Multi-objective economic/emission optimal energy management system for scheduling micro-grid integrated virtual power plant

Mohamed Lamari | Youssouf Amrane | Mohamed Boudour | Bouziane Boussahoua

Laboratory of Electrical Industrial Systems, University of Science and Technologies Houari Boumediene, Algiers, Algeria

Correspondence
Youssouf Amrane, Laboratory of Electrical Industrial Systems, University of Science and Technologies Houari Boumediene, Algiers, Algeria. Email: yamrane@usthb.dz

Abstract
Due to rapid socioeconomic growth and current environmental concerns, reducing global greenhouse gas emissions is a key step toward sustainable development. In recent years, some researchers have begun to adopt new grid management technologies such as virtual power plants (VPP) that allow them to improve energy management and cost and reduce gas emissions. The integration of distributed energy resources (DER), such as solar photovoltaic and wind power, combined with micro-turbines and energy storage systems and with the support of VPP intelligence, will contribute immensely to improving micro-grids (MGs) energy performance and reducing gas emissions. In this paper, an expert multi-objective feasibility enhanced particle swarm optimization algorithm is adopted for the optimal scheduling of energy management system to reduce the total operating cost and net emission simultaneously. The proposed algorithm is tested on an Algerian reel building-MG integrated VPP with DERs and combined cooling, heat, and power generation. Finally, different cases are simulated for a 24-h time and discussed to demonstrate the validity of the proposed VPP energy system and the effectiveness of the adopted algorithm to reduce gas emissions and the total operating cost.

KEYWORDS
distributed energy resources, energy management system, gas emission, multi-objective feasibility enhanced particle swarm optimization algorithm, operating cost, optimal scheduling, renewable energy sources, virtual power plant

1 | INTRODUCTION

As fossil fuels are rapidly depleting and global warming identified by CO₂ emissions becomes a major global problem, the search for alternative and renewable energy sources (RESs) to meet future energy demand has been developed by many scientific researchers. The use of combined cooling heating and power (CCHP) is a very attractive solution because they are inexhaustible, nonpolluting, and very suitable for new distributed energy resources (DERs), which is the most important component for the future MG.¹,² On the other hand, the
production of most RESs such as wind turbines (WT) and photovoltaic (PV) is variable and uncertain. Therefore, it’s possible to combine these uncertain production units with an energy storage system (ESS) and other flexible conventional resources units. In this context, the concept of a virtual power plant (VPP) appears.

A VPP can be considered as a set of generation units, storage units, and loads facilities, which are aggregated as a single entity for the purpose of optimizing the production of DERs. A VPP consists of networking a set of decentralized microgrids (MGs) through a single central information system that receives and sends data in real-time, the objective being to manage its individual units as a single entity. The VPP is therefore an innovative concept mainly based on information technologies (IT) developed for sustainable energy use. Therefore, the interface between VPP and MG including the DERs is provided by the energy management system (EMS) to execute the control strategies. The VPP elements and relationship with power utility are shown in Figure 1.

The EMS is the technical core of the VPP. It is a basic element for the VPP to establish a robust and sustainable energy data management system. EMS is able to collect, store and analyze data from various remote-control devices to schedule ideal operating times for power producers and consumers. For this reason, a VPP adopts the term of intelligent EMS to analyze, communicate and manage all internal and external operations of a microgrid.

The main tasks of EMS are the forecasting of the output power of DERs units, the forecasting of controllable loads, the coordination of power flows between VPP elements, the management of DER units, and the management of storage and consumption units. The purpose of the EMS is to achieve objectives such as minimizing energy production costs, minimizing greenhouse gas emissions, maximizing the profits of energy, or enhancing energy quality. To compensate for the variability, uncertainty, and intermittent nature of RESs in the MG, a collection of DERs, ESS, and controllable loads (CLs) which are aggregated and then are controlled by an EMS can solve this problem.

To minimize the energy consumption in MG systems, the research on the VPP operation scheduling model focuses on how to determine the optimal objective to build the optimization design and obtain the best scheduling. Othman et al. developed an optimal energy management problem by including an unbalanced power distribution system with a VPP with several DERs and various optimization methods are implemented. Khalaf and Wong suggested a two stages stochastic flow shop scheduling problem including intermittent renewable energies, ESS, and real-time electricity pricing. Chuantao et al. proposed an energy management system based on battery logistics by electric vessel to optimize the operation of the pelagic islanded microgrid. Roslan et al. developed an optimized controller for microgrids’ energy management schedule. Hannan et al. introduce an optimal schedule controller to manage renewable energy resources in VPP. Zhou et al. proposed a two-stage scheduling thermostatically controlled loads with RESs for the intraday electricity market. Wei et al. used a two-level scheduling model for VPP operation to reduce the deviation in the net exchange power caused by the forecast error of RESs. Hooshmand et al. proposed a comprehensive framework for standard and contingency situations for different PPVs in a real-time market. Shayegan Rad et al. proposed a stochastic scheduling design to evaluate the optimal performance of DERs of a VPP. Gerami Moghaddam presented a scheduling model for a VPP consisting of multiple DERs. Abbasi et al. designed an intra-day and real-time scheduling algorithm for German electricity market regulations. Derakhshandeh et al. presented a scenario-based stochastic generation scheduling framework considering uncertainties in industrial microgrids. Zhang et al. proposed a framework for a distribution system operator to schedule DERs. Samimi et al. presented a robust active/reactive scheduling framework for smart distribution networks. Naughton et al. introduced a framework that co-optimizes the VPP services.

