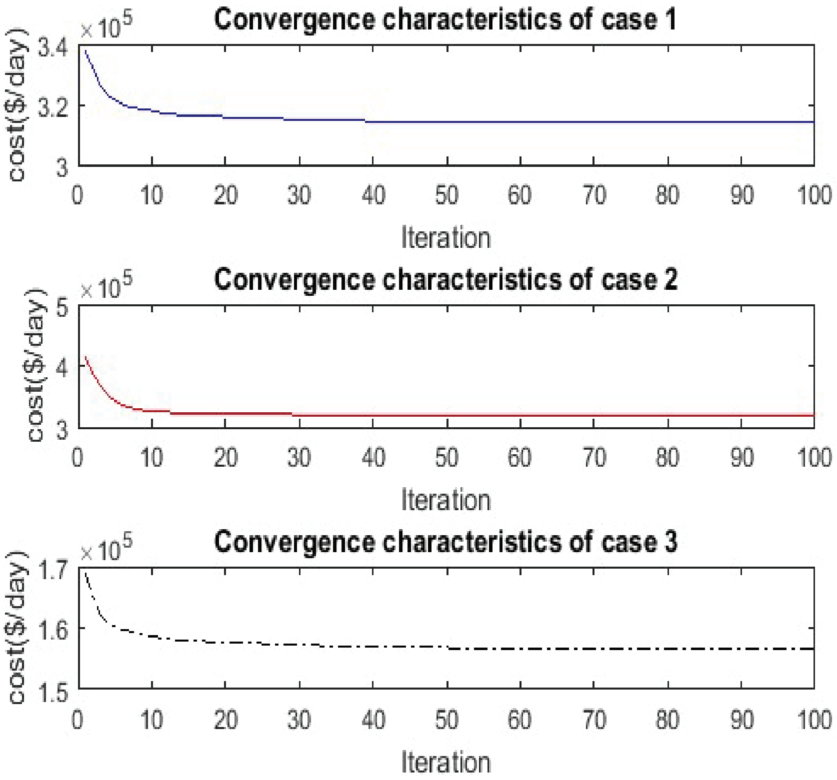

Figure 2 Convergence characteristics of case 1, case 2 and case 3.

and W2 = 0.5 as weighting factors. Table 16 shows the comparison results with other optimization methods. In Figure 3 represents the best convergence characteristics comparison of proposed algorithm with other optimization technique.

Table 13 Multi-objective economic/environmental dispatch using WOA (case 3: Total cost = 312712.51$/day, Total emission = 341.82 kg/day)

	DG Units							
	Output Power (MW)					Output Heat (MWth)		
Time(h)	PO	CHP1	CHP2	CHP3	FC	CHP1	CHP2	CHP3
1	135	43.629	18.519	55.152	6	22.341	6.9362	10.723
2	135	44.106	18.069	38.326	6	3.792	1.7427	39.465
3	134.9	43.2	17.963	38.707	5.963	25.59	6.2556	10.155
4	132.44	44	17	39.702	5.2006	13.27	6.9393	29.79

(*Continued*)

Table 13 Continued

	DG Units							
	Output Power (MW)					Output Heat (MWth)		
Time(h)	PO	CHP1	CHP2	CHP3	FC	CHP1	CHP2	CHP3
5	135	44.051	18.929	68.799	6	18.912	6.6013	39.486
6	135	47.428	21.132	100.5	6	5.5362	28.408	36.055
7	135	54.909	29.661	103.5	6	16.623	14.366	44.01
8	135	52.187	35.291	104.78	6	24.387	5.2052	60.407
9	135	56.671	39.135	98.563	6	10.186	18.902	62.912
10	135	54.032	42.748	105	6	38.552	1.8728	54.575
11	135	44.225	14.715	79.849	6	19.705	26.12	54.175
12	135	54.368	47.332	105	6	46.287	2.3919	43.321
13	135	46.541	28.669	97.5	6	31.183	23.662	35.155
14	135	41.253	55.705	84.882	6	49.704	10.57	27.725
15	135	63.301	52.359	105	6	40.829	0.14722	49.023
16	135	84.245	50.745	105	6	35.986	1.3178	57.696
17	135	62.11	28.88	105	6	29.864	18.604	61.531
18	135	94.32	55.5	105	6	37.175	17.153	60.672
19	135	100.83	52.419	105	6	43.039	8.8693	60.091
20	135	101.33	52.5	105	6	31.92	30.82	32.261
21	135	92.833	51.017	105	6	30.159	0.002645	59.838
22	135	67.148	43.042	103.5	6	18.496	3.943	62.561
23	135	57.524	25.878	99.528	6	11.619	19.474	43.907
24	135	42.924	19.323	76.173	6	30.393	15.765	23.841

