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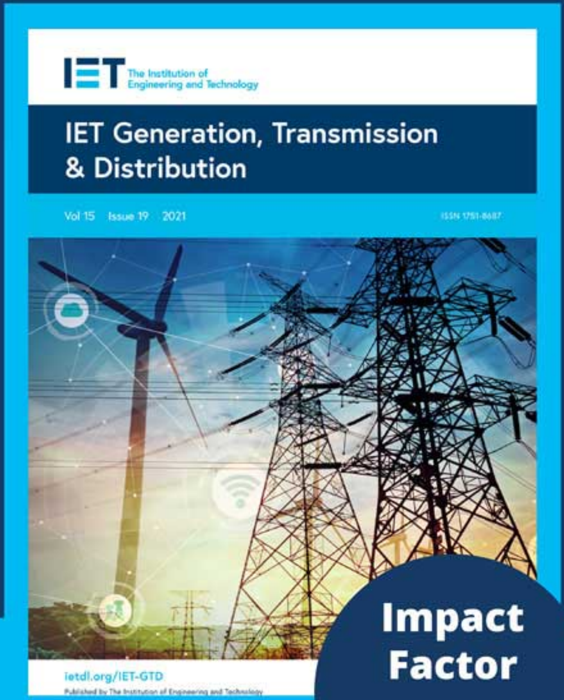

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ORIGINAL RESEARCH PAPER

A multi-objective optimization for planning of networked microgrid using a game theory for peer-to-peer energy trading scheme

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Abstract

In this paper, a multi-objective optimization technique is proposed for the planning of a networked microgrid based on peer-to-grid (P2G) and peer-to-peer (P2P) energy trading schemes. Two different criteria's including annual profit and energy index of reliability are taken into consideration to form a multi-objective function. The networked microgrid consists of three individual microgrids containing their own combinations of generation resources, batteries and residential loads. All microgrids are connected together and also to the main grid to meet the energy exchange requirements of P2P energy trading. A cooperative game theory technique based on a particle swarm optimization algorithm is used to model the networked microgrid, and to find the suitable sizes of the players that simultaneously maximize the payoff values of both objective functions. Besides, a comparative analysis is carried out for both P2G and P2P energy trading schemes. The results show that the outcomes are maximum when both criteria are considered in the optimization and P2P energy trading is carried out. The sensitivity analysis is performed on the selected parameters and verified the right change 0.003% and 4.5% in discount rate and electricity prices, respectively.

1 | INTRODUCTION

Recently, climate changes caused by global warming have become a predominant concern, and a possible solution for these changes is applying environment-friendly mechanisms in power generation [1]. The trend of power generation through renewable resources is increasing despite their intermittent nature, and the storage batteries are used with solar panels and wind turbines for obtaining a reliable and smooth generation [2]. Furthermore, it is very important to choose proper energy trading between the microgrids to have the most economical and efficient system. Peer-to-grid (P2G) is a traditional way of energy trading where microgrids can only do trading with the main grid [3]. But, the peer-to-peer (P2P) is a multidirectional way of energy trading that enables microgrids to act as the prosumers and do energy trading with the neighbouring prosumers, consumers, and the main grid as shown in Figure 1 [4]. Many researchers are conducted on the scheme of P2P energy trading [5–7]. The pricing and energy management of the power system based on different optimization techniques is mostly taken into consideration [8].

The key objectives of designing a power system are to maintain a balance between the power generation and load demand to minimize power outage probability. To meet the requirements, the networked microgrid concept is very useful where multiple microgrids are connected with each other in grid-connected mode, reducing the possibility of a power outage by organizing the load demand in a planned way [9–11]. A networked microgrid consists of multiple microgrids, where each microgrid might contain various generation resources, batteries, and residential load. Compared to the individual microgrid configuration, a networked microgrid enjoys lower cost and emission [12, 13]. Therefore, the suitable sizing of the network components is vital for the efficient and economical use of renewable resources [14, 15]. The correct use of generation resources based on load requirements is assured with the optimum sizing

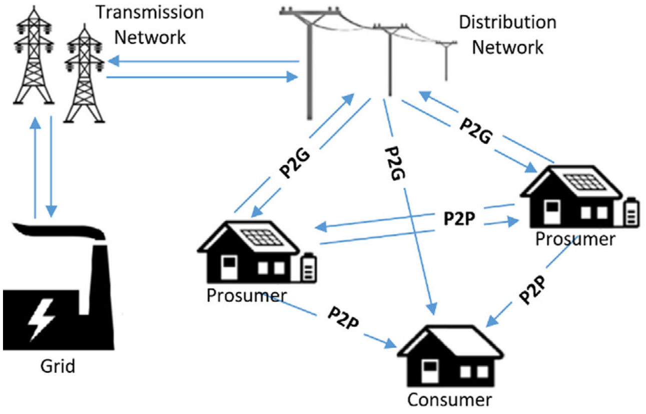

FIGURE 1 P2G and P2P types of energy trading in a network

of the networked microgrid to increase the overall profit resulting in a system with higher performance [16].

In order to optimize a power system, different optimization techniques are used to get maximum outcomes and suitable sizing [17]. In [18], for a 31-bus distribution system, a robust technique based on particle swarm optimization is used for sizing of wind turbines, fuel cells and photovoltaic cells. In [19], optimization of renewable resources, generator and converter is done based on a decision-making technique. To optimize the reliability, installation cost, and emission, a fuzzification mechanism is proposed in [20]. In [21], a technique of loss of power supply probability is proposed to optimum sizing of microgrid for their technical and economic analysis. Apart from different contributions on optimization of P2P energy trading schemes, many researchers have used game theory approaches for the pricing and energy exchange with power systems [22, 23]. Game theory is an approach of decision making, where players, consisting of their strategies and payoff values [24] have multiple choices and solve conflicts among each other. In [25, 26], two cooperative and non-cooperative game theory techniques are explained, and the best one is proposed to find the payoff value based on different objective functions. Designing a networked microgrid based on a game-theoretic technique can be a promising idea to optimize different conflicts based on multi-objective function [27]. In [20], a grid-connected hybrid power system is built through a technique of multi-objective optimization including costs, reliability, and pollutant emissions as criteria to be met. In [25], multi-objective optimization method is adopted for the planning of a hybrid power system and criteria of economy index and reliability index are considered to find the optimum results. A multi-objective optimization is also proposed in [28] to meet the requirements of environment and economic conditions by genetic algorithm, discussing the benefits of single and multi-objective optimization. In [29, 30], a technique of multi-objective optimization is performed for the planning of clustered microgrids and networked microgrids, where different criteria for optimization are considered so that the most suitable sizes for the generation resources and batteries are found. It has seen from the recent researches that multi-objective optimization is increasingly used for the planning of microgrid architectures. In this paper benchmarks of annual profit and energy index of reliability are considered to study and analyse the proposed networked microgrid.

In this paper, a multi-objective optimization is proposed for a networked microgrid based on P2P energy trading scheme. The networked architecture is designed via a cooperative type of game theory technique to get the optimum sizes of the players and payoff value from the proposed multi-objective function. Due to game theory capability to solve decision making problems involving multiple objectives, as well as complex action sequences, it has been used in past and also in recent researches. Game theory helps how strategic interactions effect decisions of individual player in competition, if each player targets to achieve the optimum payoff value. Therefore, in this research an approach of game theory is used to formulate the optimization problem to achieve the optimized results. For the networked microgrid, the multi-objective function is based upon two different criteria including annual profit and energy index of reliability. In the networked microgrid, each microgrid has wind turbines, solar panels and batteries as game players to meet their residential load requirements in grid-connected mode. Both energy trading schemes, P2G and P2P, are analysed and compared to show the excellency of the work. Sensitivity analysis is done based upon technical parameters to verify the stability of the proposed system and validate the results. In the networked microgrid, the real- world data of three remote towns such as Mount Magnet, Laverton, and Wahroonga are considered to optimize the multi-objective function. To build and simulate the networked architecture, the particle swarm optimization (PSO) algorithm is implemented in MATLAB software.