In light of the above analysis, the optimal operation of the VPP must satisfy various optimization conditions and scheduling planning become a multi-objective scheduling problem. To resolve the multi-objective scheduling problems, Samimi et al. proposed an information gap theory approach.

![Figure 1: VPP elements. VPP, virtual power plant.](image-url)
Qiu et al.,\textsuperscript{27} employed the enhanced particle swarm optimization (PSO) algorithm. Javadi et al.,\textsuperscript{28} used the augmented epsilon-constraint method, the fuzzy satisfactory decision procedure is adopted in this study. Ju et al.,\textsuperscript{29} proposed a hybrid three-stage smart solution algorithm: the entropy weight method, featuring the particle swarm optimization algorithm and the fuzzy satisfaction theory. Paterakis\textsuperscript{30} introduced a new method based on an enhanced variant of the epsilon-constraint approach. In the study conducted by Duan et al.,\textsuperscript{31} a multi-objective feasibility enhanced particle swarm optimization (MOFEPSON) algorithm was used and compared with other algorithms such as multi-objective cuckoo search optimization, multi-objective bat algorithm, multi-objective particle swarm optimization, and multi-objective gray wolf optimization algorithm. The experimental results of this comparison prove that the adopted MOFEPSON algorithm has better optimization performance than other algorithms, with more ability to generate particle swarms to facilitate global optimization.

In this study, the MOFEPSON algorithm was used to find the optimal schedule for EMS based on VPP.
integrating PV, microturbine (MT), CCHP, and a battery as a storage system for a 24-h time period in different seasons of the year using an Algerian real building-MG. MOFEPSO algorithm has the advantage of simple compilation, easy manipulation, a high convergence rate, and low storage requirement. 100 iterations are executed to obtain the best schedule to achieve the objective of minimizing the power cost, reducing peak load, and reducing greenhouse gas emissions in the MG.

The main contribution of this study is the adoption of a multi-objective optimization algorithm to manage the power exchange between the different elements of the MG and the public grid to:

- Reduce the costs of producing electricity, purchasing energy from the utility, and ESS costs.
- Achieve optimum operational cost with the best VPP scheduling to achieve stable and efficient power generation.
- Achieving the greenhouse gas emission reduction objective.
- The realistic case of an Algerian tertiary building MG has been numerically studied by applying the MOFP-SO algorithm.

The rest of the work is organized as follows: In Section 2, the objective functions and associated constraints are discussed. In Section 3, the MOFEPSO algorithm is
presented and formulated as an optimization approach. In Section 4, the simulation results of different cases are presented and evaluated. Finally, some conclusions are presented in Section 5.

2 | OPTIMIZATION MODEL

The multi-objective economic/emission optimal EMS for scheduling MG integrated VPP is defined as a problem of allocating the optimal set points for the power generation units as well as the appropriate ON or OFF states to DERs units so that the operating cost of the MG and the net emission of pollutants is minimized at the same time while satisfying the equality and inequality constraints. The mathematical model of the problem is expressed as follows.

2.1 | Objectives

The global operating cost can include the DERs fuel cost, the start-up/shutdown cost, and the power cost
exchange between the VPP and utility. The objective functions are similar to that used by Moghaddam et al.\textsuperscript{32}

2.1.1 | Objective 1: Cost minimization

The objective function can be formulated as follows:

\[
\text{Min } f_1(X) = \sum_{t=1}^{T} \text{Cost}^t = \sum_{t=1}^{T} \left\{ \sum_{i=1}^{N_g} (u_i(t)P_{G_i}(t)C_{G_i}(t)) + S_{G_i}u_i(t) - u_i(t-1)) \right\} \\
+ \sum_{j=1}^{Ns} (u_j(t)P_{G_j}(t)C_{G_j}(t)) + S_{G_j}u_j(t) - u_j(t-1)) \right\} + P_{\text{Grid}}(t)C_{\text{Grid}}(t),
\]

where

\[
X = [P_g, U_g] 1 \times 2nT,
\]

\[
P_g = [P_{G_1}, P_{G_3}],
\]

\[
n = N_g + N_s + 1.
\]

These variables can be described as follows:

\[
PG = [P_{G_1}, P_{G_2}, ..., P_{G,N_g}],
\]

\[
P_G = [P_{G_{1}}, P_{G_{2}}, ..., P_{G_{(T)}}];
\]

\[
P_s = [P_{S_1}, P_{S_2}, ..., P_{S,N_s}],
\]

\[
P_j = [P_j(1), P_j(2), ..., P_j(t), ..., P_j(T)];
\]

\[
U_g = [u_1, u_2, ..., u_n] = [u_i]_{1 \times N} \in \{0, 1\};
\]

\[
u_k = [u_k(1), u_k(2), ..., u_k(t), ..., u_k(T)];
\]

