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## Article

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Energy Reports

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*Suggested Citation:* Aghajani, Gholamreza; Ghadimi, Noradin (2018) : Multi-objective energy management in a micro-grid, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 4, pp. 218-225,  
<https://doi.org/10.1016/j.egy.2017.10.002>

This Version is available at:

<https://hdl.handle.net/10419/187897>

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# Multi-objective energy management in a micro-grid

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## ARTICLE INFO

### Article history:

Received 1 June 2017

Received in revised form 8 September 2017

Accepted 4 October 2017

### Keywords:

Micro-grid

Multi-objective optimization

Energy management

Renewable energy

## ABSTRACT

In recent years, the management and operation of micro-grids are considered by many advanced societies with regard to the development of scattered energy resources. The main goals that are paid attention in micro-grid management are the operation cost and pollution rate, which the aggregation of such contradictory goals in an optimization problem can provide an appropriate response to the management of the micro-grid. In this paper, the MOPSO method has been used for management and optimal distribution of energy resources in proposed micro-grid. On the other hand, the problem was analyzed with the NSGA-II algorithm to demonstrate the efficiency of the proposed method.

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## 1. Introduction

At present, considering the significant growth of distributed generation (DG), specifically renewable energy resources, there is a growing interest in the use of micro-grids. Micro-grids combine different DG resources, thereby providing a control system at the voltage distribution level to supply electricity or heat to a group of local loads (Xie et al., 2011; An et al., 2015; Gollou and Ghadimi, 2017). Renewable energy resources such as wind and the sun play important roles in micro-grids but they also exhibit random behavior, so it is necessary to perform appropriate planning to facilitate the suitable operation of these resources and their optimal management while considering different practical objectives. Various structures and methods have been proposed for energy management systems using different optimization algorithms for micro-grids with diverse resources. In particular, micro-grid operation has been optimized using a mixed integer nonlinear programming (MINLP) model with the aim of minimizing an objective function that considers investment, operation, repair and maintenance, and environmental costs (Xie et al., 2011). However, mathematical solution methods such as MINLP cannot optimize large-scale nonlinear problems, which must be addressed using heuristic techniques. Thus, particle swarm optimization (PSO) and genetic algorithms have been used to economically allocate power to generation units in a power grid (Moghaddam et al., 2012; Muthuswamy et al., 2015). A single-objective gravitational search algorithm was also employed for determining the optimal energy management strategy (Sharifi et al., 2017). In addition, a combination of modified

honey bee mating optimization and chaotic local search was proposed (Wu and Hao, 2014). Furthermore, a company-based energy management strategy was developed to facilitate power exchange among micro-grids using demand response and energy storage (Akbari et al., 2017), where the main focus was on the theoretical load consumption patterns of consumers, the available energy in DG resources, and an electricity cost-saving system.

In this study, we propose the use of the multi-objective PSO (MOPSO) algorithm for the optimal management of generation units in micro-grids, where demand side management and the exchange of micro-grids with the national grid are analyzed to minimize the operating costs and pollution emissions.

The remainder of this paper is organized as follows. The problem is stated fully in Section 2. We introduce micro-grids in Section 3 and the principles of multi-objective optimization are presented in Section 4. The results of simulations and numerical analyses are discussed in Section 5. Finally, we give the main conclusions of this study in Section 6.

## 2. Problem statement

In this study, we present an accurate mathematical model for energy management over the short term in order to minimize the operating costs and pollution emissions for a micro-grid.

### 2.1. Defining the objective function

The objective function is considered to include operating costs and pollution emission costs, as follows.

**Objective function cost:** Minimizing the total operating costs for a micro-grid: See Eq. (1) given in Box 1, where  $T$  is the total time period of the study (hours),  $N_g$  and  $N_s$  are the numbers of energy

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$$\text{Min } f_1(X) = \sum_{t=1}^T \left\{ \sum_{i=1}^{N_g} [U_i(t)P_{Gi}(t)B_{Gi}(t) + S_{Gi} |U_i(t) - U_i(t+1)|] - \dots \right. \\ \left. \sum_{j=1}^{N_s} [U_j(t)P_{Sj}(t)B_{Sj}(t) + S_{Sj} |U_j(t) - U_j(t-1)|] - (P_{Grid}(t)B_{Grid}(t)) \right\}, \quad (1)$$

Box 1.

generation and storage units, respectively,  $U_i(t)$  is the status of the  $i$ th unit at time  $t$  (either on or off),  $P_{Gi}(t)$  and  $P_{Sj}(t)$  are the amounts of output power for the  $i$ th unit and  $j$ th storage at time  $t$ ,  $B_{Gi}(t)$  and  $B_{Sj}(t)$  represent the energy price offered for the  $i$ th unit and  $j$ th storage at time  $t$ ,  $S_{Gi}(t)$  and  $S_{Sj}(t)$  are the startup or shut-down costs for the  $i$ th unit and  $j$ th storage, and  $P_{Grid}(t)$  and  $B_{Grid}(t)$  indicate the amounts of power exchanged with the offered market at time  $t$ .

