Faculty of Science and Engineering

Discipline of Electrical and Computer Engineering

Development and Improvement of Renewable Energy Integrated with Energy Trading Schemes based on Advanced Optimization Approaches

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Liaqat Ali

May 2021

Signature: …………………………………

Date: 07/05/2021

Dedication

The philosophers and the mentors of my life

MY MOTHER'S and *MY FATHERS'S SOULS*

Abstract

Energy issues and atmospheric pollution are increasing rapidly. Green energy production is a vital solution. In this research, different architectures of hybrid power system are proposed, which consist of different sequences of microgrids in grid-connected modes to meet residential load requirements. Each microgrid consists of distinct combination of wind turbines, photovoltaic panels and storage batteries. In order to improve the overall efficiency and profit of the hybrid power system, the approaches of microgrid clustering and networked microgrid are considered. Cooperative and non-cooperative game theory techniques are used to design proposed architectures for the suitable sizing of generation resources and batteries, and to achieve optimum payoff values. Game theory techniques, specifically, the Nash equilibrium, Shapley values and Nash bargaining solution, are implemented to achieve optimum outcomes. The game models are formulated based on single-object and multi-object optimisations, and different criteria such as annual profit, reliability index, loss of power supply probability, levelized cost of energy and energy index of reliability are considered to direct the objective functions.

In order to improve the overall reliability, minimise the power outage issues and increase the annual profit, the peer-to-peer energy trading scheme is considered for a networked microgrid. The power system models are formulated and analysed for peer-to-grid and peer-to-peer energy trading schemes. The outcomes of the multi-objective functions are also compared for both energy trading schemes to validate the results. Sensitivity analysis is performed for designed architectures to verify the effectiveness of multi-objective function and the stability for the price of electricity and discount rates. Simulation models are built in MATLAB software based on a different computation methods such as particle swarm optimization and imperialistic competition algorithm. Models are simulated for the maximum number of iterations to reach their global best values to find the optimum results.

In short, different architectures of hybrid power system are proposed, which consist of distinct combination of wind turbines, photovoltaic panels and storage batteries in grid-connected modes. To improve the systems’ efficiency, reliability and annual profit, the application of microgrid clustering and peer-to-peer energy trading are implemented. Game theory techniques are used for the optimization of power system models to find their correct sizing of the generation resources, and to achieve optimum payoff values.

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Thank you very much, everyone!

Liaqat Ali

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List of Abbreviations

i	Player in a game model
PV	Photovoltaic panel
P	Capacity of a generation resources or players
t	Time in hours
T	Total time in a year
ICC	Initial capital cost
min	Minimum
max	Maximum
P_{B_min}	Battery minimum state of charge
$\mathbb{L}$	Life span of a player
n	Number of microgrids
N	Total number of microgrids
I	Income
$P2P$	Peer-to-peer
$P2G$	Peer-to-grid
$LPSP$	Loss of power supply probability
EIR	Energy index of reliability
$LCOE$	Levelised cost of energy
IR	Index of reliability
MG	Microgrid

NMG	Networked microgrid
CMG	Clustered microgrid
$\mathfrak{R}$	Battery per unit income from reverse power
ξ_c	Charging efficiency of a battery
DC	Direct current
AC	Alternating current
$\propto$	Subsidy factor
$\mathbb{E}$	Electricity price
$\mathfrak{D}$	Discount rate
$\mathcal{v}_c$	Cut-in wind speed
$\mathcal{v}_o$	Cut-out wind speed
$\mathcal{v}_r$	Rated wind speed
$\mathcal{U}_i$	Per unit cost of the player i
$\mathcal{U}_{i\_SV}$	Per unit salvage value of the player i
$\mathcal{U}_{i\_OM}$	Per unit operation and maintenance cost of the player i

Chapter 1 Introduction

To overcome rapid increases in electricity price and demand, larger power plants are designed, or new sources of energy production are introduced into the market. Renewable energy is *the* modern form of energy production, and its use is rapidly increasing due to environmental concerns [1]. In the global environmental pollution and energy crisis, major roles are played by renewable energy sources such as wind and photovoltaic (PV) power [2]. It is important to build local generation networks, due to geographical reasons, but there are difficulties in transmission line extensions to regional areas. In Australia, 31% of the population lives in regional towns, where the electricity requirement is fulfilled through local generation resources [3]. The best method of electricity generation in remote areas is through renewable resources, in order to decrease both the costs of electricity generation and transmission [4].

As a promising clean energy resource, wind power and photovoltaic generation are experiencing rapid development. The intermittent nature of wind and photovoltaic generation can be minimised by the application of different types of energy storage systems such as batteries [5]. Power generation can be more reliable and smoother when renewable sources such as PV, wind and batteries are used together. In order to achieve the most optimum results for any kind of hybrid system, performance needs to be improved by careful planning and minimising the expenses within the system limitations [6].

1.1 Microgrid Clustering

The key objectives of designing a power system are to maintain an instantaneous balance between the power generation and load demand and to minimise power outage probability. To meet these requirements, the concept of clustered microgrid or networked microgrids is very useful, where multiple microgrids are connected with one another in a grid-connected mode, reducing the possibility of power outages by organising the load demand in a planned way [7-9]. In a clustered architecture, each microgrid can be a combination of different components, such as the battery, wind turbines and solar panels, to provide its own load requirements, along with the shared load between microgrids [10]. A networked microgrid has many benefits over a single microgrid; for instance, neighbouring microgrids have provision for connecting with one another, microgrids can support one another during emergencies such as during power outages, power shortages and excessive power generation [8, 11, 12]. As reported in [10, 13], microgrid clustering ensures lower costs and lower emission of the system architecture.

1.2 Optimisation Techniques for Microgrids

It is crucial in the power system to find the correct sizing of the components to design an efficient and economic system [7, 14]. The optimum sizing of each microgrid can guarantee the right use of generation resources with respect to the load requirements, lower the investment required to build a power system and lead to the microgrids' best performance [15, 16]. Minimum investment, maximum utilisation of generation resources and efficient performance of the generation system are guaranteed by considering the right optimisation method [15]. There are several studies that consider the sizing and optimisation of microgrid and different approaches that are used to achieve desired outcomes such as the fuzzification mechanism [17] to design a grid-connected hybrid generation system consisting of wind turbine generators, photovoltaic panels and storage batteries.