2.1.2 | Objective 2: Emission minimization

In this step, the environmental impacts of atmospheric pollutants are considered as the second objective. The second objective can be described as follows:

\[
\text{Min } f_2(X) = \sum_{t=1}^{T} \text{Emission}^t = \sum_{t=1}^{T} \left\{ \sum_{i=1}^{N_g} [u_i(t)P_{G_i}(t)E_{G_i}(t)] \\
+ \sum_{j=1}^{Ns} [u_j(t)P_{G_j}(t)E_{G_j}(t)] \\
+ P_{\text{Grid}}(t)E_{\text{Grid}}(t) \right\},
\]

The emission variables are as follows:

\[
E_{G_i}(t) = CO_{2G_i}(t) + SO_{2G_i}(t) + NOX_{G_i}(t),
\]

\[
E_{G_j}(t) = CO_{2G_j}(t) + SO_{2G_j}(t) + NOX_{G_j}(t),
\]

\[
E_{\text{Grid}}(t) = CO_{2\text{Grid}}(t) + SO_{2\text{Grid}}(t) + NOX_{\text{Grid}}(t).
\]
FIGURE 7 Daily load curve in MG test system. MG, micro-grid.
2.2 | MG constraints

2.2.1 | Power balance constraint

The total power production of DERs must satisfy the total demand inside the MG.

\[ \sum_{i=1}^{N_t} P_{gi}(t) + \sum_{j=1}^{N_j} P_{sj}(t) + P_{grid}(t) = \sum_{k=1}^{N_k} P_{lk}(t). \] (15)

2.2.2 | Energy production capacity

The active power of each DER unit is limited by lower and upper limits as follows:

\[ P_{gi,\text{min}}(t) \leq P_{gi}(t) \leq P_{gi,\text{max}}(t), \] (16)

\[ P_{sj,\text{min}}(t) \leq P_{sj}(t) \leq P_{sj,\text{max}}(t), \] (17)

\[ P_{grid,\text{min}}(t) \leq P_{grid}(t) \leq P_{grid,\text{max}}(t). \] (18)

2.2.3 | Storage limits

The following equation and constraints are expressed for a typical battery:

\[ W_{\text{ess}}(t) = W_{\text{ess}}(t-1) + \eta_{\text{charge}} P_{\text{charge}} \Delta t \]

\[ - \frac{1}{\eta_{\text{discharge}}} P_{\text{discharge}} \Delta t, \] (19)

\[ W_{\text{ess min}} \leq W_{\text{ess}}(t) \leq W_{\text{ess max}}; \ t = 1, \ldots, T, \] (20)

\[ P_{\text{charge}}(t) \leq P_{\text{charge max}} X(t); \ t = 1, \ldots, T; \ X \in [0, 1], \] (21)

\[ P_{\text{discharge}}(t) \leq P_{\text{discharge max}} Y(t); \ t = 1, \ldots, T; \ Y \in \{0, 1\}. \] (22)

3 | THE PROPOSED MOFEPSO METHOD

The method presented is based on the Particle Swarm Optimization (PSO) approach which deals exclusively with a single objective optimization problem. The new approach labeled MOFEPSO is an improved method using a Pareto dominance technique to address the multi-objective problem proposed by Sinan Hasanoglu and Dolen.\textsuperscript{33} To address severely constrained multi-objective optimization problem. MOFEPSO approach is based on the PSO technique and uses non-dominated and achievable position or solution reference frames to control the flight of achievable particles. Unlike its equivalents, MOFEPSO does not depend on any feasible solution in the initial swarm. In addition, objective functions are not evaluated for unfeasible particles. These particles fly in sensible directions, they are not allowed to move to a position where the previously satisfied constraint is violated. These specific characteristics allow MOFEPSO to gradually increase the global feasibility of the swarm and reach the optimal solution.

3.1 | Formalization

There are different objective functions required to be optimized simultaneously considering a set of equality and inequality constraints in a multi-objective optimization problem. These problems can be defined in the following general form:
\[ y = f(x) = [f_1(x), f_2(x), \ldots, f_K(x)]^T. \] (23)

Subject to:
\[ g_m(x) \leq 0, \quad m \in \mathbb{N}_{>0}^M, \] (24)

\[ h_p(x) = 0, \quad p \in \mathbb{N}_{>0}^P, \]

\[ x = [x_1, x_2, \ldots, x_N]^T \in \mathbb{R}^{N \times 1}. \] (25)

Each decision variable has minimum and maximum limits such that:

FIGURE 8  Forecasted power outputs from RESs. RES, renewable energy source.
### Table 2  
Comparison of total cost and emission.

| Season | Total cost without DERs ($) | Total cost with DERs ($) | Cost reduction (%) | Total emission without DERs (kg) | Total emission with DERs (kg) | Emission reduction (%) |
|--------|-----------------------------|--------------------------|-------------------|---------------------------------|------------------------------|------------------------|
| Winter | 7,184,922                   | 2,729,213                | 62,015            | 13,799,016                      | 11,600,002                   | 15,936                 |
| Spring | 5,795,226                   | 2,476,602                | 57,265            | 10,749,288                      | 7,318,472                    | 31,917                 |
| Summer | 10,332,88                   | 3,114,662                | 69,857            | 22,156,767                      | 20,620,001                   | 6936                   |
| Autumn | 5,485,338                   | 1,626,337                | 70,351            | 11,907,984                      | 985,811                      | 17,214                 |

Abbreviation: DER, distributed energy resource.