**Objective function for pollution:** Minimizing all the pollution attributable to the most common pollutants in a micro-grid:

$$\text{Min } f_2(X) = \sum_{t=1}^T \text{Emission}^t = \sum_{t=1}^T \left\{ \sum_{i=1}^{N_g} [U_i(t)P_{Gi}(t)E_{Gi}(t)] \right. \\ \left. + \sum_{j=1}^{N_s} [U_j(t)P_{Sj}(t)E_{Sj}(t)] + (P_{Grid}(t)E_{Grid}(t)) \right\}, \quad (2)$$

where  $E_{Gi}(t)$ ,  $E_{Sj}(t)$ , and  $E_{Grid}(t)$  represent the amounts of pollution attributable to the  $i$ th generation unit,  $j$ th storage unit, and the market at time  $t$  in kg/MWh, respectively.

## 2.2. Constraints and limitations

- Load-generation balance:

$$\sum_{k=1}^{N_k} P_{Lk}(t) = \sum_{i=1}^{N_g} [P_{Gi}(t)] + \sum_{j=1}^{N_s} [P_{Sj}(t)] + (P_{Grid}(t)), \quad (3)$$

where  $P_{Lk}$  is the amount of  $K$  at the load level and  $N_k$  is the total number of load levels present in the grid.

- Power limit of units

All the units, including DGs, storage units, and the market, have lower and upper limits for their generation power.

$$P_{Gi,\min}(t) \leq P_{Gi}(t) \leq P_{Gi,\max}(t) \\ P_{Sj,\min}(t) \leq P_{Sj}(t) \leq P_{Sj,\max}(t) \\ P_{Grid,\min}(t) \leq P_{Grid}(t) \leq P_{Grid,\max}(t) \quad (4)$$

- Limitations on the charging and discharging rates of the storage unit

$$\text{SOC}_{Sj}(t) = \text{SOC}_{Sj}(t-1) + P_{chg/Dchg}(t) \\ 0 \leq |P_{chg/Dchg}(t)| \leq P_{CDSi,\max}, \quad (5)$$

where  $\text{SOC}_{Sj}(t)$  and  $\text{SOC}_{Sj}(t-1)$  are the charging amounts of a storage unit at the current and previous times, respectively,  $P_{chg/Dchg}(t)$  is the charging (discharging) amount during the  $t$ th hour, and  $P_{CDSi,\max}$  is the maximum charging (discharging) rate.

## 3. Structure of the grid

A micro-grid is a combination of DGs, including micro-turbine, wind turbine, solar cell, fuel cell, battery, and diesel generator units, which are connected to each other as well as exchanging energy with the upstream grid. Thus, all the resources are capable of decision making and planning for energy generation, where these

control measures are facilitated by local and central controllers in micro-grids.

A schematic overview of the system considered in the present study is shown in Fig. 1, where the micro-grid includes generation resources comprising micro-turbine, wind turbine, solar cell, fuel cell, and battery units. The micro-grid also has the capability of exchanging energy with the upstream grid.

## 4. Principles of multi-objective optimization and PSO algorithms

In the real world, many problems involve the simultaneous optimization of several objective functions, which are usually not proportionate and in conflict with each other. This optimization process yields a set of responses instead of an optimal response because no single response can be obtained to optimize all the functions by considering all of the objectives simultaneously. Therefore, the multi-objective optimization problem includes a number of objective functions, which must be optimized simultaneously, and a number of equality and inequality constraints must be satisfied. Thus, this problem can be formulated as follows:

$$\text{Min } F(\vec{X}) = [f_1(\vec{X}), f_2(\vec{X}), \dots, f_N(\vec{X})]^T \\ \text{Subject to :} \\ g_i(\vec{X}) < 0 \quad i = 1, 2, \dots, N_{ueq} \\ h_i(\vec{X}) = 0 \quad i = 1, 2, \dots, N_{eq}, \quad (6)$$

where  $F$  is a vector containing the objective functions,  $X$  is a vector comprising the optimization variables of  $f_i(X)$  representing the  $i$ th objective function,  $g_i(X)$  and  $h_i(X)$  are the equality and inequality constraints, respectively, and  $N$  indicates the number of objective functions in the problem. In this study, based on the PSO algorithm (Kennedy, 2010), the multi-objective functions are solved using the MOPSO algorithm. Further details of the MOPSO algorithm, can be found in previous studies (Xuebin, 2009; Ghadimi and Firouz, 2015).

The MOPSO algorithm can be readily applied to our problem according to the following steps.

First step: Gathering input information for the program.

First, information related to the structure of the sample micro-grid, the technical and functional specifications of the elements in the grid, wind and solar power predictions for the future 24-h period, the energy price offered by the market and DG units, as well as the daily load curve are treated as the primary data.