In [18], the loss of power supply probability method is adopted to design a stand-alone photovoltaic system, and a relationship is employed between the amount of energy storage and loss of power supply probability. The trade-off method is used in [19, 20] to design a methodology for the sizing of different system components. Different algorithms are used to perform the optimisation, such as in [6], where a particle swarm optimisation algorithm is used for designing a grid-connected system, and in [7, 21, 22] an approach for hybrid power system planning is proposed. A comprehensive correction algorithm is used in [23] to estimate the thermal power seller's income, which enhances the stability of the alliance. A two-level distributed heuristic algorithm is introduced in [24] to solve the energy management problem for the PV-assisted charging station. In [25], a colonial competition algorithm is used for maintaining the frequency stability in a microgrid, and in [26] a multi-objective imperialistic competition algorithm (ICA) is used for the problems of microgrid optimisation.

1.3 Game Theory

When various components are involved in a microgrid to maximise profit, game theory is an advanced type of multi-objective optimisation to solve the decision-making problem [27]. Game theory is a decision-making process where different decision-makers are looking for their own maximum profits, and rectify different kinds of conflicts and cooperation among themselves. A game model consists of its autonomous decision-makers known as players, and its quantity should be two or more to play a game between themselves. Each player should have more than one choice; otherwise, having one choice means a player is not able to adopt a strategy to produce an outcome from a game. Usually, a game model consists of different elements, such as players, strategy and a payoff function [28, 29]. In a microgrid, game theory can be a faithful way to deal with various decision-making problems, where multiple renewable resources are used for generation.

For many years, game theory techniques have been used to solve various technical problems in different research areas, and have yielded a strong basis for market participants to achieve optimum results [25, 27, 30]. In a game model, the components of a microgrid may belong to different owners, but to achieve feasible sizing of generation capacities, each of the components prefers to collaborate for the maximisation of their profits.

A cooperative model-based game theory approach, namely the Shapely values, Auman Shapley, Nucleolus and the T-value approach, are considered in [31], to compare and assess the suitability of selected power system applications, and the results are illustrated using several approaches of sensitivity analysis. In [32] a game theory approach named dynamic population is used for the sizing of generation resources and maximisation of the utility function. Another game theory technique called Pareto optimal solution for the management of a microgrid in islanded and grid-connected modes is reported in [33]. Other game theory optimisation techniques are discussed in [34], which have been applied to various microgrid planning problems.

In [35], consumer preference-based demand response programs are developed to minimise the energy cost occurred by the consumer, and optimal scheduling of the game model is achieved by using a technique called the Nash equilibrium. A Stackelberg game-based solution is used in [36] to maximise the satisfaction level with multi-class appliance control in a microgrid.

The Nash bargaining solution is a cooperative game model of the negotiation process, which can be effectively used to meet the basic fair and efficient requirements that are important in a real-world bargaining solution [37]. The Nash bargaining solution is a bilateral negotiation process between the players to achieve maximum values of payoff when decision variables reach their optimal values within a set space [38].

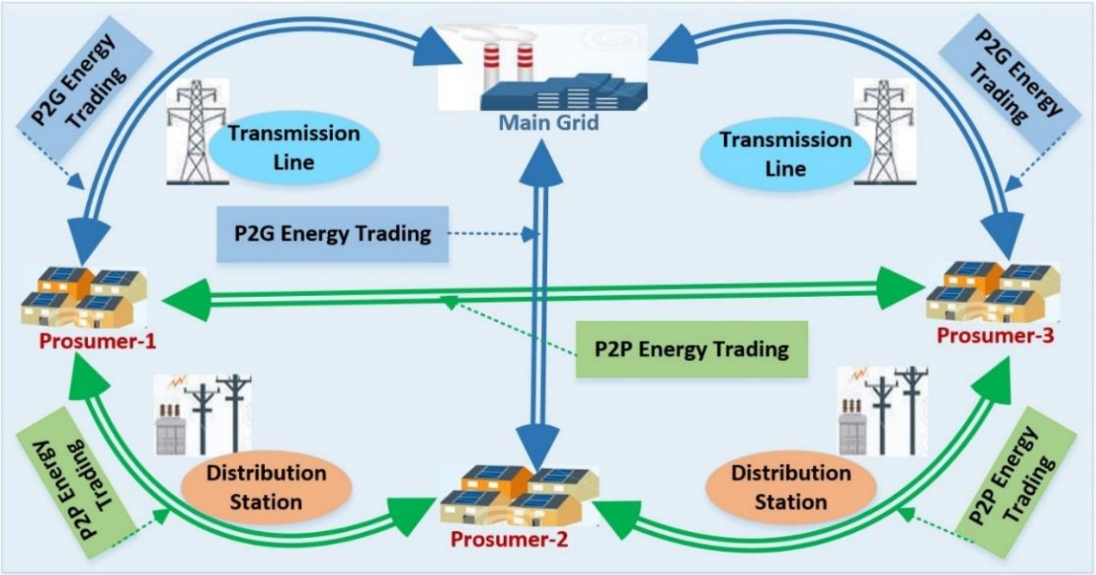


Figure 1.1 Energy trading schemes P2G and P2P

1.4 Energy Trading Schemes

To design the most efficient and economic system, it is necessary to build a proper energy trading model to organise the local energy trading between the prosumers. With a growing connection within the distribution system, traditional consumers or microgrids have the capability to act as prosumers, who can generate, consume and transfer access energy [39]. The traditional peer-to-grid (P2G) scheme is a unidirectional way to undertake energy trading, where microgrids can only buy insufficient power from the grid and sell extra power to the grid [40]. In contrast, the peer-to-peer (P2P) energy trading approach is a widely used multidirectional way where microgrids act as prosumers and can buy and sell power not only with one another but also with the main grid [41], as shown in Figure 1.1. P2P energy trading is considered a very efficient way to organise the generation resources within the clustered architecture; therefore, it becomes more attractive than traditional P2G energy trading [42-44]. Since P2P energy trading is a new concept in a clustered microgrid, proper modelling of the system model and the energy pricing play an essential role in determining the effectiveness of P2P energy trading on a clustered microgrid in terms of financial profits [45].

Figure 1.2 Towns of Australia Laverton, Mount Magnet and Wahroonga

1.5 Considered Towns of Australia

To find the optimum results and the accurate sizes of the system components, the real-time weather data and the electrical load profiles of three different towns in Australia are considered. The state of Western Australia (WA) is generously blessed with solar and wind energy resources, and can very effectively meet its residents' energy requirements. Therefore, to meet the state's large load requirements, many small and large renewable energy units are installed in various locations [46, 47]. New South Wales (NSW) has some of Australia's best renewable generation locations through solar and wind resources, and the NSW Government is promoting investment to grow renewable energy-based farms [48, 49]. Laverton and Mount Magnet are two remote towns of WA and are located 957 km and 560 km, respectively, northeast of the state’s capital, Perth, as shown in Figure 1.2. The third town, Wahroonga, is a suburb of NSW and is located 19 km northwest of the state’s capital, Sydney.