This research work is the continuation of the author's recent research, where a decision making based technique is used in [31, 32] to find the suitable solution and sizes of proposed standalone hybrid power system, the game theory based single-objective optimization techniques are used in [25, 33–35] for the planning of multiple microgrids. Multiple set of microgrids are formulated with respect to the game theory techniques, and a single residential load is connected with the architecture for the planning and optimization of payoff value. In [36], a network microgrid is planned and analysed based on single-objective function, and the P2P energy trading is performed for two microgrids which are connected with different residential loads. Most of recent researches, have more focused on microgrids, with limited research contribution on clustered microgrids where more than one microgrids are considered to perform energy trading. Therefore, in this research, a typical networked microgrids with combinations of three different microgrids, and multi-objective optimization is formulated based on game theory technique to meet the load requirements of three different towns. On the other hand, results are analysed for P2G and P2P energy trading schemes, an innovative real-world data based renewable energy system is modelled and input data is fetched from Australian electricity market to perform the analysis. The contributions of this research are summarised as follows:

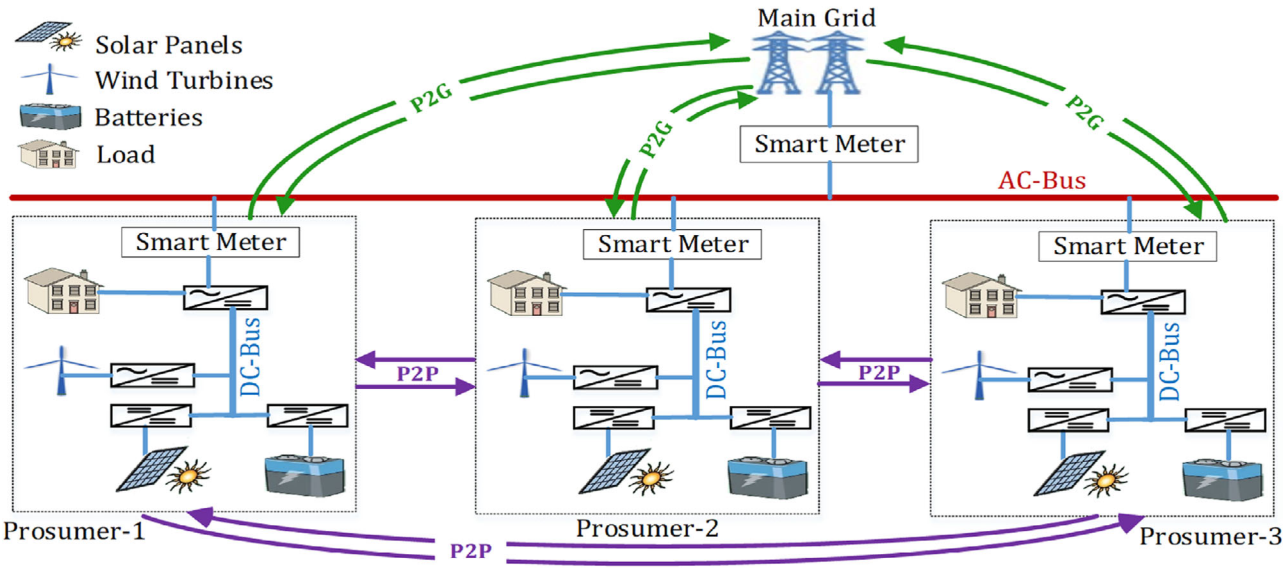

FIGURE 2 Networked microgrid for P2G and P2P energy trading

- A typically networked microgrid is designed that consists of three microgrids and different technical parameters are considered to formulate the architecture.
- A technique of multi-objective optimization is performed based on criteria of annual profit and energy index of reliability. A networked microgrid is then modelled as per Nash equilibrium game theory technique to find the most suitable sizes of the players and optimized payoff values.
- A two-stage control framework is designed for P2P and P2G energy trading, and a comparative analysis between both schemes is accordingly given to validate the results.
- For the proposed networked microgrid, real-world based data of Australian electricity market for weather forecast and load profiles are considered for the analysis to find their most feasible sizes of generation resources, and batteries, and to achieve accurate results.

The remainder of this paper is organized as follows. Section-3 designs the model for networked architecture. In Section-4 problem is formulated with respect to technical constraints. In Section-5 the used game theory techniques for the proposed model are illustrated. Simulation results and analysis are explained in Section-6. In the end, Section-7 has concluding remarks.

2 | THE OPERATION MODEL FOR NETWORKED MICROGRID

In this section, the architecture of networked microgrid is presented in a grid-connected mode for three different microgrids based on a P2P energy trading scheme. A networked microgrid can consist of *n* number of microgrids, but in this research, a simple architecture in which three microgrids are connected with each other through bidirectional power link to do energy exchange is considered. Each microgrid has wind turbines, solar panels, and batteries for power generation to meet the residential load requirements. In the networked microgrid, for P2P energy trading, all microgrids act as prosumers with the capability of buying power shortage and selling excess generated power from/to the main grid and the other prosumers, respectively. In the energy trading scheme, the first priority of the prosumers is to perform the power exchange within the connected prosumers, and any further requirement of power exchange will be fulfilled through the main grid. Smart meters are installed at both sides of distribution and transmission lines to record the values of power generated, transferred, and consumed within the networked microgrid.

Figure 2 illustrates the block diagram of the networked microgrid in which each microgrid is a combination of wind turbines, solar panels, batteries and residential load in the grid-connected mode. A shared dc-link is connected with the solar panels and wind turbines through unidirectional dc/dc and ac/dc converters, respectively. A bidirectional dc/dc converter is connected between storage batteries and a shared dc-link. A dc/ac converter is installed to link dc-bus to the ac-bus and the main grid. The flow of P2G and P2P energy trading is shown within the microgrids, and to or from the main grid. Within the architecture, the cash flow is in the opposite direction of the energy flow for both energy trading schemes. The energy flow refers to the power flow, whereas the cash flow refers to the annual profit obtained from the energy trading schemes. In the networked microgrid, the load requirements of each microgrid are firstly met through its own generated power. If it is not enough, then the microgrid buys the power from one of the microgrid within the architecture that generates excess power. Finally, the main grid will help to meet the requirement if there is any power shortage not provided by prosumers.

3 | PROBLEM FORMULATION AND TECHNICAL CONSTRAINTS

To formulate the multi-objective function, a typical grid-connected networked microgrid is considered based on P2P and P2G energy trading schemes. A technique of cooperative game theory is developed to find the correct sizing of the players and the payoff value [25, 33]. Wind turbines $\mathscr{W}$, solar panels $\mathscr{SP}$, and batteries $\mathscr{B}$ are the decision-making players for each microgrid. The sizes of the players are represented as $\mathscr{P}_{\mathscr{W}}$, $\mathscr{P}_{\mathscr{SP}}$ and $\mathscr{P}_{\mathscr{B}}$, and their strategic spaces are shown as $(\mathscr{P}_{\mathscr{W}}^{min}, \mathscr{P}_{\mathscr{W}}^{max})$, $(\mathscr{P}_{\mathscr{SP}}^{min}, \mathscr{P}_{\mathscr{SP}}^{max})$, and $(\mathscr{P}_{\mathscr{B}}^{min}, \mathscr{P}_{\mathscr{B}}^{max})$ for a wind turbine, solar panel, and battery, respectively. The criteria of annual profit (*APF*) and energy index of reliability (*EIR*) are considered to formulate the multi-objective function for both energy trading schemes.