Second step: Initialization

In this step, a primary population is defined by considering the limitations on the problem according to Eq. (7):

$$X^0 = [X_1, X_2, \dots, X_N]^T, \quad (7)$$

where  $X$  is a decision variable vector that includes the output power of units and the on/off status of units, which is described

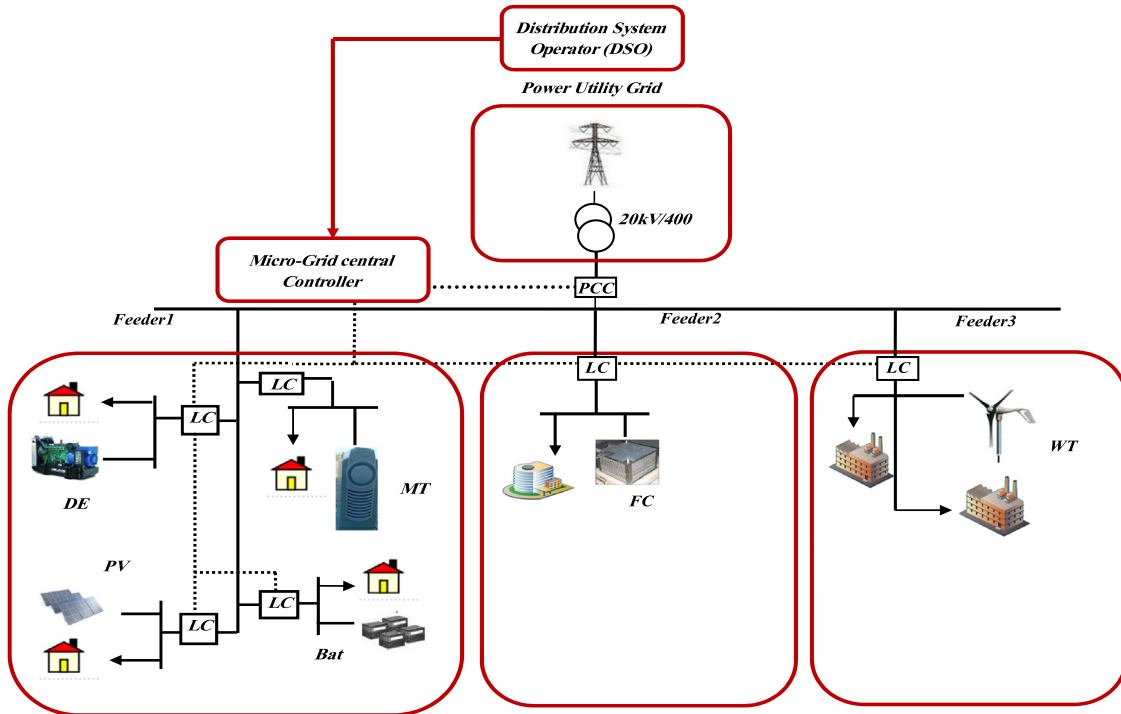


Fig. 1. Schematic configuration of the micro-grid.