The weather forecast and residential load profiles of the selected towns are used in the analysis, but the geographical distance between the towns is not taken into account. Laverton’s weather is semi-arid, with a mix of hot summer and a mild to cold winter, and its mean daily temperature drops from 36℃ in January to 17℃ in July [50]. The average wind speed in Laverton throughout the year varies approximately between 5–7 m/s [51]. The climate condition of Mount Magnet is arid, with colder winters and hot summers. The average daily temperature range varies between 37.9℃ in January to 18.8℃ in July, and the average wind speed varies between 5–6 m/s [52, 53]. Wahroonga’s weather temperature varies between 11℃ to 27℃ from winter to summer, and average wind speed varies between 4–6 m/s [54].

In Figure 3, hourly weather forecast data of wind speeds, solar radiation and residential loads are shown for the remote towns of Laverton, Mount Magnet and Wahroonga. The electrical load profiles of the towns are illustrated in Figure 1.3 (a), where Laverton has a dense load profile with average and maximum load demand of 409.03 kW and 1150 kW, respectively. Mount Magnet has a denser load profile with average and maximum load demand of 654.05 kW and 1390 kW, respectively. Wahroonga has a comparatively thin load profile with average and maximum load demand of 180 kW and 1220 kW, respectively. Wind speed profiles are illustrated in Figure 1.3 (b), where Laverton has an average, and maximum wind speed of 5 m/s, and 14.1 m/s, respectively, Mount Magnet has an average and maximum wind speed of 4.17 m/s, and 11.2 m/s, respectively, and Wahroonga has an average and maximum wind speed of 4.81 m/s and 11.5 m/s, respectively. Solar radiation profiles are illustrated in Figure 1.3 (c), where Laverton has maximum solar radiation of 1046 Watt/m^2, Mount Magnet has maximum solar radiation of 1051 Watt/m^2, and Wahroonga has maximum solar radiation of 1000 Watt/m^2. The weather forecast and electrical load data of Laverton, Mount Magnet, and Wahroonga are considered for Microgrid 1 from July 2014 to June 2015, Microgrid 2 from June 2015 to May 2016, and Microgrid 3 from July 2012 to June 2013, respectively [55-57].

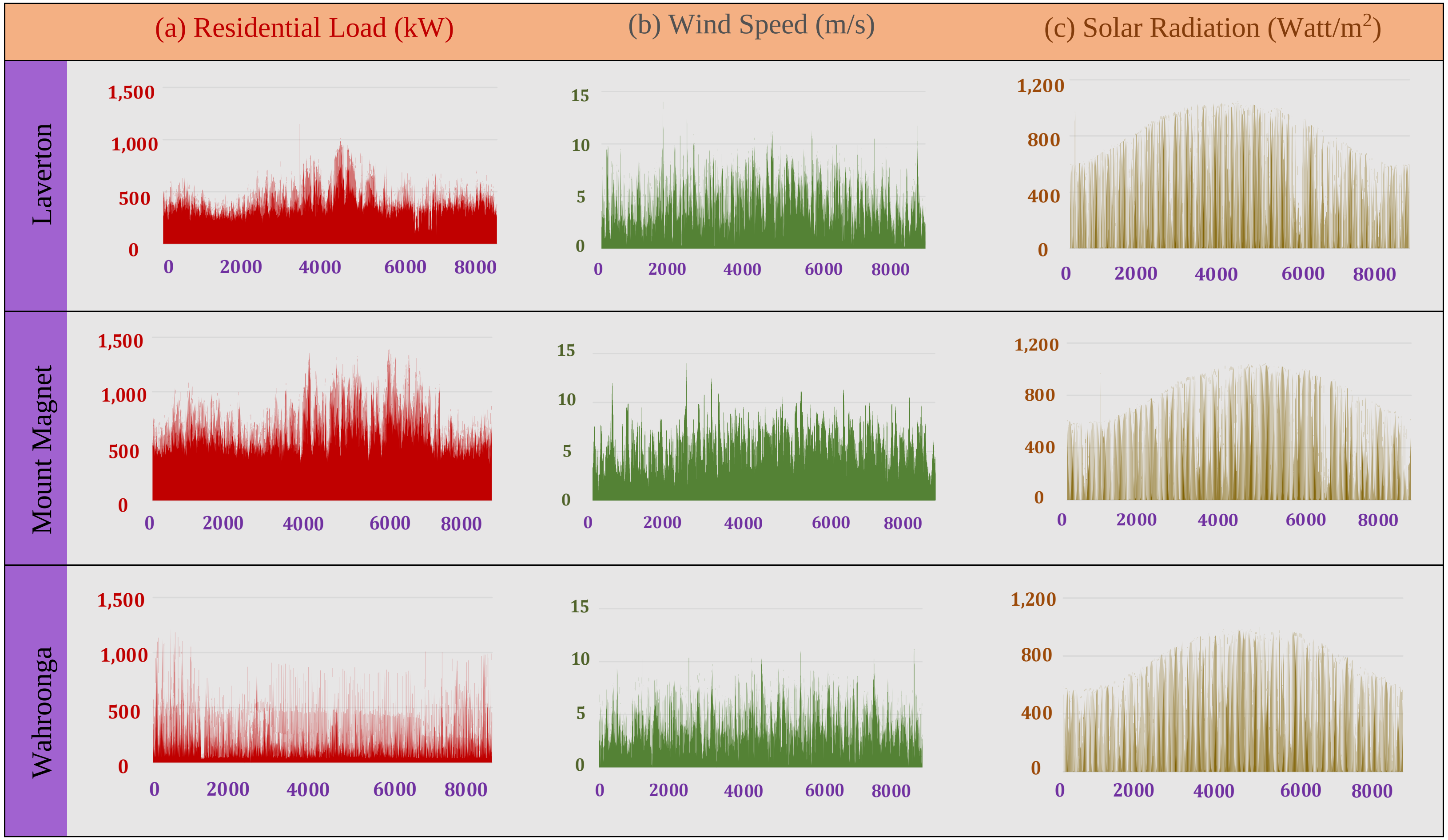


Figure 1.3 Weather forecast data and residential load profiles of Australian towns for 8764 hours

1.6 Research Motivation and Gaps

Microgrid and Research on renewable power system, has 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 typical hybrid power and clustered microgrids with combinations of multiple generation resources and battery energy storage system, and modern optimization approaches are considered to meet the residential load requirements.