3.1 | Annual profit

To calculate the annual profit [37] of the networked microgrid for P2G and P2P energy trading schemes, the important technical parameters need to be considered. The maximizing objective function for *APF* is expressed as follow:

$$\mathscr{f}(APF_i) = max(\mathbf{I}_{i_{\mathscr{SE}}} + \mathbf{I}_{i_{\mathscr{SL}}} + \mathbf{I}_{i_{\mathscr{AS}}} - \mathbf{C}_{i_{\mathscr{IN}}} - \mathbf{C}_{i_{\mathscr{OM}}} - \mathbf{C}_{i_{\mathscr{ES}}} - \mathbf{C}_{i_{\mathscr{P}C}}) \tag{1}$$

The power generated by the wind turbine $p_{\mathscr{W}}(t)$ and the storage battery $p_{\mathscr{B}}(t)$ are found as:

$$p_{\mathscr{W}}(t) = \begin{cases} 0 v(t) < v_c or v(t) \geq v_o \\ \dfrac{\mathscr{P}_{\mathscr{W}} * (v(t) - v_c)}{v_r - v_c} v_c \leq v(t) < v_r \\ \mathscr{P}_{\mathscr{W}} v_r \leq v(t) < v_o \end{cases} \tag{2}$$

$$p_{\mathscr{B}}(t) = \begin{cases} p_{\mathscr{B}}(t-1) + \xi_c * \Delta(t-1) \Delta(t-1) \geq 0 \\ p_{\mathscr{B}}(t-1) + \Delta(t-1) \Delta(t-1) < 0 \end{cases} \tag{3}$$

$$\Delta(t-1) = p_{\mathscr{W}}(t-1) + p_{\mathscr{SP}}(t-1) - \mathscr{P}_{\mathscr{D}}(t-1) \tag{4}$$

where $t = 1, 2, 3, \ldots, 8760$ hours. $\mathscr{P}_{\mathscr{D}}(t-1)$ and $\Delta(t-1)$ denote the electrical load $\mathscr{P}_{\mathscr{D}}(t)$ and the difference between the total generation capacity in the hour $(t-1)$.

The design details of solar panels are not considered, and their hourly solar power $p_{\mathscr{SP}}(t)$ is used to define the sunlight fluctuant nature. The annual $\mathbf{C}_{i\_\mathscr{OM}}$ of each player, is found by multiplying its per unit operation and maintenance cost by its generation capacity. The $\mathbf{I}_{i\_\mathscr{AS}}$ of the storage batteries are calculated, and for the wind turbines and the solar panels, its value will be zero. The annual $\mathbf{C}_{i\_\mathscr{IN}}$, $\mathbf{I}_{i\_\mathscr{SL}}$, and $\mathbf{C}_{i\_\mathscr{P}C}$ for the players are:

$$\mathbf{C}_{i\_\mathscr{IN}} = \mathscr{P}_i * \mathscr{U}_i * \mathfrak{D}(1+\mathfrak{D})^{\mathbb{L}_i} / ((1+\mathfrak{D})^{\mathbb{L}_i} - 1) \tag{5}$$

$$\mathbf{I}_{i\_\mathscr{SL}} = \mathscr{P}_i * \mathscr{V}_{i\_\mathscr{SL}} * \mathfrak{D} / ((1+\mathfrak{D})^{\mathbb{L}_i} - 1) \tag{6}$$

$$\mathbf{C}_{i\_\mathscr{P}C} = \mathbf{C}_{\mathscr{P}C} * \mathscr{P}_i / (\mathscr{P}_{\mathscr{W}} + \mathscr{P}_{\mathscr{SP}} + \mathscr{P}_{\mathscr{B}}) \tag{7}$$

The value of $\mathbf{I}_{i\_\mathscr{SL}}$ will become zero when storage batteries are outdated. The annual $\mathbf{C}_{i\_\mathscr{ES}}$ and $\mathbf{C}_{\mathscr{P}C}$ for the players can be found as follows:

$$\mathbf{C}_{i\_\mathscr{ES}} = \sum_{t=1}^{T} k(t) * \left(\mathscr{P}_{\mathscr{UB}}(t) - \mathscr{P}_{\mathscr{PG}}(t)\right) \tag{8}$$

$$\mathbf{C}_{\mathscr{P}C} = \sum_{t=1}^{T} \mathbb{E}(t) * \mathscr{P}_{\mathscr{PG}}(t) \tag{9}$$

$$\mathscr{P}_{\mathscr{UB}}(t) = \mathscr{P}_{\mathscr{D}}(t) - p_{\mathscr{W}}(t) - p_{\mathscr{SP}}(t) - (p_{\mathscr{B}\_SOC}(t) - \mathscr{P}_{\mathscr{B}\_min}) \tag{10}$$

The value fixed as $k(t) = 1.5 \times \mathbb{E}(t)$ [25]. In the same way the annual $\mathbf{I}_{i\_\mathscr{SE}}$ for the solar panels and the wind turbines will be calculated as:

$$\mathbf{I}_{i\_\mathscr{SE}} = (1+\mathscr{F}) \times \sum_{t=1}^{T} \mathbb{E}(t) \times \mathscr{P}_{i\_\mathscr{SE}}(t) \tag{11}$$

$$\mathscr{P}_{i\_\mathscr{SE}}(t) = \begin{cases} p_i(t) \mathscr{P}_{\mathscr{SR}}(t) \leq 0 \\ \dfrac{p_i(t) * \mathscr{P}_{\mathscr{CN}}(t)}{(p_{\mathscr{W}}(t) + p_{\mathscr{SP}}(t))} \mathscr{P}_{\mathscr{SR}}(t) > 0 \end{cases} \tag{12}$$

$$\mathscr{P}_{\mathscr{SR}}(t) = p_{\mathscr{W}}(t) + p_{\mathscr{SP}}(t) - (\mathscr{P}_{\mathscr{D}}(t) + \mathscr{P}_{\mathscr{TC}} + (\mathscr{P}_{\mathscr{B}} - p_{\mathscr{B}\_SOC}(t)) \tag{13}$$

The annual incomes $\mathbf{I}_{i\_\mathscr{AS}}$ and $\mathbf{I}_{i\_\mathscr{SE}}$ for the storage batteries can be found as follows:

$$\mathbf{I}_{\mathscr{B}\_\mathscr{AS}} = \mathfrak{R} \times \sum_{t=1}^{T} (p_{\mathscr{B}\_SOC}(t) - \mathscr{P}_{\mathscr{B}\_\mathscr{SE}}(t) - \mathscr{P}_{\mathscr{B}\_min}) \tag{14}$$

$$\mathbf{I}_{\mathscr{B}\_\mathscr{SE}} = (1+\mathscr{F}) \times \sum_{t=1}^{T} \mathbb{E}(t) \times \mathscr{P}_{\mathscr{B}\_\mathscr{SE}}(t) \tag{15}$$

$$\mathscr{P}_{\mathscr{B}\_\mathscr{SE}}(t) = \begin{cases} \Delta p_{\mathscr{B}\_SOC}(t) \Delta p_{\mathscr{B}\_SOC}(t) > 0 \\ 0 \Delta p_{\mathscr{B}\_SOC}(t) \leq 0 \end{cases} \tag{16}$$