### Table 3  
Economic power scheduling using MOFEPSO in winter.

| Time (h) | Electrical load (MW) | Utility cost ($/kWh) | Output power (MW) | Scheduling |
|----------|----------------------|----------------------|-------------------|------------|
|          |                      |                      |       | Utility | PV | MT | CCHPe | ESS |
| 1        | 0.120                | 0.043                | 0.170            | 0.000 | 0.000 | 0.020 | −0.070 | 1 | 0 | 0 | 1 | 1 |
| 2        | 0.174                | 0.043                | 0.215            | 0.000 | 0.000 | 0.029 | −0.070 | 1 | 0 | 0 | 1 | 1 |
| 3        | 0.210                | 0.043                | 0.245            | 0.000 | 0.000 | 0.035 | −0.070 | 1 | 0 | 0 | 1 | 1 |
| 4        | 0.240                | 0.043                | 0.270            | 0.000 | 0.000 | 0.040 | −0.070 | 1 | 0 | 0 | 1 | 1 |
| 5        | 0.516                | 0.043                | 0.500            | 0.000 | 0.000 | 0.086 | −0.070 | 1 | 0 | 0 | 1 | 1 |
| 6        | 0.738                | 0.043                | 0.685            | 0.000 | 0.000 | 0.123 | −0.070 | 1 | 0 | 0 | 1 | 1 |
| 7        | 1.224                | 0.099                | 1.020            | 0.000 | 0.000 | 0.204 | 0.000 | 1 | 0 | 0 | 1 | 0 |
| 8        | 0.900                | 0.099                | 0.750            | 0.000 | 0.000 | 0.150 | 0.000 | 1 | 0 | 0 | 1 | 0 |
| 9        | 1.290                | 0.099                | 0.566            | 0.509 | 0.000 | 0.215 | 0.000 | 1 | 1 | 0 | 1 | 0 |
| 10       | 1.590                | 0.099                | 0.636            | 0.689 | 0.000 | 0.265 | 0.000 | 1 | 1 | 0 | 1 | 0 |
| 11       | 1.824                | 0.099                | 0.747            | 0.773 | 0.000 | 0.304 | 0.000 | 1 | 1 | 0 | 1 | 0 |
| 12       | 1.920                | 0.099                | 0.786            | 0.814 | 0.000 | 0.320 | 0.000 | 1 | 1 | 0 | 1 | 0 |
| 13       | 2.352                | 0.099                | 1.134            | 0.826 | 0.000 | 0.392 | 0.000 | 1 | 1 | 0 | 1 | 0 |
| 14       | 2.028                | 0.099                | 0.876            | 0.814 | 0.000 | 0.338 | 0.000 | 1 | 1 | 0 | 1 | 0 |
| 15       | 2.070                | 0.099                | 0.952            | 0.773 | 0.000 | 0.345 | 0.000 | 1 | 1 | 0 | 1 | 0 |
| 16       | 2.784                | 0.099                | 1.631            | 0.689 | 0.000 | 0.464 | 0.000 | 1 | 1 | 0 | 1 | 0 |
| 17       | 1.578                | 0.099                | 0.806            | 0.509 | 0.000 | 0.263 | 0.000 | 1 | 1 | 0 | 1 | 0 |
| 18       | 3.468                | 0.478                | 0.000            | 0.000 | 2.890 | 0.578 | 0.000 | 0 | 0 | 1 | 1 | 0 |
| 19       | 1.806                | 0.478                | 0.000            | 0.000 | 1.505 | 0.301 | 0.000 | 0 | 0 | 1 | 1 | 0 |
| 20       | 4.308                | 0.478                | 0.000            | 0.000 | 3.100 | 0.718 | 0.490 | 0 | 0 | 1 | 1 | 1 |
| 21       | 1.068                | 0.478                | 0.000            | 0.000 | 0.890 | 0.178 | 0.000 | 0 | 0 | 1 | 1 | 0 |
| 22       | 0.480                | 0.099                | 0.400            | 0.000 | 0.000 | 0.080 | 0.000 | 0 | 0 | 0 | 1 | 0 |
| 23       | 0.186                | 0.099                | 0.155            | 0.000 | 0.000 | 0.031 | 0.000 | 1 | 0 | 0 | 1 | 0 |
| 24       | 0.138                | 0.043                | 0.185            | 0.000 | 0.000 | 0.023 | −0.070 | 1 | 0 | 0 | 1 | 1 |

Abbreviations: CCHPe, combined cooling heating and power electrical power production; ESS, energy storage system; MOFEPSO, multi-objective feasibility enhanced particle swarm optimization; MT, microturbine; PV, photovoltaic.
TABLE 4  Economic power scheduling using MOFEPSO in spring.