On the other hand, an innovative real-world data based renewable energy systems are modelled and input data is fetched from Australian electricity market to perform the analysis. The proposed models are formulated based on game theory techniques, and single and multi-objective optimization is performed based on various criteria to achieve the optimized results. MATLAB software is used to design and simulate the hybrid power system and clustered microgrid. The numerical analysis is then carried out by the particle swarm optimization and imperialistic competitive algorithm. The suitable sizes of generation resources and storage energy system are proposed and optimum payoff values are achieved to create realistic models, under the specified time series sequence.

1.7 Research Contributions

The main contributions of this research are:

- Designing a two-stage control framework or P2P and P2G energy trading, and a comparative analysis between both schemes is accordingly given to validate the results. Performing a technique of multi-objective optimisation to achieve optimized results.
- Using different game theory techniques to optimise the proposed hybrid power systems for its correct sizing and to achieve optimal payoff values. Comparing cooperative and non-cooperative game theory approaches for the hybrid power system, and the most economical one is proposed.

- Considering a real-word based weather forecast data and load profiles are considered from three towns of Australia for the analysis to find their most feasible sizes of generation resources, and batteries, and to achieve accurate results.
- Validating the feasibility of proposed renewable systems by performing a sensitivity analysis.
- Using PSO and ICA algorithms to simulate renewable energy systems in MATLAB software. Running the simulation models for the maximum number of iterations to reach its global best values to achieve optimised results.

1.8 Aims and Objectives of the thesis

The primary goal of this research is to develop a renewable power systems integrated with peer-to-peer energy trading schemes based on advanced optimization approaches. Thereby, the specific research aims and objectives are:

- To develop different architectures in grid-connected mode with a combination of multiple renewable energy resources, battery and residential loads.
- To model typical game theory models with different combinations of microgrids considered, such as single-microgrid, two-microgrids and three microgrids models.
- To design advanced approaches of microgrid clustering and networked microgrids to control the effect of the unsteady nature of renewable resources, minimise the power outages, and confirm smoother power generation.
- To formulate the proposed models based on single-objective and multi-objective optimisation techniques and consider different criteria, such as annual profit, reliability index, loss of power supply probability, levelised cost of energy and energy index of reliability.

- To analyse power system models based on peer-to-grid and peer-to-peer energy trading schemes. Illustrate and compare the results to propose the most feasible power system. Perform the sensitivity analysis to validate the results and verify the stability of the power system models.

1.9 Structure of the Thesis

The remainder of the thesis is organised as follows:

Chapter 2 describes how a game-theoretic technique called the Nash equilibrium is designed for a hybrid power system to evaluate the capacity allocation of its components and to find the maximum annual profit. Cooperative and non-cooperative game models are analysed, and the most profitable one is proposed. The results are validated with sensitivity analysis. Also, a comparative analysis is performed with one of the models in [58]. The work of this chapter is submitted in the following paper:

> L. Ali, S. M. Muyeen and A. Ghosh, “Development and Planning of a Hybrid Power System based on Advance Optimization Approach”, submitted to the 2021 Australasian Universities Power Engineering Conference (AUPEC2021), Perth, Australia, 2021, Submission-ID: 4.

Chapter 3 shows how a networked microgrid is planned using two game-theoretic approaches. Microgrids that have different combinations of generation resources and batteries are considered to perform the capacity allocation of generation resources and to find the optimum value of the objective function. Game theory techniques of Nash equilibrium and Shapely value were used, and the most efficient one is identified based on the results. The realistic data of load profile, wind speed and solar radiation are considered for the Western Australian town of Mount Magnet. The work of this chapter is published in the following papers:

1. L. Ali, S.M. Muyeen, H. Bizhani, and A. Ghosh, “Comparative Study on Game-Theoretic Optimum Sizing and Economical Analysis of a Networked Microgrid”, *Energies* 2019, Vol. 12, No. 20, 4004. DOI: 10.3390/en12204004.
2. L. Ali, H. Bizhani, S.M. Muyeen, and A. Ghosh, “Optimal sizing of a networked microgrid using Nash equilibrium for mount magnet”, *International Journal of*

Smart Grid and Clean Energy, Vol. 9, No. 1, January 2020, pp 82–90. DOI: 10.12720/sgce.9.1.82-90.

Chapter 4 introduces a cooperative type of game theoretical technique to model a grid-connected clustered microgrid. The selected microgrid consists of different combinations of generation resources such as wind turbines, solar cells and batteries. The technique of the Nash bargaining solution is adopted in this study for capacity allocation of generation resources and batteries, and also to maximise the annual profit of individual microgrids and its cluster. A particle swarm optimisation algorithm is developed to find the most feasible Nash bargaining solution. The work of this chapter is published in the following papers:

1. L. Ali, S.M. Muyeen, H. Bizhani, and A. Ghosh, "Optimal planning of Clustered Microgrid using a Technique of Cooperative Game Theory", *Electric Power Systems Research*, Vol. 183, June 2020, 106262. DOI: 10.1016/j.epsr.2020.106262.
2. L. Ali, S. M. Muyeen and H. Bizhani, "Optimal Sizing and Profit Maximization of Clustered Microgrid using Game Theory Techniques", 2019, 9th IEEE International Conference on Power and Energy Systems (ICPES), Perth, Australia, 2019, pp. 1–6, DOI: 10.1109/ICPES47639.2019.9105648.

Chapter 5 proposes an approach of the multi-microgrids system consisting of three different microgrids and architectures that are modelled based on a cooperative game theory technique in grid-connected mode. Multi-objective optimisation is performed for the sizing of generation resources and storage batteries in order to achieve optimum payoff values. The technical criteria for the multi-objective function are selected as a levelised cost of energy and reliability index. The real-time weather data and load profiles of three different towns in Australia are taken to perform the analysis and validate the results. The work of this chapter is published in the following paper:

1. L. Ali, S. M. Muyeen, H. Bizhani, and M.G. Simoes "Game Approach for Sizing and Cost Minimization of a Multi-microgrids using a Multi-objective Optimization", *2021 IEEE Green Technologies Conference (GreenTech)*, 2021, pp. 507-512, DOI: 10.1109/GreenTech48523.2021.00085.

2. L. Ali, S. M. Muyeen, H. Bizhani, and M.G. Simoes "Peer-to-Peer Energy Trading and Planning of Multi-microgrid System using a Multi-Objective Optimization," under review in the *IEEE Transactions on Industry Applications*, 2021, Manuscript ID: 2021-IACC-0551.