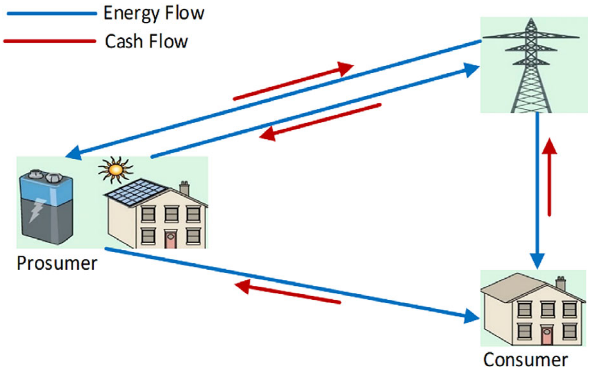

FIGURE 3 Power and cash flow for P2G and P2P Energy Trading

It is evident from the above equations that the maximization of the annual profit not only depend upon the parameters of each player but also affect the output values of other players. The value of *APF* for the first microgrid MG_1 is found as:

$$f\left(APF_{MG\_1}\right) = \max\left(APF_{\mathcal{W}} + APF_{\mathcal{SP}} + APF_{\mathcal{B}}\right) \tag{17}$$

The annual profit of the networked microgrid *NMG* considering three different microgrids under the P2G energy trading scheme where microgrids can only sell or purchase power with the main grid is expressed as follows:

$$f\left(APF_{NMG\_P2G}\right) = \max\left(\sum_{1}^{n} APF_{MG\_n}\right) n \in \{1, 2, 3\} \tag{18}$$

Microgrids act as the prosumers for the P2P energy trading and allow the networked microgrid to exchange the power between the prosumer-prosumer and the prosumer-grid. Nowadays, the P2P energy trading scheme is becoming more popular compared to the traditional P2G energy trading scheme because prosumers have more options to buy/sell power, making them more efficient. The P2P energy trading cheers the prosumers to exchange power between each other, with the prosumers, and also with the main grid. Therefore, the scheme increases the overall profit of the architecture. The cash flow is in the opposite direction of P2G and P2P energy trading as shown in Figure 3. Similar to P2G energy trading, for the P2P energy trading most of the equations will be the same except the $\mathbf{I}_{i\_\mathcal{SE}}$ and $\mathbf{C}_{i\_\mathcal{P}C}$ where the prosumers are selling or purchasing power either among each other or with the main grid. The architecture is designed in a way that the first priority of the prosumer is to exchange excess power or power shortage with the nearest prosumer or with any prosumer within the network to meet the requirement. In the second priority, if the prosumers are unable to meet the power requirement, then it will do the power exchange with the main grid. The value of *APF* for the first prosumer PR_1 is found as:

$$f\left(APF_{PR\_1}\right) = \max\left(APF_{\mathcal{W}} + APF_{\mathcal{SP}} + APF_{\mathcal{B}}\right) \tag{19}$$

The value of *APF* for the networked microgrid *NMG* considering three different prosumers under the P2P energy trading scheme is expressed as follows:

$$f\left(APF_{NMG\_P2P}\right) = \max\left(\sum_{1}^{n} APF_{PR\_n}\right) n \in \{1, 2, 3\} \tag{20}$$

3.2 | Energy index of reliability

The quality of load supply in the networked microgrid is examined by the system reliability. The reliability of the networked microgrid is measured by the energy index of reliability [20]. For a microgrid, the *EIR* is found from the energy not supplied E_{NS_MG}, and is calculated as follows:

$$EIR_{MG} = \left(1 - \frac{E_{NS\_MG}}{E_{MG}}\right) \tag{21}$$

where E_{MG} is total annual energy supplied by generation resources and batteries from a microgrid. The annual E_{NS_MG} for a microgrid, can be found as follows:

$$E_{NS\_MG} = \sum_{t=1}^{T} \left(\mathcal{P}_{\mathcal{D}}(t) - \mathcal{P}_{\text{Total}}(t)\right) \times u(t) \tag{22}$$

where $\mathcal{P}_{\text{Total}}$ and $u(t)$ are the total power generated by a microgrid and a step function in hour t, respectively. The difference between $\mathcal{P}_{\mathcal{D}}(t)$ and $\mathcal{P}_{\text{Total}}(t)$ is the power shortage in hour$t$. If the total generated power is lower than the load demand the value of $u(t)$ will be one. Otherwise, the $u(t)$ will be zero if the generated power will be either equal or more than the load demand. The value of the $\mathcal{P}_{\text{Total}}(t)$ is found as follows:

$$\mathcal{P}_{\text{Total}}(t) = p_{\mathcal{W}}(t) + p_{\mathcal{SP}}(t) + p_{\mathcal{B}}(t) + \mathcal{P}_{g}(t) \tag{23}$$

where $p_{\mathcal{B}}(t)$ and $\mathcal{P}_{g}(t)$ indicate the available power supply from batteries and the power purchased from the main grid in hour t, respectively. The term $p_{\mathcal{B}}(t)$ is the difference between the battery charge level $p_{\mathcal{B}\_SOC}(t)$ in hour$t$ and the $\mathcal{P}_{\mathcal{B}\_min}$.

If three microgrids work in grid-connected mode to perform P2G energy trading the energy index of reliability for the networked microgrid is found as follows:

$$f\left(EIR_{NMG\_P2G}\right) = \max\left(\sum_{1}^{n} EIR_{MG\_n}\right) n \in \{1, 2, 3\} \tag{24}$$

If the grid-connected networked microgrid is designed with respect to P2P energy trading, the value of *EIR* is calculated as follows:

$$f\left(EIR_{NMG\_P2P}\right) = \max\left(\sum_{1}^{n} EIR_{PR\_n}\right) n \in \{1, 2, 3\} \tag{25}$$

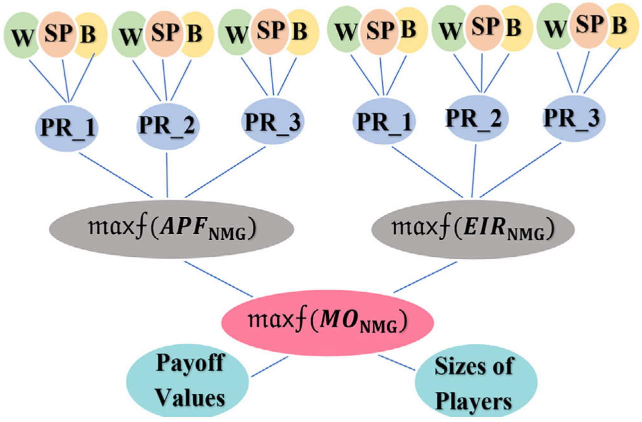

FIGURE 4 Flow of multi-objective optimization

3.3 | Multi-objective function

The technique of multi-objective optimization is used when several criteria need to be met simultaneously in an electrical system. In [36, 38], a technique of multi-objective (MO) function is used in a way that the multiple criteria are met simultaneously to provide the requirement of the optimization model. The annual profit and energy index of reliability are the set criteria in this research. Since the both objective functions have different unit values, therefore, their per-unit values are considered to formulate the multi-objective function. As both criteria are maximizing function, therefore, multi-objective function will be formulated as a maximizing problem as shown in Figure 4. If n number of microgrids are connected in the networked microgrid, the value of $f(MO_{NMG})$ is obtained as:

$$f(MO_{NMG}) = \mathbf{max}\left(k_1 \sum_{1}^{n} APF_{MG_{n\,PU}} + k_2 \sum_{1}^{n} EIR_{MG_{n\,PU}}\right) \tag{26}$$

wherek_1 and k_2 are the constant-coefficients for the annual profit, and the energy index of reliability, respectively. The ranges of constant coefficients k_1 and $k_2$are $0 < k_1 < 1$ and $0 < k_2 < 1$, respectively. The values of both coefficients are the weighting values that determine the preferred objective function in this multi-objective function. Since both objectives have the same importance, therefore, these factors are considered the same equal 0.5.