| Time (h) | Electrical load (MW) | Utility cost ($/kWh) | Output power (MW) | Scheduling Utility PV MT CCHPe ESS |
|----------|---------------------|----------------------|-------------------|-------------------------------|
| 1        | 0.090               | 0.043                | 0.145             | 0.000                         | 0.015 | -0.070 | 1 0 0 1 1 |
| 2        | 0.102               | 0.043                | 0.155             | 0.000                         | 0.017 | -0.070 | 1 0 0 1 1 |
| 3        | 0.084               | 0.043                | 0.140             | 0.000                         | 0.014 | -0.070 | 1 0 0 1 1 |
| 4        | 0.186               | 0.043                | 0.225             | 0.000                         | 0.031 | -0.070 | 1 0 0 1 1 |
| 5        | 0.564               | 0.043                | 0.540             | 0.000                         | 0.094 | -0.070 | 1 0 0 1 1 |
| 6        | 0.924               | 0.043                | 0.840             | 0.000                         | 0.154 | -0.070 | 1 0 0 1 1 |
| 7        | 0.348               | 0.099                | -0.204            | 0.314                         | 0.058 | 0.000   | 1 1 1 0 1 |
| 8        | 0.366               | 0.099                | -0.288            | 0.593                         | 0.061 | 0.000   | 1 1 0 1 0 |
| 9        | 0.978               | 0.099                | 0.090             | 0.725                         | 0.163 | 0.000   | 1 1 0 1 0 |
| 10       | 1.212               | 0.099                | 0.211             | 0.799                         | 0.202 | 0.000   | 1 1 0 1 0 |
| 11       | 1.386               | 0.099                | 0.315             | 0.840                         | 0.231 | 0.000   | 1 1 0 1 0 |
| 12       | 1.320               | 0.099                | 0.237             | 0.863                         | 0.220 | 0.000   | 1 1 0 1 0 |
| 13       | 1.266               | 0.099                | 0.185             | 0.870                         | 0.211 | 0.000   | 1 1 0 1 0 |
| 14       | 1.788               | 0.099                | 0.627             | 0.863                         | 0.298 | 0.000   | 1 1 0 1 0 |
| 15       | 1.548               | 0.099                | 0.450             | 0.840                         | 0.258 | 0.000   | 1 1 0 1 0 |
| 16       | 1.572               | 0.099                | 0.511             | 0.799                         | 0.262 | 0.000   | 1 1 0 1 0 |
| 17       | 2.118               | 0.099                | 1.040             | 0.725                         | 0.353 | 0.000   | 1 1 0 1 0 |
| 18       | 1.200               | 0.478                | 0.000             | 0.593                         | 0.407 | 0.200   | 0 1 1 1 0 |
| 19       | 1.758               | 0.478                | 0.000             | 0.314                         | 1.151 | 0.293   | 0 1 1 1 0 |
| 20       | 2.640               | 0.478                | 0.000             | 0.000                         | 2.200 | 0.440   | 0 0 1 1 0 |
| 21       | 3.276               | 0.478                | 0.000             | 0.000                         | 2.240 | 0.546   | 0 0 1 1 1 |
| 22       | 0.804               | 0.099                | 0.670             | 0.000                         | 0.134 | 0.000   | 1 0 0 1 0 |
| 23       | 0.102               | 0.099                | 0.085             | 0.000                         | 0.017 | 0.000   | 1 0 0 1 0 |
| 24       | 0.084               | 0.043                | 0.140             | 0.000                         | 0.014 | -0.070 | 1 0 0 1 1 |

Abbreviations: CCHPe, combined cooling heating and power electrical power production; ESS, energy storage system; MOFEPSO, multi-objective feasibility enhanced particle swarm optimization; MT, microturbine; PV, photovoltaic.

\[ x_n^L \leq x_n \leq x_n^U, \quad n \in \mathbb{N}_{>0}^N. \]  

(26)

All equality constraints are transformed into inequality constraints using:

\[ |h_p(x)| - \varepsilon \leq 0. \]  

(27)

A flowchart illustrating how MOFEPSO operates is presented in Figure 2.

3.2 Initialization

The initialization routines should be performed before the main iterations of the MOFEPSO in Figure 3.

The initialization routine is summarized in the flowchart shown in Figure 2. The random initialization of the MOFEPSO starts with an initialization of the position matrix \( X \) and the velocity matrix \( V \). These matrices can be defined as follows:

\[ X = [x_{1,n}] \in \mathbb{R}^{L \times N}, \]  

(28)

\[ V = [v_{1,n}] \in \mathbb{R}^{L \times N}, \quad i \in \mathbb{N}_{>0}^L \quad \text{and} \quad n \in \mathbb{N}_{>0}^N, \]  

(29)

\[ x_{i,n} = [x_{i,1} \ x_{i,2} \ ... \ x_{i,N}], \]  

(30)

\[ v_{i,n} = a^\nu (2r - 1)(x_{i,n}^U - x_{i,n}^L), \quad r \in [0, 1] \subset \mathbb{R}, \]  

(31)

\[ a^\nu = 0.3. \]
### Table 5: Economic power scheduling using MOFEPSO in summer.