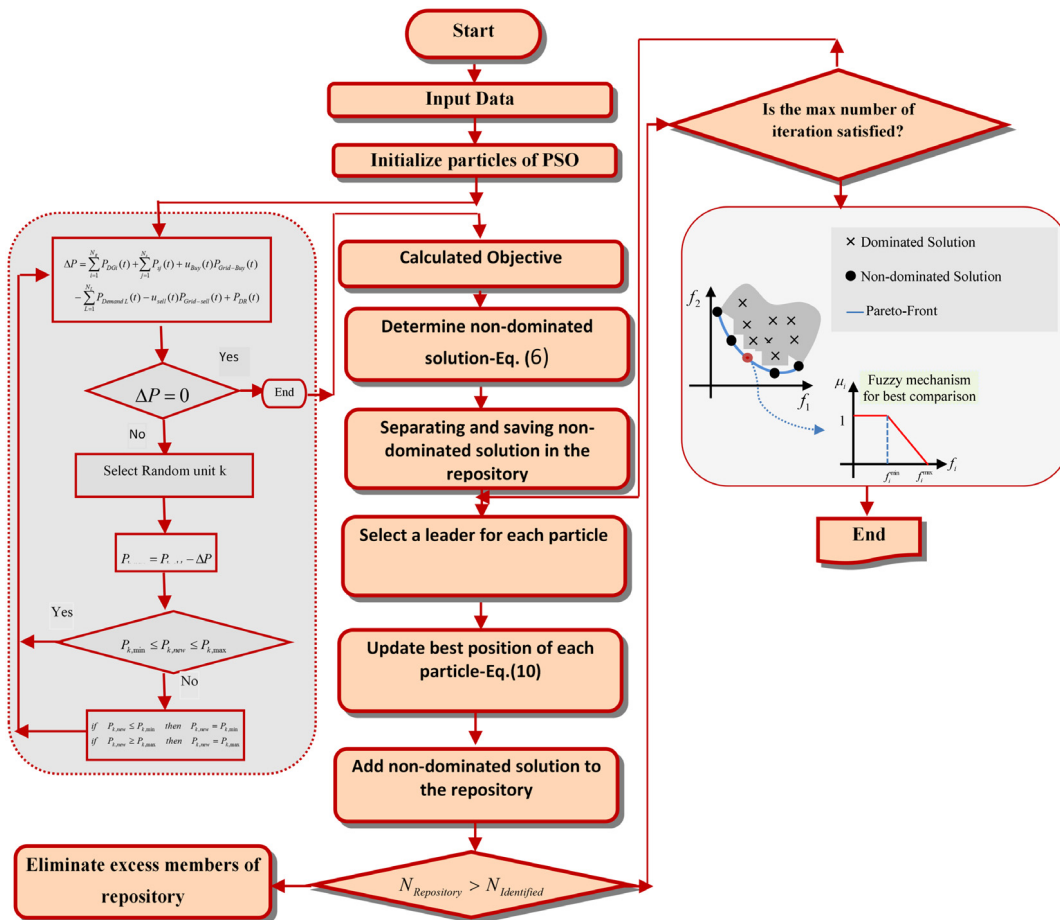


Fig. 2. Flowchart illustrating the implementation of the MOPSO algorithm.

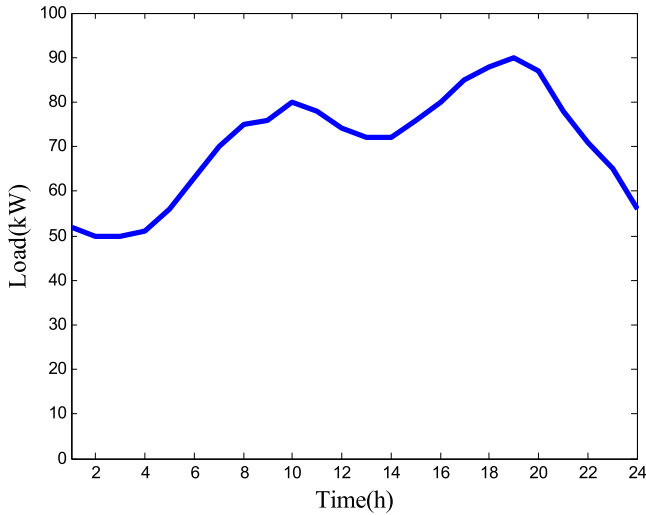


Fig. 3. Daily load profile for the micro-grid considered in this study.

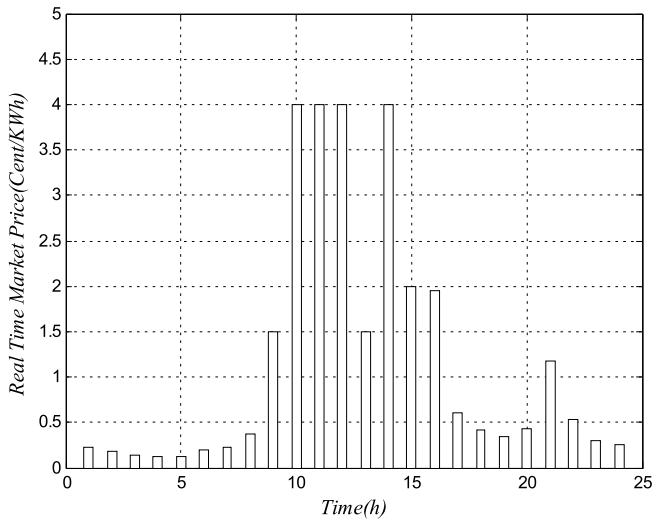


Fig. 4. Market price curve.

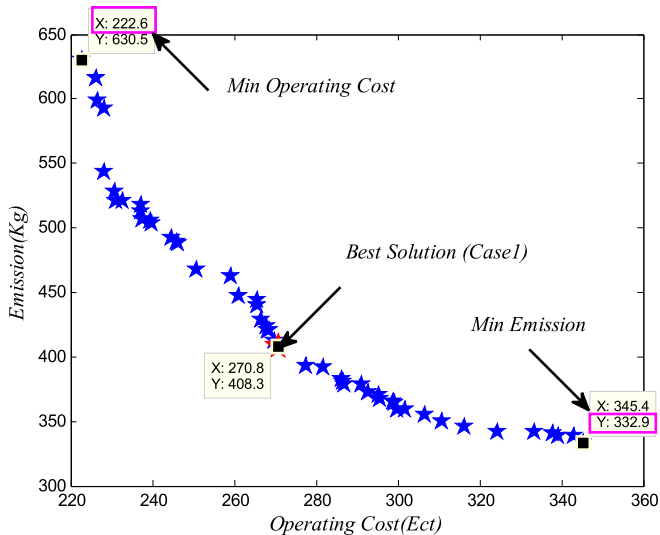


Fig. 5. Distribution of the Pareto criterion for operating and pollution costs considering the basic state.