4 | A GAME THEORY TECHNIQUE

In the modern fields, different methods are proposed to do the optimization process to achieve the desired goals. Game theory is a very helpful technique to solve decision-making problems and to perform multi-objective optimization. A game model can be organized either in a cooperative or a non-cooperative way to find the optimum values of the payoff. In a non-cooperative game model, the players have the option to make a decision in their own way to optimize the payoff values. However, in a cooperative game model, the players are arranged in multiple set of coalitions and cooperate with each other to reach the optimum value of payoff [39]. The current research works prove that cooperative type of game models is more efficient and profitable than non-cooperative ones [25]. In this paper, a cooperative game technique Nash equilibrium is used to design a networked microgrid. In a cooperative game model, multiple coalitions are possible if the number of players is more than two.

In the networked microgrid, three players including wind turbines, solar panels, and batteries are considered. Therefore, the game model can have four different kinds of coalitions. It has three different set of coalitions, where two players are cooperating with each other and the third one will be independent, like $\{(\mathscr{W},\mathscr{SP}), (\mathscr{B})\}$. In the fourth set, all three players are in one coalition $\{(\mathscr{W},\mathscr{SP},\mathscr{B})\}$ and cooperating with each other. To explain the Nash equilibrium, one of the coalition sets $\{(\mathscr{W},\mathscr{SP},\mathscr{B})\}$ is considered where all the players are cooperating with each other. It is also evident from [33] that the game model gives maximum profit when all the players cooperate with each other in a single coalition. Therefore, in this research game models for each microgrid are considered where all the players are in a single coalition and cooperate with each other. The optimum sizes of the players at the Nash equilibrium point $(\mathscr{P}^*_{\mathscr{W}}, \mathscr{P}^*_{\mathscr{SP}}, \mathscr{P}^*_{\mathscr{B}})$, and the payoff value based on iteration j is found as follows:

4.1: Input electrical load profile, weather forecast data solar radiation and wind speed.

4.2: In the networked microgrid, choose randomly the initial sizes of the players $(\mathscr{P}^0_{\mathscr{W}}, \mathscr{P}^0_{\mathscr{SP}}, \mathscr{P}^0_{\mathscr{B}})$ within strategic limits.

4.3: In the selected set of coalition $\mathscr{W}$, $\mathscr{SP}$, and $\mathscr{B}$ are cooperating with each other $\{(\mathscr{W},\mathscr{SP},\mathscr{B})\}$. Consider j^{th} iteration $(\mathscr{P}^j_{\mathscr{W}}, \mathscr{P}^j_{\mathscr{SP}}, \mathscr{P}^j_{\mathscr{B}})$, which based on its previous iteration $(\mathscr{P}^{j-1}_{\mathscr{W}}, \mathscr{P}^{j-1}_{\mathscr{SP}}, \mathscr{P}^{j-1}_{\mathscr{B}})$ as:

$$\left(\mathscr{P}^{j-1}_{\mathscr{W}}, \mathscr{P}^{j-1}_{\mathscr{SP}}, \mathscr{P}^{j-1}_{\mathscr{B}}\right) = arg \max_{\mathscr{P}_{\mathscr{W}}\mathscr{P}_{\mathscr{SP}}P_{\mathscr{B}}} \mathscr{P}F_{\mathscr{W}\mathscr{SP}\mathscr{B}}\left(\mathscr{P}_{\mathscr{W}}, \mathscr{P}_{\mathscr{SP}}, \mathscr{P}_{\mathscr{B}}\right)$$

4.4: Share with every player in the coalition about the strategic sizes of the third step.

4.5: Check the coalition results, if none of the players changes its sizes during the whole iteration, this means Nash equilibrium is achieved $(\mathscr{P}_{\mathscr{W}}, \mathscr{P}_{\mathscr{SP}}, \mathscr{P}_{\mathscr{B}}) = (\mathscr{P}^*_{\mathscr{W}}, \mathscr{P}^*_{\mathscr{SP}}, \mathscr{P}^*_{\mathscr{B}})$. In case, if the condition is not met, go back to step 4.3.

In order to make multi-optimization of networked microgrid based on P2P energy trading scheme, the game model is built and simulated in MATLAB software using a modified PSO algorithm. PSO algorithm is a computational method to optimize different problems iteratively to improve the desired

FIGURE 5 Towns of Australia Laverton, Mount Magnet, and Wahroonga

outcome, and being frequently used in many research fields to solve different optimization functions [40, 41]. In the simulation model, to find the optimum sizes of the players and the payoff value, the selected population size and the maximum number of iterations are 100 and 250, respectively.

5 | RESULTS AND DISCUSSIONS

5.1 | Considered microgrids in Australia

In order to make the results more realistic and accurate, the weather forecast data and load profiles of three different towns named Mount Magnet, Laverton, and Wahroonga in Australia are considered as shown in Figure 5 [42, 43]. Most parts of Australia have generous resources of solar and wind energy. Therefore, in different cities many large and small renewable energy-based projects are installed to meet the load requirements [47–50]. Mount Magnet and Laverton are located at 560 km and 957 km of Western Australia's capital Perth, respectively. The location of third town Wahroonga is 19 km northwest of New South Wale's capital Sydney. In this research, the profiles of solar radiations, wind speed, and residential loads are considered as shown in Figure 5, but the geographical distance is not used in the transmission line.

The average wind speed of Laverton is between approximate 5–7 m/s, and its mean daily temperature varies from summer 36 °C to winter 17 °C [51, 52]. The mount magnet climate temperature changes from 37.9 °C in summer to 18.8 °C in winter, with average wind speed flows between 5–6 m/s [53, 54]. The climate temperature of the Wahroonga drops from 27 °C in summer to 11 °C in winter, and its average wind speed changes between 4–6 m/s [55]. The maximum and minimum values, and the trend of the solar radiations, wind speed, and residential loads are shown in Figure 6. Weather forecast and residential load data of the Laverton, Mount Magnet, and Wahroonga are taken from July 2014 to June 2015 for microgrid-1, from June 2015 to May 2016 for Microgrid-2, and from July 2012 to June 2013 for microgrid-3, respectively.