| Time (h) | Electrical load (MW) | Utility cost ($/kWh) | Output power (MW) | Scheduling |
|----------|----------------------|-----------------------|-------------------|------------|
|          |                      |                       | Utility PV | MT | CCHPe | ESS | Utility PV | MT | CCHPe | ESS |
| 1        | 0.165                | 0.043                 | 0.208     | 0.000 | 0.000 | 0.028 | 0.000     | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1 | 0 | 0 | 1 | 1 |
| 2        | 0.341                | 0.043                 | 0.354     | 0.000 | 0.000 | 0.057 | 0.000     | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1 | 0 | 0 | 1 | 1 |
| 3        | 1.042                | 0.043                 | 0.939     | 0.000 | 0.000 | 0.174 | 0.000     | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1 | 0 | 0 | 1 | 1 |
| 4        | 1.716                | 0.043                 | 1.500     | 0.000 | 0.000 | 0.286 | 0.000     | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1 | 0 | 0 | 1 | 1 |
| 5        | 0.643                | 0.043                 | 0.606     | 0.000 | 0.000 | 0.107 | 0.000     | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1 | 0 | 0 | 1 | 1 |
| 6        | 0.415                | 0.043                 | 0.384     | 0.032 | 0.000 | 0.069 | 0.000     | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 1 | 1 | 0 | 1 | 1 |
| 7        | 0.370                | 0.099                 | 0.004     | 0.319 | 0.000 | 0.047 | 0.000     | 0.000 | 1 | 1 | 0 | 1 | 0 | 0 |
| 8        | 0.664                | 0.099                 | 0.005     | 0.552 | 0.000 | 0.107 | 0.000     | 0.000 | 1 | 1 | 0 | 1 | 0 | 0 |
| 9        | 1.816                | 0.099                 | 0.829     | 0.684 | 0.000 | 0.303 | 0.000     | 0.000 | 1 | 1 | 0 | 1 | 0 | 0 |
| 10       | 2.239                | 0.099                 | 1.113     | 0.753 | 0.000 | 0.373 | 0.000     | 0.000 | 1 | 1 | 0 | 1 | 0 | 0 |
| 11       | 2.570                | 0.099                 | 1.346     | 0.796 | 0.000 | 0.428 | 0.000     | 0.000 | 1 | 1 | 0 | 1 | 0 | 0 |
| 12       | 2.443                | 0.099                 | 1.215     | 0.821 | 0.000 | 0.407 | 0.000     | 0.000 | 1 | 1 | 0 | 1 | 0 | 0 |
| 13       | 2.351                | 0.099                 | 1.130     | 0.829 | 0.000 | 0.392 | 0.000     | 0.000 | 1 | 1 | 0 | 1 | 0 | 0 |
| 14       | 3.312                | 0.099                 | 1.939     | 0.821 | 0.000 | 0.552 | 0.000     | 0.000 | 1 | 1 | 0 | 1 | 0 | 0 |
| 15       | 2.858                | 0.099                 | 1.586     | 0.796 | 0.000 | 0.476 | 0.000     | 0.000 | 1 | 1 | 0 | 1 | 0 | 0 |
| 16       | 2.788                | 0.099                 | 1.570     | 0.753 | 0.000 | 0.465 | 0.000     | 0.000 | 1 | 1 | 0 | 1 | 0 | 0 |
| 17       | 2.901                | 0.099                 | 1.733     | 0.684 | 0.000 | 0.483 | 0.000     | 0.000 | 1 | 1 | 0 | 1 | 0 | 0 |
| 18       | 3.923                | 0.478                 | 0.000     | 0.552 | 2.717 | 0.654 | 0.000     | 0.000 | 1 | 1 | 1 | 1 | 0 | 0 |
| 19       | 2.219                | 0.478                 | 0.000     | 0.319 | 1.530 | 0.370 | 0.000     | 0.000 | 0 | 1 | 1 | 1 | 0 | 0 |
| 20       | 3.249                | 0.478                 | 0.000     | 0.032 | 2.676 | 0.542 | 0.000     | 0.000 | 0 | 1 | 1 | 1 | 0 | 0 |
| 21       | 4.886                | 0.478                 | 0.000     | 0.000 | 3.851 | 0.814 | 0.490     | 0 | 0 | 1 | 1 | 1 | 1 |
| 22       | 2.541                | 0.099                 | 0.000     | 0.000 | 2.118 | 0.424 | 0.000     | 0 | 0 | 0 | 1 | 1 | 0 |
| 23       | 6.069                | 0.099                 | 0.000     | 0.000 | 5.057 | 1.011 | 0.490     | 0 | 0 | 0 | 1 | 1 | 0 |
| 24       | 1.488                | 0.043                 | 1.310     | 0.000 | 0.000 | 0.248 | 0.000     | 0.000 | 0 | 0 | 0 | 1 | 1 | 1 |

Abbreviations: CCHPe, combined cooling heating and power electrical power production; ESS, energy storage system; MOFEPSO, multi-objective feasibility enhanced particle swarm optimization; MT, microturbine; PV, photovoltaic.

After the initialization, the constraint matrix is calculated such that:

\[
C = [c_{i,m}] \in \mathbb{R}^{I \times M},
\]

\[
c_{i,*} = [g_1(x_{i,*}^T) \ g_2(x_{i,*}^T) \cdots g_M(x_{i,*}^T)].
\]

The next step is to determine the set of best global positions \(B\) (gbest), and the set of best local positions \(D_i\) (pbest).

\[
B = \left\{ b_\emptyset = (b_\emptyset^X, b_\emptyset^Y) \mid \emptyset \in \mathbb{N}_{>0} \right\},
\]

\[
D_i = \left\{ d_{i,\omega} = (d_{i,\omega}^X, d_{i,\omega}^Y) \mid \omega \in \mathbb{N}_{>0} \right\}. \tag{35}
\]

The positions can only be in the pbest or gbest sets if they are feasible.