Chapter 6 proposes a multi-objective optimisation for a networked microgrid based on a peer-to-peer energy trading scheme. The networked architecture is designed based on the Nash equilibrium to achieve the optimum sizes of the players and payoff values. The multi-objective function is based on different criteria, including annual profit, energy index of reliability and loss of power supply probability. The energy trading schemes, peer-to-grid and peer-to-peer are analysed and compared to show the efficacy of the proposed method. Sensitivity analysis is performed based on technical parameters to verify the stability of the proposed system. The work of this chapter is published in the following papers:

1. L. Ali, S. M. Muyeen, A. Ghosh and H. Bizhani, “Optimal Sizing of Networked Microgrid using Game Theory considering the Peer-to-Peer Energy Trading”, in the 2020 2nd IEEE International Conference on Smart Power & Internet Energy Systems (SPIES), Bangkok, Thailand, 2020, pp. 322-326, DOI: 10.1109/SPIES48661.2020.9243067.
2. L. Ali, S.M Muyeen, H. Bizhani, and A. Ghosh, “A Multi-objective Optimization for Planning of Networked Microgrid using a Game Theory for P2P Energy Trading Scheme”, peer-reviewed in the *Journal IET Generation, Transmission & Distribution*, 2021, Manuscript ID: GTD-2021-01-0036.
3. L. Ali, S.M Muyeen, H. Bizhani, and A. Ghosh, “A Peer-to-peer Energy Trading for a Clustered Microgrid – Game Theoretical Approach”, *International Journal of Electrical Power and Energy Systems*, Vol. 133, 2021, 107307, DOI: 10.1016/j.ijepes.2021.107307.

Chapter 7 highlights the key research findings and concludes the significant contributions. This chapter also suggests future directions in this research area.

1.10 Publications Arising from this Thesis

1.10.1 Journal Papers

1. L. Ali, S.M. Muyeen, H. Bizhani, and A. Ghosh, “Comparative Study on Game-Theoretic Optimum Sizing and Economical Analysis of a Networked Microgrid”,” *Energies* 2019, Vol. 12, No. 20, 4004. DOI: 10.3390/en12204004.
2. L. Ali, H. Bizhani, S.M. Muyeen, and A. Ghosh, “Optimal sizing of a networked microgrid using Nash equilibrium for mount magnet”,” *International Journal of Smart Grid and Clean Energy*, Vol. 9, No. 1, January 2020, pp 82–90. DOI: 10.12720/sgce.9.1.82-90.
3. L. Ali, S.M. Muyeen, H. Bizhani, and A. Ghosh, “Optimal planning of Clustered Microgrid using a Technique of Cooperative Game Theory”,” *Electric Power Systems Research*, Vol. 183, June 2020, 106262. DOI: 10.1016/j.epsr.2020.106262.

4. L. Ali, S.M Muyeen, H. Bizhani, and A. Ghosh, “A Peer-to-peer Energy Trading for a Clustered Microgrid – Game Theoretical Approach”, *International Journal of Electrical Power and Energy Systems*, Vol. 133, 2021, 107307, DOI: 10.1016/j.ijepes.2021.107307.
5. L. Ali, S.M Muyeen, H. Bizhani, and A. Ghosh, “A Multi-objective Optimization for Planning of Networked Microgrid using a Game Theory for P2P Energy Trading Scheme”,” peer-reviewed in the *Journal IET Generation, Transmission & Distribution*, 2021, Manuscript ID: GTD-2021-01-0036.
6. L. Ali, S. M. Muyeen, H. Bizhani, and M.G. Simoes "Peer-to-Peer Energy Trading and Planning of Multi-microgrid System using a Multi-Objective Optimization," under review in the *IEEE Transactions on Industry Applications*, 2021, Manuscript ID: 2021-IACC-0551.

1.10.2 Conference Papers

7. L. Ali, S. M. Muyeen and H. Bizhani, “Optimal Sizing and Profit Maximization of Clustered Microgrid using Game Theory Techniques”, 2019 from the 9th IEEE International Conference on Power and Energy Systems (ICPES), Perth, Australia, 2019, pp. 1–6, DOI: 10.1109/ICPES47639.2019.9105648.

8. L. Ali, S. M. Muyeen, A. Ghosh and H. Bizhani, “Optimal Sizing of Networked Microgrid using Game Theory considering the Peer-to-Peer Energy Trading”, 2020 2nd IEEE International Conference on Smart Power & Internet Energy Systems (SPIES), Bangkok, Thailand, 2020, pp. 322–326, DOI: 10.1109/SPIES48661.2020.9243067.
9. L. Ali, S. M. Muyeen, H. Bizhani, and M.G. Simoes “Game Approach for Sizing and Cost Minimization of a Multi-microgrids using a Multi-objective Optimization”, *2021 IEEE Green Technologies Conference (GreenTech)*, 2021, pp. 507-512, DOI: 10.1109/GreenTech48523.2021.00085.
10. L. Ali, S. M. Muyeen and A. Ghosh, “Development and Planning of a Hybrid Power System based on Advance Optimization Approach”, submitted to the 2021 IEEE Australasian Universities Power Engineering Conference (AUPEC2021), Perth, Australia, 2021, Submission ID: 4.

Chapter 2 Planning of a Hybrid Power System Based on Optimization Approach

In this chapter, a hybrid power system is designed based on a game theory approach consisting of different components like wind turbines, PV panels and batteries in grid-connected mode. Nowadays, as energy problems and atmospheric pollution is increasing rapidly, green energy production is playing a vital contribution. The Game Theory-based approach Nash equilibrium has been used to achieve desired objective functions and to perform analysis to reach towards the goals. Game theoretical models of the non-cooperative and cooperative game are considered, and wind turbines, PV panels and batteries are taken as players and the life-cycle income is chosen as payoffs. To obtain Nash equilibriums, a multi-objective particle swarm optimization algorithm has been developed in MATLAB. The sensitivity analysis is performed to validate the stability of Nash equilibriums for the price of electricity and discount rates. In the end, the outcomes of the proposed model are compared with recent research work to check the feasibility and validate the results.

This chapter is based on the research paper “Development and Planning of a Hybrid Power System based on Advance Optimization Approach” submitted in 2021 to the Australasian Universities Power Engineering Conference (AUPEC2021).

2.1 Statement of Contribution

The authors listed below have certified that:

- They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise.
- There are NO conflicts of interest. They agree to the use of the publication in the student's thesis and its publication on the Curtin University online database.

Paper:

"Development and Planning of a Hybrid Power System based on Advance Optimization Approach", submitted in the 2021 Australasian Universities Power Engineering Conference (AUPEC2021), 2021, Submission-ID: 4.