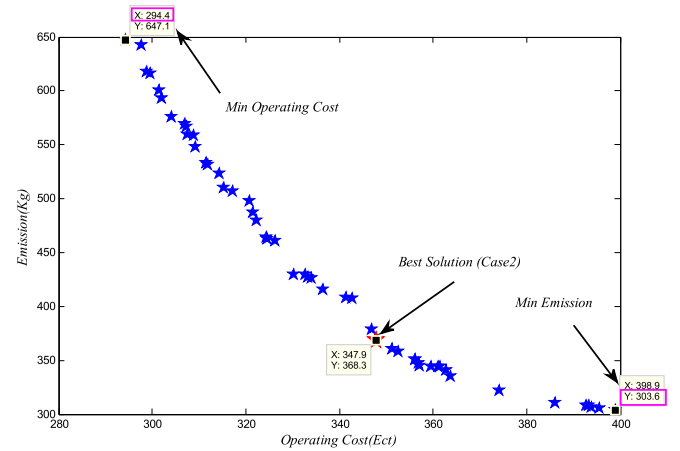


Fig. 6. Distribution of the Pareto criterion for the operating and pollution costs by considering the maximum capacity of renewable energy (Max-Renew).

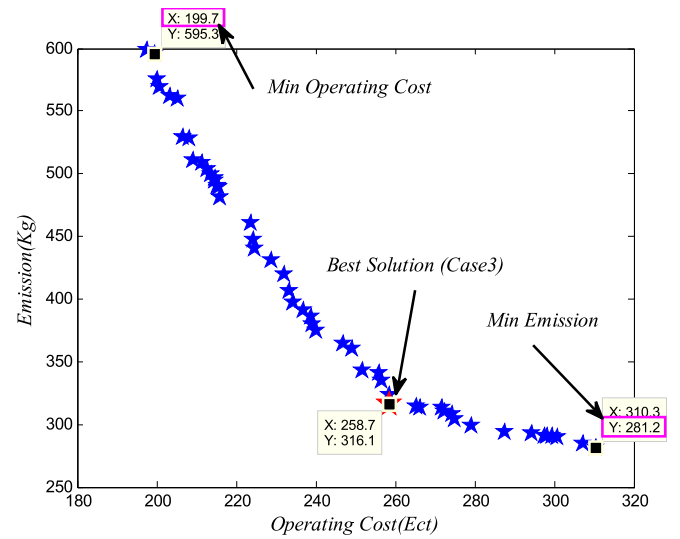


Fig. 7. Distribution of the Pareto criterion for the operating and pollution costs when considering unlimited power exchange between LV and MV.

according to the following relationship:

$$X = [P_g, I_g]_{1 \times 2nT}$$

$$P_g = [P_{DG1}, P_{DG2}, \dots, P_{DGN_{DG}}, P_{s1}, P_{s2}, \dots, P_{sN_s}, P_{Grid}]$$

$$I_g = [I_{DG1}, I_{DG2}, I_{DGN_{DG}}, I_{s1}, I_{s2}, \dots, I_{sN_s}, I_{Grid}]$$

$$n = N_{DG} + N_s + 2$$
(8)

where  $n$  is the number of decision variables,  $N_{DG}$  and  $N_s$  are the numbers of generation and storage units, respectively,  $T$  is the time period considered,  $P_g$  represents a vector of the active power including all the DGs and storage units, and  $I_g$  is the mode vector, which indicates the on or off status of the units at time  $t$ .

Third step: Apply the load flow algorithm to the generated population.

For every population generated, the load distribution algorithm specified in Fig. 2 is implemented and the corresponding fitting, pollution, and cost objective functions are calculated.

Fourth step: Identify non-dominated solutions.

Fifth step: Separate non-dominated solutions and save them in an archive.

Sixth step: Select the best particle from the archive of non-dominated solutions as a leader.

**Table 1**  
Bids and technical coefficient of the DG sources.

Unit	Type	Bid (€Cent/KWh)	Start-up/Shut-down Cost (€Cent)	$P_{min}$ (KW)	$P_{max}$ (KW)
1	MT	0.457	0.960	6.000	30.000
2	PAFC	0.294	1.650	3.000	30.000
3	Bat	0.380	0.000	-30.000	30.000
4	PV	2.584	0.000	0.000	25.000
5	WT	1.073	0.000	0.000	15.000
6	Grid	-	0.000	-30.000	30.000

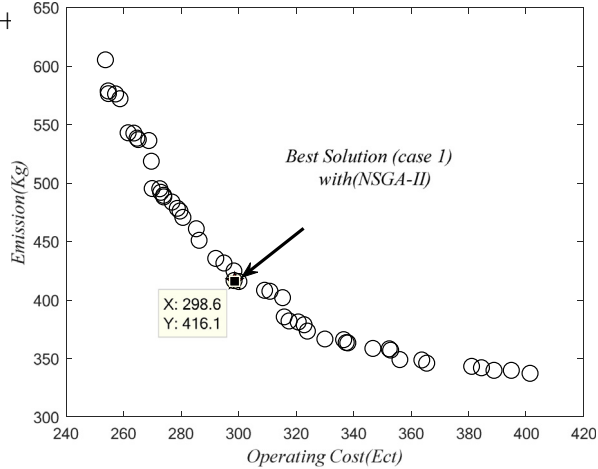
**Table 2**  
Emissions coefficients for the DG sources.