Table 14 Corresponding cost values of economic/environmental dispatch for 24 hrs using WOA

	DG Units				
	Cost ($/MW)				
Time(h)	PO	CHP1	CHP2	CHP3	FC
1	1356.3	2941.1	3347.4	2913.9	5.202
2	1356.3	2926.9	3312.7	2452.2	5.202
3	1354.8	2931.6	3323.6	2465.3	5.1699
4	1319.6	2937.4	3288.9	2574.3	4.5089
5	1356.3	2950.4	3362.2	3318.5	5.202
6	1356.3	3062.3	3538.6	4350.9	5.202
7	1356.3	3385.3	3822.9	4429.6	5.202
8	1356.3	3291.9	4018	4459.3	5.202
9	1356.3	3445.1	4247	4311.2	5.202
10	1356.3	3408.3	4322.2	4471	5.202

(*Continued*)

Table 14 Continued

	DG Units				
	Cost ($/MW)				
Time(h)	PO	CHP1	CHP2	CHP3	FC
11	1356.3	2959.1	3274.3	3796.2	5.202
12	1356.3	3449.1	4526	4474.5	5.202
13	1356.3	3080.6	3824.9	4281.8	5.202
14	1356.3	2928.2	4949.1	3861.8	5.202
15	1356.3	3801.1	4740.8	4459.8	5.202
16	1356.3	4681.5	4673.6	4467.4	5.202
17	1356.3	3716.2	3809.7	4468.8	5.202
18	1356.3	5130.7	4977.3	4463.2	5.202
19	1356.3	5445.8	4788	4459.4	5.202
20	1356.3	5426.8	4920.7	4459.7	5.202
21	1356.3	5040.3	4679.5	4458.8	5.202
22	1356.3	3897.4	4344.4	4429.7	5.202
23	1356.3	3482.8	3690.2	4281.3	5.202
24	1356.3	2932.9	3411.8	3520.2	5.202

Table 15 Emission values of economic/environmental dispatch for 24 hrs using WOA

	DG Units				
	Emission (Kg/MW)				
Time(h)	PO	CHP1	CHP2	CHP3	FC
1	11.913	0.071988	0.040741	0.060667	2.0881
2	11.913	0.072774	0.039751	0.042158	2.0881
3	11.895	0.07128	0.039519	0.042578	2.0752
4	11.466	0.0726	0.0374	0.043672	1.8098
5	11.913	0.072684	0.041645	0.075679	2.0881
6	11.913	0.078257	0.046489	0.11055	2.0881
7	11.913	0.090599	0.065255	0.11385	2.0881
8	11.913	0.086108	0.077641	0.11526	2.0881
9	11.913	0.093508	0.086098	0.10842	2.0881
10	11.913	0.089153	0.094046	0.1155	2.0881
11	11.913	0.072972	0.032373	0.087834	2.0881
12	11.913	0.089706	0.10413	0.1155	2.0881
13	11.913	0.076792	0.063072	0.10725	2.0881
14	11.913	0.068067	0.12255	0.09337	2.0881
15	11.913	0.10445	0.11519	0.1155	2.0881
16	11.913	0.139	0.11164	0.1155	2.0881
17	11.913	0.10248	0.063536	0.1155	2.0881

(*Continued*)