Contributors	**Statement of contribution**	**% Total Contribution**
Liaqat Ali	Conceptualisation, visualisation, methodology, simulation validation, data analysis and drafting the manuscript.	80
S.M. Muyeen	Conceptualisation, supervision and critical revision of the paper.	10
Arindam Ghosh	Supervision and critical revision of the paper.	10

Principle Supervisor Confirmation

I have sighted email or other correspondence from the co-authors confirming their certifying authorship.

Associate Professor S.M. Muyeen

______________________1st April 2021

2.2 Hybrid Power System

A hybrid power system operates in the grid-connected mode that includes the wind turbine, PV panels and batteries, as illustrated in Figure 2.1 [15, 17]. The main purpose of this research is to find the optimum capacity of all three players based on renewable resources and selected parameters and to analyse the Nash equilibrium values for different game theory-based combinations and validate the results with a sensitivity check.

A game is a procedure where not only different decisions are made, but also profit is maximised by decision-makers. Various types of conflicts and cooperations among the decision-makers are studied in game theory [59]. Many components are considered during the analysis, such as players, strategies and payoff. In the proposed hybrid power system, complete one-year data for wind, solar and load are considered; however, 24-hour profiles are shown for load and wind in Figures 2.2 and 2.3 respectively, and per unit photovoltaic power for 24 hours are given in Figure 2.4.