TABLE 1 Input parameters

Parameters	Values (units)	Parameters	Values (units)
$\mathbb{E}$	0.12 \$/kWh	$\mathbf{C}_{\mathcal{OM}}$ of $\mathcal{W}$	20 \$/(kW year)
$\mathfrak{D}$	12%	$\mathcal{V}_{\mathcal{SL}}$ of $\mathcal{W}$	77 \$/kW
$\mathcal{v}_{c}$	3 m/s	$\mathcal{U}_{\mathcal{SP}}$	1890 \$/kW
$\mathcal{v}_{o}$	20 m/s	$\mathbb{L}_{\mathcal{SP}}$	20 years
$\mathcal{v}_{r}$	12 m/s	$\mathbf{C}_{\mathcal{OM}}$ of $\mathcal{SP}$	20 \$/(kW year)
$\mathbb{E}_{\mathrm{P}}$ [44]	0.15 \$/kWh	$\mathcal{V}_{\mathcal{SL}}$ of $\mathcal{SP}$	189 \$/kW
$\mathbb{E}_{\mathrm{SG}}$ [45]	0.10 \$/kWh	$\mathbb{L}_{\mathcal{B}}$	10 years
$\mathbb{E}_{\mathrm{PG}}$ [46]	0.28 \$/kWh	$\mathcal{U}_{\mathcal{B}}$	100 \$/kW
$\mathbb{L}_{\mathcal{W}}$	20 years	$\mathbf{C}_{\mathcal{OM}}$ of $\mathcal{B}$	1 \$/(kW year)
$\mathcal{U}_{\mathcal{W}}$	770 \$/kW	$\mathcal{P}_{\mathcal{B}\_min}$	50 W

5.2 | Single-objective analysis for $\mathscr{f}$ (*APF*) and $\mathscr{f}$ (*EIR*)

To evaluate and analyse the networked microgrid, the simulation model is designed in MATLAB software based on a PSO algorithm. The input parameters of [33] are used as shown in Table 1 for the optimization of the proposed architecture. In this research, the cooperative game theory technique is used, and three different players are working in cooperation; therefore, four sets of coalitions are possible. It is analysed in [25, 34], if three players are making four sets of coalitions in the

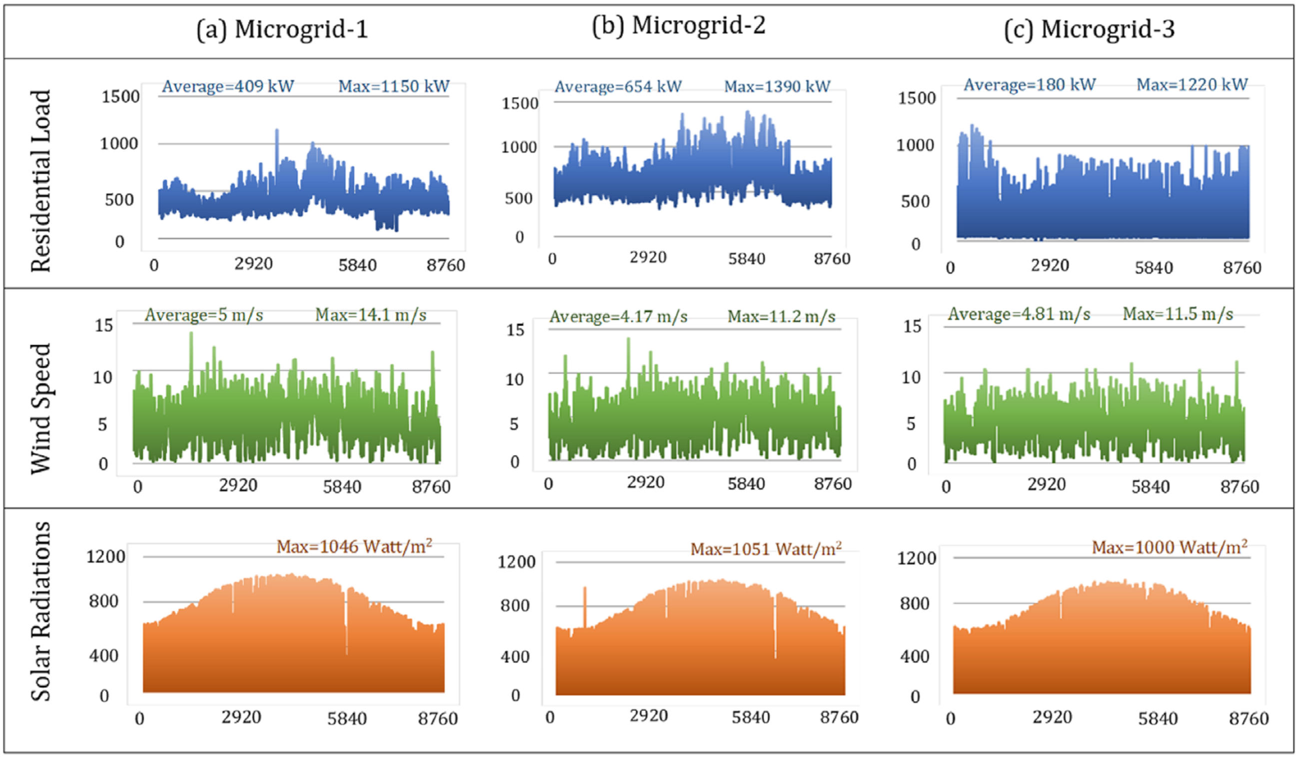

FIGURE 6 Weather, and load profiles for a networked microgrid

TABLE 2 Results for optimization of $f(APF_{\mathrm{NMG}})$ as an objective function

		Optimum sizes of the players					Payoff of objective functions	
Coalition	**Towns of Australia**	$\mathscr{P}^*_{\mathscr{W}}$ **(kW)**	$\mathscr{P}^*_{\mathscr{SP}}$ **(kW)**	$\mathscr{P}^*_{\mathscr{B}}$ **(kW)**	$\mathscr{P}_T$ **(kW)**	**Energy trading schemes**	$f(APF_{\mathrm{NMG}})$ **($/year)**	$f(EIR_{\mathrm{NMG}})$ **(p.u)**
$(\mathscr{W}, \mathscr{SP}, \mathscr{B})$	Laverton	890	531	298	1719	P2G	**1.500555e+9**	0.989860
	Mt. Magnet	920	586	396	1902			
						P2P	**1.501028e+9**	0.995921
	Wahroonga	850	412	207	1469			

cooperative game model, then the payoff will be optimum when all the players are working in a single coalition and cooperating with each other. In the analysis of this research, only a coalition is considered where all the three players $\mathscr{W}$, $\mathscr{SP}$, and $\mathscr{B}$ are cooperating a single coalition $\{(\mathscr{W}, \mathscr{SP}, \mathscr{B})\}$ to achieve the best value of the multi-objective function and optimum sizes of the players.

Table 2 illustrates the results for both energy trading schemes when the optimization is performed with respect to the single objective function $f(APF)$ for networked microgrid so that the optimum sizes of the players $(\mathscr{P}^*_{\mathscr{W}}, \mathscr{P}^*_{\mathscr{SP}}, \mathscr{P}^*_{\mathscr{B}})$ at Nash equilibrium are found. Later on, the value of second object function $f(EIR)$ is calculated at the optimized values of the players. In a similar way, if the optimization is performed for the $f(EIR)$ as single objective function, the payoff values for both objective functions and optimized sizes of the players are shown in Table 3 for both energy trading schemes. Both objective functions in the simulation are maximizing, and therefore, the payoff values of $f(APF_{\mathrm{NMG}})$ and $f(EIR_{\mathrm{NMG}})$ are higher in case of P2P energy trading scheme. For the P2G energy trading energy exchange is only happening between the microgrids and the main grid that decreases the overall annual profit and reliability of the networked microgrid. It is also evident from the results that the value of $f(APF_{\mathrm{NMG}})$ is higher when the $f(APF)$ is optimized as single objective function compared to its value when $f(EIR)$ is optimized as a single objective function. In a similar way, the payoff value of $f(EIR_{\mathrm{NMG}})$ is higher when the optimization is performed with respect to $f(EIR)$, and its value drops down when $f(APF)$ is considered for single-objective optimization.