Unit	Type	CO <sub>2</sub> (kg/MWh)	SO <sub>2</sub> (kg/MWh)	NO <sub>x</sub> (kg/MWh)
1	MT	720	0.0036	0.1
2	PAFC	460	0.003	0.0075
3	Bat	10	0.0002	0.001
4	PV	0	0	0
5	WT	0	0	0
6	Grid	950	0.5	2.1

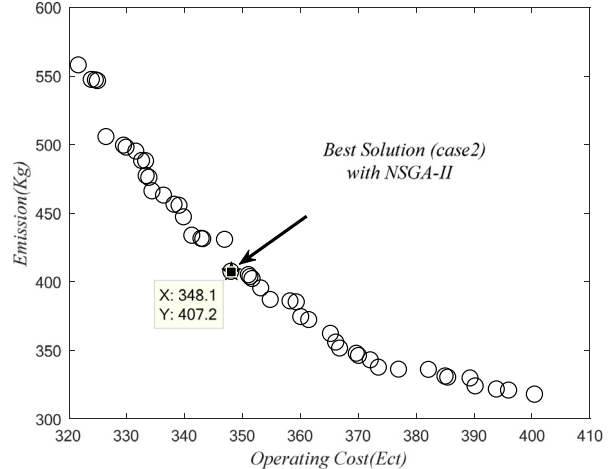
Seventh step: Determine the new speed and position of each particle using the following formula.

$$x_{id}^{t+1} = x_{id}^t + v_{id}^{t+1}$$

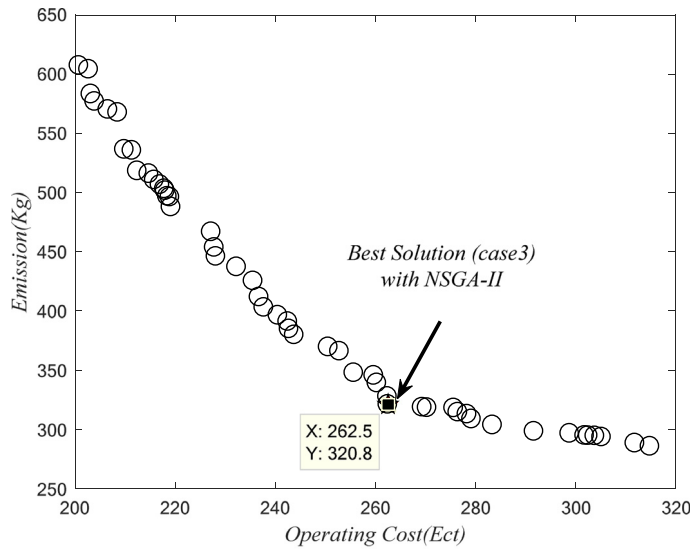
$$v_{id}^{t+1} = w \times v_{id}^t + c_1 rand_1 \times (P_{bestid}^t - x_{id}^t)$$



(a)



(b)



(c)

**Fig. 8.** Convergence characteristic of NSGA-II algorithm (a) in the scenario 1 and (b) in the scenario 2 and (c) in the scenario 3.



**Table 3**  
Predicted values of WT and PV.

Hour	WT (kW)	PV (kW)	Hour	WT (kW)	PV (kW)
1	1.7850	0	13	3.9150	23.90
2	1.7850	0	14	2.3700	21.05
3	1.7850	0	15	1.7850	7.875
4	1.7850	0	16	1.3050	4.225
5	1.7850	0	17	1.7850	0.550
6	0.9150	0	18	1.7850	0
7	1.7850	0	19	1.3020	0
8	1.3050	0.200	20	1.7850	0
9	1.7850	3.750	21	1.3005	0
10	3.0900	7.525	22	1.3005	0
11	8.7750	10.45	23	0.9150	0
12	10.410	11.95	24	0.6150	0

Eighth step: Update the best position of each particle as follows.

$$P_{best,i}(t+1) = \begin{cases} P_{best,i}(t) & P_{best,i}(t) < X_i(t+1) \\ X_i(t+1) & X_i(t+1) < P_{best,i}(t) \\ \text{select randomly} & \\ (P_{best,i}(t) \text{ or } X_i(t+1)) & \text{otherwise} \end{cases} \quad (10)$$

Ninth step: Remove non-dominated members from the archive.

Tenth step: Investigate the stop conditions.

If favorable optimal conditions for the problem responses have been established, the algorithm is stopped; otherwise, return to step 6.

Eleventh step: Select the best interactive solution.

After obtaining the optimal Pareto solution, choosing a better solution from optimal solution is considered necessary and vital for management of the micro-grid. Therefore, in order to achieve this objective, we can use the fuzzy decision-making function with a membership function that can determine the exact value of the variables using Eq. (11).

$$\mu_i^k = \begin{cases} 1 & f_i \leq f_i^{\min} \\ \frac{f_i^{\max} - f_i}{f_i^{\max} - f_i^{\min}} & f_i^{\max} < f_i < f_i^{\min} \\ 0 & f_i \geq f_i^{\max} \end{cases} \quad (11)$$