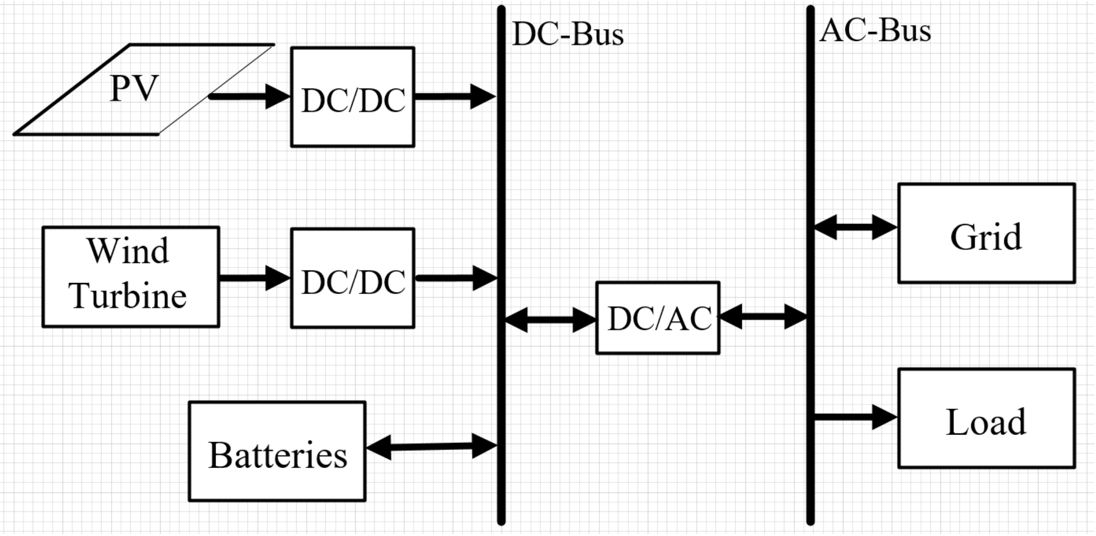


Figure 2.1 Schematic diagram for proposed hybrid power system

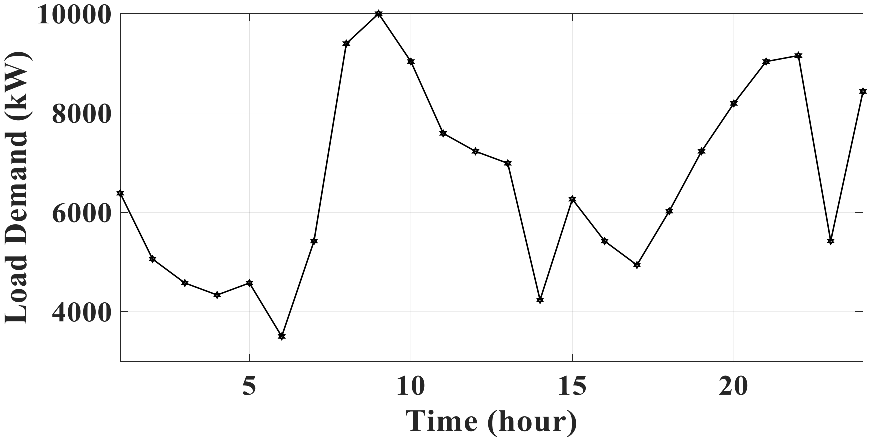


Figure 2.2 24-hour electric-load profile

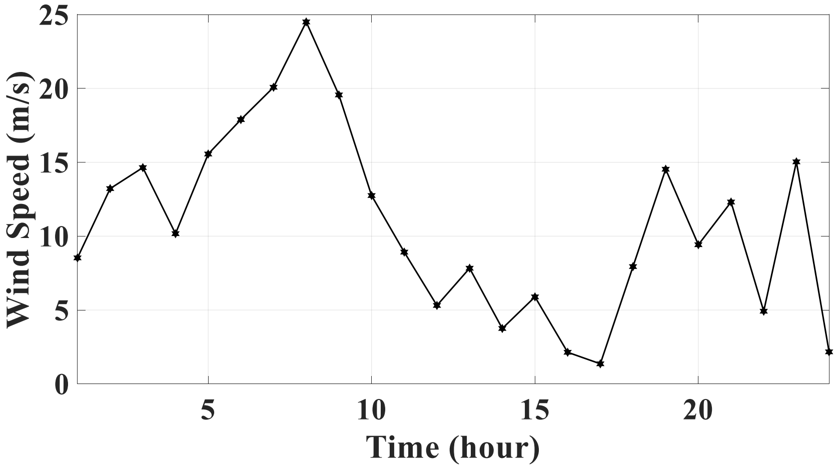


Figure 2.3 24 hours wind-speed profile

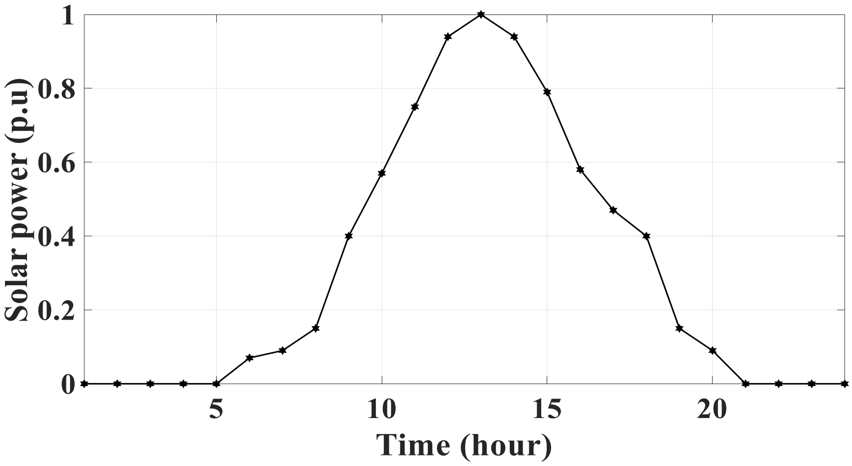


Figure 2.4 24-hour solar-power profile

2.3 Problem Formulation

The growing applications of renewable energy sources with unpredictability and variability of the power generation have become a serious concern for electric utilities, because they may cause grid stability problems. Recently, the application of battery storage technology has been considered as a solution to overcome the stochastic nature and the unpredictable output power production of hybrid power systems. Game theory is an effective tool that can resolve various decision-making problems for multiple players to maximise their profit [60]. “Game Theory is a scientific field dealing with the study and analysis of strategic, rational decision process of individuals and their interactions in the environment” [61]. It is applicable in the different fields, where the outcomes of an action are not dependent on predetermined actions, but depends on a certain amount of choice. There is no boundary to the application of game theory; it ranges from simple issues such as the determination of a favoured option that involves logic, and mathematics to solve complex issues such as social behaviour, economical behaviour, ethics, engineering and biological theory of choice, among others. The main elements of any game are its participating, autonomous decision-makers, known as players. A game must have two or more known number of players. The choices for each player must be more than one, since a game where players have only one choice has no strategy, and hence cannot affect the outcome of the game [27].

2.3.1 Game Theory Elements

Three different players are considered for the game theory model: wind generators (W), PV panels (S) and batteries (B). The capacities for all the three players are their strategies or decision variables, represented by P_W, P_S and P_B. The limits of each decision variable are between the strategic spaces.

$$P_W \,\epsilon\, \{\varphi_W = \left[P_W^{min}, P_W^{max}\right]\} \tag{2.1}$$

$$P_S \,\epsilon\, \{\varphi_S = \left[P_S^{min}, P_S^{max}\right]\} \tag{2.2}$$

$$P_B \,\epsilon\, \{\varphi_B = \left[P_B^{min}, P_B^{max}\right]\} \tag{2.3}$$

In the proposed hybrid system, to achieve the maximum payoff, different factors are taken into consideration, such as income from selling power (I_{SEL}), any subsidy from the government, players’ salvage values (I_D), investment cost (C_{INV}), the cost for operation and maintenance (C_{OM}), ancillary income ($\mathrm{I_{AUX}}$), and cost of energy that cannot be supplied (C_{ENS}) etc. In this research, to make the system simple, ancillary income is only considered for storage batteries and its value is zero for the other two players.

In the game model, for every player, the Nash equilibrium is denoted by P_W^*, P_S^* and P_B^*. The Nash equilibrium can only be achieved if every player will compete against one another, and as a result, the capacity of each player can produce a maximum profit.

2.3.2 Payoff for the Players

In this research, all parameters are taken for a complete year and accordingly, annual values of income/cost are considered to calculate the payoff.

A. Wind Generators

Wind speed $\mathrm{v(t)}$ of a complete year is considered for a wind generator to calculate the output power $\mathrm{p_W(t)}$ as the following:

$$p_W(t) = \begin{cases} 0 & v(t) < \mathcal{v}_c \; or \; v(t) \geq \mathcal{v}_o \\ \dfrac{P_W(v(t) - \mathcal{v}_c)}{\mathcal{v}_r - \mathcal{v}_c} & \mathcal{v}_c \leq v(t) < \mathcal{v}_r \\ P_W & \mathcal{v}_r \leq v(t) < \mathcal{v}_o \end{cases} \tag{2.4}$$

where *t*=1, 2,…, 8760 h. $\mathcal{v}_c$, $\mathcal{v}_r$, and $\mathcal{v}_o$ are cut-in, rated and cut-out wind speeds, respectively.

In this case, the payoff I_W depends on the wind speed, electric load, installation capacity and different policies and so on. The maximum consumed power in the hybrid power system in hour t is:

$$P_{max}(t) = P_d(t) + P_l^{max} + (P_B - p_B(t)) \tag{2.5}$$

where $P_d(t)$, $P_l^{max}$and $p_B(t)$ indicates the capacity of electrical load, the capacity of transmission line between hybrid system and grid, and capacity of storage batteries in hour t, respectively. The surplus power $P_{MAR}(t)$ generated from the hybrid system during hour t:

$$P_{MAR}(t) = p_W(t) + p_S(t) - P_{max}(t) \tag{2.6}$$

where $p_S(t)$ shows the power generated by PV panels in hour t.

Wind generator power selling $P_{WSEL}(t)$ in hour t is:

$$P_{WSEL}(t) = \begin{cases} p_W(t) & P_{MAR}(t) \le 0 \\ \dfrac{p_W(t) * P_{max}(t)}{(P_W(t) + P_S(t))} & P_{MAR}(t) > 0 \end{cases} \tag{2.7}$$

Wind generator income from selling power $I_{WSEL}(t)$ is:

$$I_{WSEL}(t) = \sum_{t=1}^{T} (1{+}\propto) * \mathbb{E}(t) * P_{WSEL}(t) \tag{2.8}$$

where T, $\propto$, and $\mathbb{E}(t)$ are the number of hours in a year, subsidy factor and electricity price, respectively.

$$C_{WINV} = \mathcal{U}_W * P_W * \mathfrak{D}(1 + \mathfrak{D})^{\mathbb{L}_W}/((1 + \mathfrak{D})^{\mathbb{L}_W} - 1) \tag{2.9}$$

where $\mathcal{U}_W$, $\mathfrak{D}$, and $\mathbb{L}_W$ are the per-unit price of wind generator, discount rate, and life span of wind generator, respectively

The unbalanced power $\Delta P(t)$ in the hybrid power system in hour t is:

$$\Delta P(t) = P_d(t) - p_W(t) - p_S(t) - (p_B(t) - P_{B\,min}) \tag{2.10}$$

The power purchased from the grid $P_g(t)$ in hour t:

$$P_g(t) = \begin{cases} 0 & \Delta P(t) \le 0 \\ \Delta P(t) & 0 < \Delta P(t) \le P_l^{max} \\ P_l^{max} & \Delta P(t) > P_l^{max} \end{cases} \tag{2.11}$$

Therefore, energy not supplied $P_{ENS}(t)$ in hour t is:

$$P_{ENS}(t) = \Delta P(t) - P_g(t) \tag{2.12}$$

Total compensation cost C_{ENS} for energy not supplied is:

$$C_{ENS} = \sum_{t=1}^{T} k(t) P_{ENS}(t) \tag{2.13}$$

where $k(t) = 1.5\mathbb{E}(t)$. $\mathrm{C_{ENS}}$ is divided among all the players, and a criterion with respect to each player capacity is considered.