Table 15 Continued

	DG Units				
	Emission (Kg/MW)				
Time(h)	PO	CHP1	CHP2	CHP3	FC
18	11.913	0.15563	0.1221	0.1155	2.0881
19	11.913	0.16637	0.11532	0.1155	2.0881
20	11.913	0.16719	0.1155	0.1155	2.0881
21	11.913	0.15317	0.11224	0.1155	2.0881
22	11.913	0.11079	0.094693	0.11385	2.0881
23	11.913	0.094914	0.056931	0.10948	2.0881
24	11.913	0.070825	0.04251	0.08379	2.0881

Table 16 Comparison of results with other optimization technique

	Proposed Method		CSA	
Mode of Operations	Cost ($/day)	Emission (kg/day)	Cost ($/day)	Emission (kg/day)
Autonomous mode	**313952.75**	**339.35**	314218.44	340.55
Grid Tied mode	**318733.35**	**324.51**	319245.98	327.19
Using weighting factors in autonomous mode	**312712.51**	**341.82**	312726.65	342.56

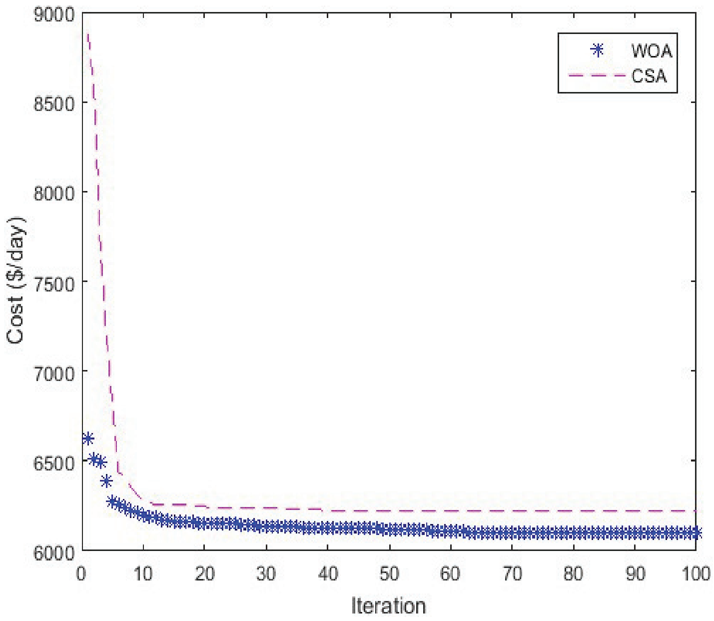

Figure 3 Comparison of convergence characteristics.

6 Conclusion

In this paper, an optimal allocation of RES integrated CHP based micro-grid is considered and two main objective functions are investigated. The proposed objective functions are economic/environmental scheduling of the proposed micro-grid. The considered test system can be operated in both grid connected and autonomous mode. The considered test system consists of renewable and non-renewable sources such as one conventional power only unit, three combined heat and power units, one fuel cell unit and renewable units. Due to the problem complexity, non-convexity and non-linearity a novel optimization approach is used to find the optimum solution for this proposed problem. Simulation results obtained in autonomous mode including RES cost is 313952.75$/day compared with grid connected mode. The operation cost of RES integrated CHP based micro-grid in 318733.35$/day in comparison with autonomous mode. From the above conclusion the RES integrated CHP based MG in autonomous mode by integrating both RES and DER's, electrical and heat demands are satisfied by RES, PO, CHP and FC units, this can lead to better scheduling of MG. The preference are given to RES is reduced both economic and environmental concerns. It is concluded, that the optimal scheduling of RES integrated CHP based micro-grid can be obtained in autonomous mode of operation. Similarly the better trade-off between the two objectives are achieved by using weighting factors $w_1 = 0.5$ and $w_2 = 0.5$ and the total operation cost and emission obtained in autonomous mode is 312712.51$/day and 341.82 kg/day respectively. Finally, the comparison of results obtained with Cuckoo Search Algorithm shows, the proposed WOA gives optimal results for multi-objective problems.

Nomenclature

CSA	Cuckoo Search Algorithm
CHP	Combined Heat and Power
DER	Distributed Energy Resources
FC	Fuel Cell
MG	Micro-Grid
PO	Power Only Unit
PV	Photovoltaic
RES	Renewable Energy Sources
WOA	Whale Optimization Algorithm
WT	Wind Turbine

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