### 4.1 Case description (Figure 4)

To evaluate the performance of the proposed algorithm for the optimal scheduling of the energy management system, an Algerian building MG is defined as the test...
system. This system is consisted of two PVs (2 × 0.5 MW), four CCHPs (4 × 1.058 MW), three MTs (2 × 2.5 MW, +1 × 0.4 MW), and two ESSs (2 × 0.225 MW). The assumption is that all the DREs produce only active power. The total load is composed of cold/heat load and electrical load. As shown in Figure 5, the cold/heat load is supplied only by the CCHPth power, while the electrical load is supplied by the utility, CCHP electrical power production (CCHPe), PV power, MT power, and ESS. The CCHPe power is estimated at 25% of the thermal power produced. The MG test system single line diagram is illustrated in Figure 4.

The hourly forecasted utility energy prices for the period under review are represented in Figure 6.34 The total load demand within the MG over a 24-h period on a typical day of each season of the year is shown in Figure 7. The maximum and the minimum power generation limits, cost information, startup/shut-down costs, and emissions for each unit are given in Table 1. The power outputs achieved from RESs are shown in Figure 8.35

### 4.2 Simulation

In this simulation, it is supposed that all DERs produce electricity within their capacity limits while respecting the required constraints. The initial charge of the battery is zero. The DERs can switch between ON/OFF modes. The simulation results for the four seasons of the year are

| Time (h) | Electrical load (MW) | Utility cost ($/kWh) | Output power (MW) | Scheduling |
|----------|----------------------|----------------------|-------------------|------------|
|          |                      |                      |       Utility PV MT CCHPe ESS | Utility PV MT CCHPe ESS |
|          |                      |                      | 0.096 0.043 0.160 0.000 0.000 0.016 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 0.108 0.043 0.160 0.000 0.000 0.018 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 0.090 0.043 0.145 0.000 0.000 0.015 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 0.198 0.043 0.235 0.000 0.000 0.033 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 0.594 0.043 0.565 0.000 0.000 0.099 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 0.978 0.043 0.885 0.000 0.000 0.163 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 0.366 0.099 0.305 0.000 0.000 0.061 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 0.390 0.099 0.086 0.239 0.000 0.065 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 1.032 0.099 0.328 0.532 0.000 0.172 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 1.278 0.099 0.390 0.675 0.000 0.213 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 1.464 0.099 0.470 0.750 0.000 0.244 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 1.392 0.099 0.373 0.787 0.000 0.232 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 1.338 0.099 0.317 0.798 0.000 0.223 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 1.890 0.099 0.788 0.787 0.000 0.315 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 1.632 0.099 0.610 0.750 0.000 0.272 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 1.656 0.099 0.705 0.675 0.000 0.276 0.061 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 2.238 0.099 1.333 0.532 0.000 0.373 0.315 0.000 1 0 0 1 0 | 1 0 0 1 0 |
|          |                      |                      | 1.266 0.478 0.000 0.239 0.816 0.211 0.000 0 1 1 1 0 | 0 1 1 1 0 |
|          |                      |                      | 1.854 0.478 0.000 0.000 1.545 0.309 0.000 0 0 1 1 0 | 0 0 1 1 0 |
|          |                      |                      | 2.784 0.478 0.000 0.000 2.320 0.464 0.000 0 0 1 1 0 | 0 0 1 1 0 |
|          |                      |                      | 1.446 0.478 0.000 0.000 0.715 0.241 0.000 0 0 1 1 1 | 0 0 1 1 1 |
|          |                      |                      | 3.462 0.099 0.000 0.000 2.885 0.577 0.000 0 0 1 1 0 | 0 0 1 1 0 |
|          |                      |                      | 0.846 0.099 0.705 0.000 0.000 0.141 0.000 0 1 0 1 0 | 0 1 0 1 0 |
|          |                      |                      | 0.900 0.043 0.145 0.000 0.000 0.015 0.000 0 0 0 1 1 | 0 0 0 1 1 |

Abbreviations: CCHPe, combined cooling heating and power electrical power production; ESS, energy storage system; MOFEPSO, multi-objective feasibility enhanced particle swarm optimization; MT, microturbine; PV, photovoltaic.
FIGURE 9  Power balance curve of DERs microgrid optimal scheduling. DER, distributed energy resource; ESS, energy storage system; MT, microturbine; PV, photovoltaic.
presented in Table 2. The output power of the DERs in winter, spring, summer, and autumn is tabulated respectively in Tables 3–6. The power balance curve of DERs microgrid optimal scheduling is shown in Figure 9.

As shown in Tables 3–6, the utility takes the initiative to provide load demand within the MG during the early hours of the day when utility cost is low. It is an economic policy to reduce the total cost of MG. Other DERs, such as PV and CCHP, produce power at its maximum rate during most hours of the day. Because of the continuous demand for heating and cooling energy in MG throughout the day, the CCHP is always switched ON mode. Generally, the ESS is charged in the early hours of the day when load demand and utility cost are low. This event shows that it is more efficient to charge the ESS using utility to reduce peak load demand and cost later. During the high utility cost period, the battery is discharged at times of high load demand to supply the MG. In terms of the objective functions, MT start up only when there is a peak periods of load demand and when the utility cost is high. As can be seen in Figure 9, from the 18th to the 22nd hour of the day, the MG generally operates in standalone mode, which is very economical and approves the efficiency of the proposed algorithm for the optimal scheduling of energy management system used in this study.