**Table 4**  
Allocation of optimal power considering the operating costs and emissions objectives (Main case).

Hour	Units					
	MT (kW)	PAFC (kW)	WT (kW)	PV (kW)	Batt (kW)	Utility (kW)
1	9.5335	23.5693	0	0	5.4700	13.4271
2	6	30	0	0	-15.4764	29.4764
3	8.0095	22.4317	0.4167	0	-10.8579	30
4	6	28.9535	0.0169	0	-13.7025	29.7319
5	7.0713	5.7000	0.4998	0	16.4577	26.2710
6	7.0021	26.3207	0.6011	0	5.10665	23.9693
7	6.0000	22.8271	0.1785	0	12.5727	28.4216
8	25.9720	22.9524	0.4205	0.18	14.0498	11.4251
9	29.9719	28.5555	1.7270	3.2437	30	-17.4983
10	30	30	3.09	7.5249	29.9996	-20.6146
11	30	30	8.3762	9.6237	30	-30
12	30	30	10.41	3.59	30	-30
13	29.9870	30	3.915	0	29.8944	-21.7965
14	30	30	2.2209	9.6644	30	-29.8854
15	30	29.7784	1.785	7.0875	30	-22.6509
16	30	30	1.305	4.2035	29.9999	-15.5085
17	30	29.9324	1.5176	0.2743	29.9997	-6.7241
18	19.1125	28.2711	0.2106	0	14.2696	26.1360
19	22.5324	30	0.3906	0	16.7978	20.2790
20	24.2994	30	0.9540	0	21.4849	10.2616
21	29.9996	30	1.0067	0	29.9944	-13.0008
22	21.6007	29.9711	1.3005	0	26.9955	-8.8678
23	9.1837	21.7484	0.4320	0	3.6356	30
24	26.7621	27.30	0.6150	0	-7.5793	8.9022

Where  $\mu_i^k$  indicates the optimality value of the objective function  $i$  among the  $k$ -optimal Pareto solution and  $f_i^{\max}$  and  $f_i^{\min}$  indicate the upper and lower limit of  $i$ th objective function, respectively.

Fig. 2 shows a flowchart illustrating the proposed algorithm for solving the optimization problem.

### 5. Simulation results

We applied the proposed MOPSO algorithm to the micro-grid considered in this study. To demonstrate the efficiency of the proposed model, the optimization problem was planned and implemented in three states: (1) basic operation (main case), which represents the normal function of the grid; (2) operation at the maximum capacity of renewable energy (Max-Renew), which represents the use of the maximum generation capacity for wind and solar units per day; and (3) operation in the case of unlimited power exchange between LV and MV.

In all cases, we assumed that the DGs operated at a unit power coefficient. The load curve for the micro-grid is shown in Fig. 3, which is equivalent to an energy demand of 1695 kWh. The economic and technical specifications of the units are presented in Tables 1 and 2. The market price offered is shown in Fig. 4. The output power levels of the wind turbine and solar cell based on the predicted values are given in Table 3 (Chen et al., 2011). In the sample grid, the battery considered had a capacity of 30 kWh, which amounted to almost 4 kWh after considering the residential feeder with a maximum charging power of 230 V and a 16-A household electricity system.

#### Scenario 1. Basic operation

The numerical results obtained from simulations of the basic case and by simultaneously considering two incompatible functions, i.e., operating costs and pollution emissions, using the MOPSO algorithm are presented in Table 4.

The objectives of operating costs and pollution emissions conflict with each other, and thus according to Fig. 5, the movement from the primary points in the diagrams to their terminal points, as well as on the Pareto path, represent changes in the operating pattern from lower cost and higher pollution to greater cost and lower pollution. The optimal operating settings could be determined using the fuzzy mechanism. Based on the simulation results,

**Table 5**  
Allocation of optimal power considering the costs and emissions objectives (Max-Renew case).

Hour	Units					
	MT (kW)	PAFC (kW)	WT (kW)	PV (kW)	Batt (kW)	Utility (kW)
1	6.2306	30	1.785	0	28.6743	-14.69
2	6	28.4874	1.785	0	30	-16.2724
3	10.4696	3	1.785	0	30	4.745379
4	8.7633	26.4815	1.785	0	30	-16.0299
5	6	3	1.785	0	30	15.215
6	6	21.6428	0.915	0	28.6528	5.789243
7	6.4153	30	1.785	0	30	1.799643
8	30	29.2890	1.305	0.2	29.9998	-15.7939
9	30	30	1.785	3.75	30	-19.535
10	30	29.9754	3.09	7.525	30	-20.5904
11	29.0146	29.8838	8.775	10.45	29.8765	-30
12	22.0767	29.5632	10.41	11.95	30	-30
13	14.2435	29.9414	3.915	23.9	30	-30
14	23.5104	30	2.37	21.05	25.0696	-30
15	30	30	1.785	7.875	30	-23.66
16	30	30	1.305	4.225	30	-15.53
17	30	30	1.785	0.55	30	-7.335
18	30	30	1.785	0	30	-3.785
19	30	30	1.302	0	30	-1.302
20	30	30	1.785	0	30	-4.785
21	30	30	1.3005	0	30	-13.3005
22	30	30	1.3005	0	30	-20.3005
23	9.5731	30	0.915	0	30	-5.4881
24	6	30	0.615	0	30	-10.615

**Table 6**  
Allocation of optimal power while considering the operating costs and emissions objectives (unlimited exchange between LV and MV).