TABLE 3 Results for optimization of $f(EIR_{\text{NMG}})$ as an objective function

		Optimum sizes of the players					Payoff of objective functions	
Coalition	Towns of Australia	$\mathscr{P}^*_{\mathscr{W}}$ (kW)	$\mathscr{P}^*_{\mathscr{SP}}$ (kW)	$\mathscr{P}^*_{\mathscr{B}}$ (kW)	$\mathscr{P}_T$ (kW)	Energy trading schemes	$f(APF_{\text{NMG}})$ (\$/year)	$f(EIR_{\text{NMG}})$ (p.u)
$(\mathscr{W}, \mathscr{SP}, \mathscr{B})$	Laverton	883	496	309	1688	P2G	1.491103e+9	**0.989957**
	Mt. Magnet	950	651	210	1811			
						P2P	1.491568e+9	**0.995937**
	Wahroonga	850	461	201	1512			

TABLE 4 Results for a multi-objective function $f(MO_{\text{NMG}})$

		Optimum sizes of the players					Payoff of objective functions		
Coalition	Towns of Australia	$\mathscr{P}^*_{\mathscr{W}}$ (kW)	$\mathscr{P}^*_{\mathscr{SP}}$ (kW)	$\mathscr{P}^*_{\mathscr{B}}$ (kW)	$\mathscr{P}_T$ (kW)	Energy trading schemes	$f(MO_{\text{NMG}})$ (p.u)	$f(APF_{\text{NMG}})$ (\$/year)	$f(EIR_{\text{NMG}})$ (p.u)
$(\mathscr{W}, \mathscr{SP}, \mathscr{B})$	Laverton	900	521	264	1685	P2G	**0.8968629**	1.514346e+9	0.989989
	Mt. Magnet	950	538	340	1828				
						P2P	**0.9005483**	1.514812e+9	0.995976
	Wahroonga	850	460	305	1615				

5.3 | Results and analysis of $f(MO_{NMG})$ optimization

To perform the optimization of networked microgrid, a multi-objective function $f(MO_{NMG})$ is designed based on two criteria APF_{NMG} and EIR_{NMG} for both energy trading schemes. Table 4 shows the payoff values of $f(APF_{\text{NMG}})$ and $f(EIR_{\text{NMG}})$, and suitable sizes of the players $(\mathscr{P}^*_{\mathscr{W}}, \mathscr{P}^*_{\mathscr{SP}}, \mathscr{P}^*_{\mathscr{B}})$ for networked microgrid after the simulation process of $f(MO_{NMG})$ at Nash equilibrim point for P2G and P2P. The multi-objective function is maximizing; therefore, the sizes of the players will be optimized at the maximum value of $f(MO_{NMG})$. The payoff values for P2P energy trading are higher than P2G, and as a result, P2P scheme has a design with better reliability, more annual profit, and minimum possibility of losing the power supply. Besides, for the multi-objective optimization the individual payoff values of $f(APF_{\text{NMG}})$ and $f(EIR_{\text{NMG}})$ are higher than the payoff value for the single objective optimization, that validate the effectiveness of $f(MO_{NMG})$.

In order to reach the global best values of $f(MO_{NMG})$ the simulation model is run for 250 iterations. However, the best results of 125 iterations are only shown for P2G and P2P energy trading schemes in Figure 7. The optimized sizes of the players $(\mathscr{P}^*_{\mathscr{W}}, \mathscr{P}^*_{\mathscr{SP}}, \mathscr{P}^*_{\mathscr{B}})$ at maximum values of $f(MO_{NMG})$ 0.8968629 p.u. and 0.9005483 p.u. for P2G and P2P energy trading schemes are shown in Table 5, respectively. It is also evident from the Figure 8 that the values of $f(MO_{NMG})$ are slightly changing until 60 iterations, and then the increase is very sudden until 100 iterations, and after that, the results start getting closer to its maximum value until reaching the final values at 125 iterations. Figure 7 shows the suitable sizes of the players $(\mathscr{P}^*_{\mathscr{W}}, \mathscr{P}^*_{\mathscr{SP}}, \mathscr{P}^*_{\mathscr{B}})$ and total size of available power $(\mathscr{P}_T = \mathscr{P}^*_{\mathscr{W}} + \mathscr{P}^*_{\mathscr{SP}} + \mathscr{P}^*_{\mathscr{B}})$ for the three microgrids in networked architecture. Since the residential load of microgrid-2 is the highest, therefore, it has a maximum value of $\mathscr{P}_T$ to meet the load requirements. Microgrid-2 has a lower capacity of $\mathscr{P}_T$, and microgrid-3 has the lowest value of $\mathscr{P}_T$ because of the lowest residential load requirements. If the sizes of the players are compared in Tables 2–4, it shows the similarity among their sizes at Nash equilibrium points and validates the results $\mathscr{P}^*_{\mathscr{W}} > \mathscr{P}^*_{\mathscr{SP}} > \mathscr{P}^*_{\mathscr{B}}$ [25].

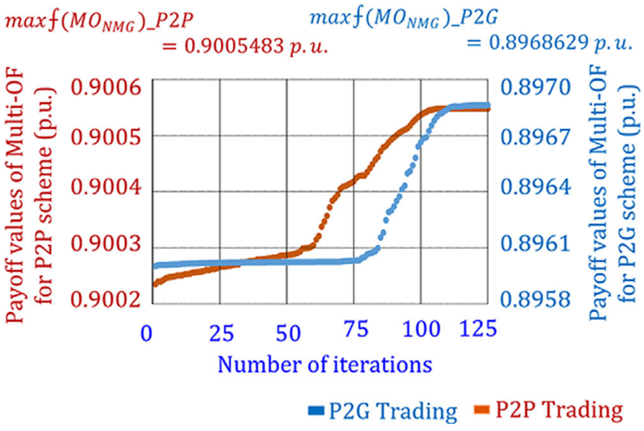

FIGURE 7 Payoff values of multi-objective function for P2G and P2P energy trading schemes

TABLE 5 Results of $f(APF_{\text{NMG}})$after the sensitivity analysis

Sensitivity parameters		$f(APF_{\text{NMG}})$ (\$/year)			
		P2G Trading	ΔAPF_{P2G} (%)	P2P Trading	ΔAPF_{P2P} (%)
Discount rate $\mathfrak{D}$ (%)	$\mathfrak{D} - 1\%$	1.514389e+9	+0.003	1.514854e+9	0.003
	$\mathfrak{D}$	1.514346e+9		1.514812e+9	
	$\mathfrak{D} + 1\%$	1.514303e+9	−0.003	1.514769e+9	−0.003
Electricity price $\mathbb{E}$ (\$/kWh)	$\mathbb{E} - 0.01$	1.445412e+9	−4.55	1.445878e+9	−4.55
	$\mathbb{E}$	1.514346e+9		1.514812e+9	
	$\mathbb{E} + 0.01$	1.583280e+9	+4.55	1.583745e+9	4.55