As Figure 10 shows, the contribution of the utility to the power balance is reduced to 22.75% in the spring.
season when the production of RESs is favorable. Similarly, in the winter season which represents the unfavorable case for the production of RESs, the participation of the network is also reduced up to 37.07%. The participation of the DERs in the power balance is increased with an average rate of 69.74%. The CCHPe energy participation is practically constant with a rate of 16.66%, this participation rate greatly depends on the site weather zone, it works with maximum efficiency where heating and cooling demands are mostly uniform through most of the year.

According to Table 2, the total cost and the total emission in the MG without DERs are the highest, while after the integration of DERs and the multi-objective optimization algorithm, the total cost and total emission are reduced. In summary, the results of the proposed optimal energy management system for scheduling MG integrated VPP can significantly reduce the cost and reduce the emission by 70.35% and 31.91%, respectively. So, the scheduling strategy proposed in this paper is effective and economical.

5 Conclusion

In this paper, the concept of VPP with multi-objective feasibility enhanced particle swarm optimization algorithm is introduced and applied to solve the optimal scheduling MG integrating VPP with DERs for an Algerian reel MG-building generation. To study the performance of the proposed methodology, several season cases were proposed. The statistical results indicate that the proposed optimization approach reduced the operating cost which includes the fuel costs of DERs, start-up/shut-down costs, and utility costs. At the same time, the algorithm can reduce the amount of CO₂, SO₂, and NOₓ gases significantly. Scheduling DERs from peak to off-peak also reduces the peak load, which significantly increases the reliability of the utility. Overall, the result showed the reliable and satisfying performance of the proposed algorithm for managing the MG including PV, micro-turbines, ESS, and CCHP generation and leads to better performance for VPP. Future work also considers another optimal energy management approach to further reduce total operating cost and net emissions, as well as extending the work to consider the energy selling to utilities.

NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| C_d(t) | bids of the DERs at hour t |
| C_s(t) | bids of storage at hour t |
| S_gi | start-up or shut-down costs for ith DER |
| P_grid(t) | active power which is bought from the utility at time t |
| C_grid(t) | bid of utility at time t |
| X | variables vector which includes active power of units |
| n | number of state variables |
| N_g | number of generation units |
| N_s | number of storage unit |
| P_g | power vector including active powers of DERs generation units |
| U_g | vector of ON or OFF states of all units during each hour of the day |
| T | total number of hours |
| P_gi(t) | real power outputs of ith generator at time t |
| P_sj(t) | real power outputs of jth storage unit at time t |
| u_k(t) | status of unit k at hour t |
| E_grid(t) | amount of pollutants emission in kg MW h⁻¹ for utility at hour t |
| E_gi(t) | amount of pollutants emission in kg MW h⁻¹ for each generator at hour t |
| E_sj(t) | amount of pollutants emission in kg MW h⁻¹ for storage at hour t |
| CO₂(t) | amounts of CO₂ emission from ith DER sources at hour t |
| SO₂(t) | amounts of CO₂ emission from ith DER sources at hour t |
| NOₓ(t) | amounts of NOₓ emission from ith DER sources at hour t |
| CO₂_storage(t) | amounts of CO₂ emission from jth storage unit at tth hours of the day |
| SO₂_storage(t) | amounts of SO₂ emission from jth storage unit at tth hours of the day |
| NOₓ_storage(t) | amounts of NOₓ emission from jth storage unit at tth hours of the day |
| CO₂_grid(t) | amounts of CO₂ emission from utility at hour t |
| SO₂_grid(t) | amounts of SO₂ emission from utility at hour t |
| NOₓ_grid(t) | amounts of NOₓ emission from utility at hour t |
| P_lk | amount of kth load level and N_k is the total number of load levels |
| P_g_min(t) | minimum active powers of ith DER |
| P_s_min(t) | minimum active powers of jth storage unit |
| P_grid-min(t) | minimum active powers of utility at the time t |
| P_g_max(t) | maximum active power generation of corresponding DERs at hour t |
| P_s_max(t) | maximum active powers generation of storage at the time t |
\( P_{\text{grid}, \text{max}}(t) \) maximum active power generation of utility at hour \( t \)

\( W_{\text{ess}}(t) \) amount of energy storage inside the battery at hour \( t \)

\( P_{\text{charge}} \) permitted rate of charge during a period of time \( \Delta t \)

\( P_{\text{discharge}} \) permitted rate of discharge during a period of time \( \Delta t \)

\( \eta_{\text{charge}} \) efficiency of the battery during charge process

\( \eta_{\text{discharge}} \) efficiency of the battery during discharge process

\( W_{\text{ess min}} \) lower limits on amount of energy storage inside the battery

\( W_{\text{ess max}} \) upper limits on amount of energy storage inside the battery

\( P_{\text{charge max}} \) maximum rate of battery charge during each time interval \( \Delta t \)

\( P_{\text{discharge max}} \) maximum rate of battery discharge during each time interval \( \Delta t \)

\( K \) number of objective functions

\( x \) decision vector

\( M \) number of inequality constraints

\( P \) number of equality constraints

\( N \) number of particles in the swarm

\( r \) number of decision variables

\( a^e \) velocity initialization factor

\( \Theta \) number of non-dominated positions

\( \omega \) number of non-dominated positions associated with the \( i \)th particle

**ORCID**

Youssouf Amrane [http://orcid.org/0000-0001-9727-8890](http://orcid.org/0000-0001-9727-8890)

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