Hour	Units					
	MT (kW)	PAFC (kW)	WT (kW)	PV (kW)	Batt (kW)	Utility (kW)
1	30	30	1.785	0	30	-39.785
2	6	30	0	0	30	-16
3	6	30	0.057586	0	30	-16.0576
4	6	30	0	0	30	-15
5	30	30	1.785	0	29.98214	-35.7671
6	6	30	0.150786	0	30	-3.15079
7	6	30	0	0	30	4
8	22.39027	30	0	0.2	30	-7.59027
9	30	30	1.785	3.75	30	-19.535
10	30	30	3.09	7.525	30	-20.615
11	30	30	8.775	10.45	30	-31.225
12	29.99636	30	10.41	11.95	30	-38.3564
13	30	29.99792	3.915	23.8537	30	-45.7666
14	30	30	2.37	21.05	30	-41.42
15	30	30	1.785	7.875	29.42601	-23.086
16	30	30	1.305	4.225	30	-15.53
17	30	30	1.785	0.55	30	-7.335
18	30	30	0.549261	0	30	-2.54926
19	30	29.4948	1.302	0	30	-0.7968
20	30	30	1.785	0	30	-4.785
21	29.75761	30	0	0	29.38668	-11.1443
22	29.9409	29.98905	1.196552	0	30	-20.1265
23	29.34543	30	0.077245	0	29.6169	-24.0396
24	30	30	0.595721	0	29.99458	-34.5903

in the first hours of the day, most of the micro-grid load was supplied by the fuel cell and upstream grid, and thus due to the load peak and increase in the market price offered, the DG units increased their generation according to the priority requirements of minimum costs and pollution.

By contrast, energy purchasing from the upstream grid was replaced with energy sales by the micro-grid controller in the peak hours in order to achieve economically superior operation. Furthermore, battery charging in the micro-grid occurred in the early hours of the day with lower price tariffs, whereas discharging occurred later in the day with the growth of the price curve.

### Scenario 2. Operating at the maximum capacity of renewable energy

The numerical results obtained from the simulation in the second case while satisfying each of the economic and pollution objectives are shown in Table 5, and the Pareto curve for these objectives is presented in Table 6. According to the results obtained for the second case, the maximum use of wind and solar units with low pollution and high costs increased the operating costs for the micro-grid by 28.4% compared with the previous scenario, but the pollution rate was reduced by 10%.

### Scenario 3. Unlimited power exchange between LV and MV

The numerical results obtained for the third case are presented in Table 6, which show that allowing unlimited power exchange and simultaneously considering the economic and environmental objectives reduced the micro-grid operating costs by 5% compared with the basic scenario. Moreover, the pollution rate was reduced by 22.5% compared with the basic scenario. Fig. 7 shows the



**Table 7**  
Comparison of best compromise solution.

Scenario		MOPSO	NSGA-II
First case	Operation Cost (€ct)	270.8	298.6
	Emission (kg)	408.3	416.1
Second case	Operation Cost (€ct)	347.9	348.1
	Emission (kg)	368.3	407.2
Third case	Operation Cost (€ct)	258.7	262.5
	Emission (kg)	316.1	320.8

**Table 8**  
The time to solve the problem with MOPSO and NSGA-II algorithms.

Scenario	MOPSO (s)	NSGA-II (s)
First case	359.3	384.5
Second case	373.4	396.7
Third case	402.3	432.4

Pareto curve obtained when operating in the unlimited exchange scenario. In order to demonstrate efficiency of MOPSO algorithm, the results were compared with those of non-dominated sorting genetic algorithm (NSGA-II) algorithm. However, according to Figs. 5–8, it can be said that MOPSO algorithm had better performance in finding the optimal interaction point between operational cost and pollution emissions in all cases, compared with NSGA-II algorithm. Table 7 shows the results of this comparison.

In order to solve the problem, a laptop 2.5 MHz with 4 GB of RAM with MATLAB software is used; the time required to solve the problem is according to Table 8, if two algorithms of MOPSO and NSGA-II are used. The results of this table show that the proposed algorithm has faster speed in solving a problem.

## 6. Conclusion

In this paper, problem solution of optimal operation management from a micro-grid was considered as an optimization function with two incompatible objectives that are operation cost and emission's propagation. Then total operation cost of micro-grid and pollutant-induced emission were analyzed in three scenarios. The simulation results showed that having infinite power exchange between LV- and MV networks was one of the best scenarios among the proposed scenarios. When this state is compared with second scenario, the operation cost is reduced by 26% and amount of emission is reduced by 15%. On the other hand, when it com-

pared with first scenario, the operation cost is reduced by 5% and amount of emission is reduced by 23%. On the other hand, the results suggest that widespread use of renewable energy resources can be a major contribution to reduction in the amount of micro-grid's pollution, while its operation costs will increase in the short term.

In this study, an MOPSO method was used to find the optimal solution based on fuzzy technique; finally, the results are compared with NSGA-II algorithm to show the efficiency of proposed algorithm.

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