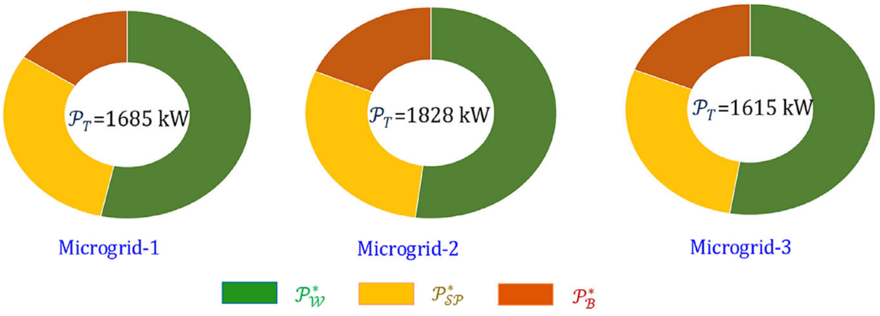

FIGURE 8 Sizes of the players for three microgrids in networked architecture

5.4 | Sensitivity analysis of the proposed model

The capacity allocation of the players to get maximum payoff values based on the game theory technique is performed on the basis of Table 1 input parameters. In this section, the effect of changing some parameters will be analysed, and the results are compared. To perform the sensitivity analysis two parameters including the electricity prices$\mathbb{E}$ and the discount rates $\mathfrak{D}$ are considered for both P2P and P2G energy trading schemes. The objective function $f(APF_{\text{NMG}})$ will be more influenced with the selected sensitivity values, therefore, its effect is shown in Table 5 and Figure 9 to validate the payoff results. It can be seen that the percentage increase in the APF_{NMG} value is 0.003 % as the $\mathfrak{D}$ reduced 1%, and when the $\mathfrak{D}$ increased 1 %, the percentage change inAPF_{NMG} value is decreased by 0.003 %. The trend of percentage change in APF_{NMG} value is similar for $\mathfrak{D}$ for both energy trading schemes P2P and P2G energy trading that verifies the results. In the case of the P2P energy trading scheme, the results consider both possible ways of energy trading schemes P2P and P2G. The influence of $\mathbb{E}$ is more on the APF_{NMG} value than the discount rate. Therefore, as the $\mathbb{E}$s are increased to 0.01 kWh, the percentage increase in the APF_{NMG} value is 4.55%. On the other hand, when the $\mathbb{E}$ is decreased to 0.01 kWh, the APF_{NMG} value experiences a 4.55 % decrease. The influence in the APF_{NMG} value with respect to the $\mathbb{E}$ s is also validated for both energy trading schemes.

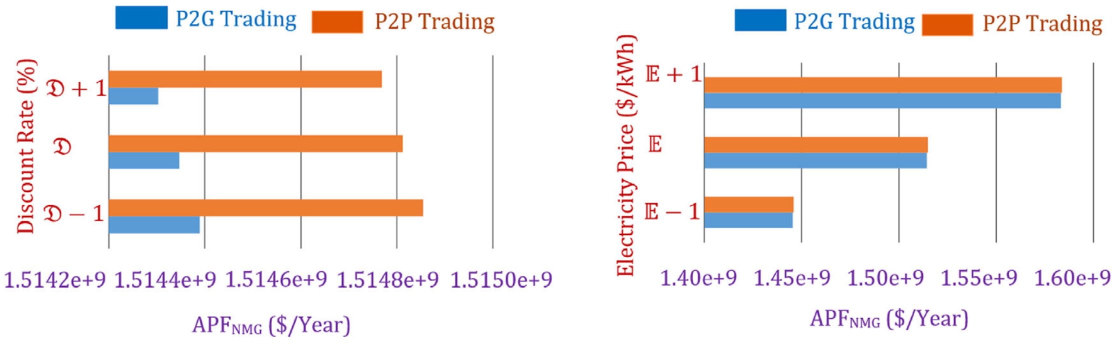

FIGURE 9 Sensitivity analysis of APF_{NMG} for P2G and P2P energy trading schemes

6 | CONCLUSION

In this paper, an $f(MO_{\text{NMG}})$ for the optimum sizing of renewable energy resources to get the maximum payoff values from a clustered microgrid is presented. The architecture is designed based on a Nash equilibrium game theory technique for both P2P and P2G energy trading schemes. The criteria of APF_{NMG} and EIR_{NMG} are considered for the optimization of $f(MO_{\text{NMG}})$ in MATLAB software based on PSO algorithm with 250 iterations to reach its optimum values. The results are compared for both single-objective and multi-objective optimizations. The outcomes clearly show that the payoff values are the best when both criteria are considered as $f(MO_{\text{NMG}})$. Consequently, the sizes of the players are most suitable after the multi-objective optimization. The sizes of the players are further verified, as their trend is similar $\mathscr{P}^*_{\mathscr{W}} > \mathscr{P}^*_{\mathscr{SP}} > \mathscr{P}^*_{\mathscr{B}}$ in all the payoff values of P2P and P2G energy trading. Finally, the sensitivity analysis is performed with respect to $\mathfrak{D}$ and $\mathbb{E}$ that verify the feasibility of formulated multi-objective function for the clustered microgrid.

NOMENCLATURE

$\mathscr{P}_i$	Size or capacity of player i (kW)
$\mathscr{P}_{\mathscr{B}\_min}$	Minimum capacity of a battery (kW)
$\mathscr{P}_{\mathscr{CN}}(t)$	Maximum power consumed (kW)
$\mathscr{P}_{\mathscr{D}}(t)$	Load demand (kW)
$\mathscr{P}_{\mathscr{PG}}(t)$	Power purchased from grid (kW)
$\mathscr{P}_{\mathscr{SR}}(t)$	Surplus power (kW)
$\mathscr{P}_{\mathscr{TC}}$	Maximum transmission line capacity (kW)
$\mathscr{P}_{\mathscr{UB}}(t)$	Unbalance power (kW)
$\mathscr{P}_{i\_\mathscr{SE}}$	Power selling (kW)
$\mathscr{U}_i$	Per unit cost of player i (p.u.)
$\mathscr{V}_{i\_\mathscr{SL}}$	Per unit salvage value of player i (p.u)
$p_{\mathscr{B}\_SOC}$	Battery state of charge (kW)
$p_i(t)$	Capacity of player i in hour t (kW)
v_o	Cut-out wind speed (m/s)
v_c	Cut-in wind speed (m/s)
v_r	Rated wind speed (m/s)
$\mathbb{E}_{\text{P}}$	Electricity price between the prosumers (\$/kWh)
$\mathbb{E}_{\text{PG}}$	Electricity price purchasing power from the grid (\$/kWh)
$\mathbb{E}_{\text{SG}}$	Electricity price selling power to the grid (\$/kWh)
$\mathbb{L}_i$	Life span of player i (years)
$\mathbf{C}_{i_{\mathscr{ES}}}$	Annual cost for energy not served (\$)
$\mathbf{C}_{i_{\mathscr{IN}}}$	Annual investment cost (\$)
$\mathbf{C}_{i_{\mathscr{OM}}}$	Annual operation and maintenance cost (\$)
$\mathbf{C}_{i_{\mathscr{P}C}}$	Total cost of purchasing power (\$)
$\mathbf{C}_{\mathscr{PG}}$	Cost for purchasing power from the grid (\$)
$\mathbf{C}_i$	Annual cost of player i (\$)
$\mathbf{I}_{i_{\mathscr{AS}}}$	Annual ancillary service benefits (\$)
$\mathbf{I}_{i_{\mathscr{SE}}}$	Annual income for power selling (\$)
$\mathbf{I}_{i_{\mathscr{SL}}}$	Annual salvage value (\$)
$\mathbf{I}_i$	Annual income of player i (\$)
ξ_c	Battery charging efficiency (%)
$\mathscr{F}$	Subsidy coefficient (p.u.)
$\mathfrak{R}$	Per-unit income from reserve power (p.u.)
T	Total number of hours in a year (hours)
$k(t)$	Per-unit compensation (p.u.)
n	Number of microgrids (Unit)
$v(t)$	Wind speed in hour t (m/s)
$\mathfrak{D}$	Discount rate (%)
$\Delta(t)$	Difference between total generation and load in hour t (kW)

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DATA AVAILABILITY STATEMENT

Data available on request from the authors.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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