Wind generator compensation cost C_{WENS} for energy not supplied is:

$$C_{WENS} = C_{ENS} P_W/(P_W + P_S + P_B) \tag{2.14}$$

Cost for power purchased C_{PUR} from a grid is:

$$C_{PUR} = \sum_{t=1}^{T} \mathbb{E}(t) P_g(t) \tag{2.15}$$

Power purchased C_{WPUR} from grid assigned to wind generator is:

$$C_{WPUR} = C_{PUR} * P_W/(P_W + P_S + P_B) \tag{2.16}$$

Wind generator salvage value I_{WD} is:

$$I_{WD} = P_W \mathcal{U}_{W\_SV} \mathfrak{D}/((1+\mathfrak{D})^{\mathbb{L}_W} - 1) \tag{2.17}$$

where $\mathcal{U}_{W\_SV}$ is the per-unit salvage value of the wind generator. Wind generator operation and maintenance (OM) cost C_{WOM} is:

$$C_{WOM} = P_W \mathcal{U}_{W\_OM} \tag{2.18}$$

where $\mathcal{U}_{W\_OM}$ is the per-unit OM cost of the wind generator. Wind Generator Ancillary Income for the proposed system is $I_{WAUX} = 0$.

Wind generator annual total payoff I_W is:

$$I_W = I_{WSEL} + I_{WD} + I_{WAUX} - C_{WINV} - C_{WOM} - C_{WENS} - C_{WPUR} \tag{2.19}$$

B. Photovoltaic Panels

The basic details of PV panels are considered to analyse the irregular sunlight nature for one complete year of PV power $p_S(t)$ in hourly intervals. However, most of the expressions to calculate the payoff I_S of PV panels is the same as previous wind generation. To calculate the selling income of PV panels, the selling power from photovoltaic $P_{SSEL}(t)$ is the same as $P_{WSEL}(t)$*:*

$$P_{SSEL}(t) = \begin{cases} p_S(t) & P_{MAR}(t) \le 0 \\ \dfrac{p_S(t) * P_{max}(t)}{(P_W(t) + P_S(t))} & P_{MAR}(t) > 0 \end{cases} \tag{2.20}$$

$$I_{SSEL}(t) = \sum_{t=1}^{T} (1 + \propto) \mathbb{E}(t) P_{SSEL}(t) \tag{2.21}$$

Photovoltaic panels' investment cost is:

$$C_{SINV} = \mathcal{U}_S * P_S * \mathfrak{D}(1+\mathfrak{D})^{\mathbb{L}_S}/((1+\mathfrak{D})^{\mathbb{L}_S} - 1) \tag{2.22}$$

Photovoltaic panels’ compensation cost for ENS is:

$$C_{SENS} = C_{ENS} * P_S/(P_W + P_S + P_B) \tag{2.23}$$

Photovoltaic panels’ power purchased from grid:

$$C_{SPUR} = C_{PUR} * P_S/(P_W + P_S + P_B) \tag{2.24}$$

Photovoltaic panel’s salvage value is:

$$I_{SD} = P_S * \mathcal{U}_{S_{SV}} * \mathfrak{D}/((1 + \mathfrak{D})^{\mathbb{L}s} - 1) \tag{2.25}$$

Photovoltaic panels’ OM cost:

$$C_{SOM} = P_S * \mathcal{U}_{S\_OM} \tag{2.26}$$

The same as wind generator Photovoltaic panels’ ancillary income $\mathrm{I_{SAUX}} = 0$.

PV panels’ total payoff is:

$$I_S = I_{SSEL} + I_{SD} + I_{SAUX} - C_{SINV} - C_{SOM} - C_{SENS} - C_{SPUR} \tag{2.27}$$

C. Storage Batteries

The change (Δ) in the stored energy of the battery is with respect to the power distribution among the load demand and generated power. In the hybrid system, when the surplus power is generated, batteries will charge, otherwise, they will discharge. In this research, sources of power generation are wind and PV, however, the electrical load will consume the power. In the case of hour $t - 1$ as:

$$\Delta(t - 1) = p_W(t - 1) + p_S(t - 1) - p_d(t - 1) \tag{2.28}$$

The energy of batteries at an hour (t) will be:

$$p_B(t) = \begin{cases} p_B(t - 1) + \xi_c \Delta(t - 1) & \Delta(t - 1) \geq 0 \\ p_B(t - 1) + \Delta(t - 1) & \Delta(t - 1) < 0 \end{cases} \tag{2.29}$$

where ξ_c is battery charging efficiency. In any case, $\mathrm{p_B(t)}$ must be within the limits $P_{B\,min} \leq p_B(t) \leq P_B$ and:

$$\Delta p_B(t) = p_B(t) - p_B(t + 1) \tag{2.30}$$

The power selling from batteries is:

$$P_{BSEL}(t) = \begin{cases} \Delta p_B(t) & \Delta p_B(t) > 0 \\ 0 & \Delta p_B(t) \leq 0 \end{cases} \tag{2.31}$$

The selling income of batteries is:

$$I_{BSEL}(t) = \sum_{t=1}^{T} (1{+}\propto) * \mathbb{E}(t) * P_{BSEL}(t) \tag{2.32}$$

The investment cost of batteries is:

$$C_{BINV} = \mathcal{U}_B * P_B * \mathfrak{D}(1 + \mathfrak{D})^{\mathbb{L}_B} / ((1 + \mathfrak{D})^{\mathbb{L}_B} - 1) \tag{2.33}$$

The compensation cost for ENS of batteries is:

$$C_{BENS} = C_{ENS} * P_B / (P_W + P_S + P_B) \tag{2.34}$$

The cost for power purchased from grid of batteries is:

$$C_{BPUR} = C_{PUR} * P_B / (P_W + P_S + P_B) \tag{2.35}$$

In case of batteries, if the batteries are out of work, the savage value cannot positive, therefore, $I_{BD} = 0$.

Operation and maintenance (OM) cost of batteries is:

$$C_{BOM} = P_B * \mathcal{U}_{B\_OM} \tag{2.36}$$

Batteries' ancillary income depend on the supplied reserve power:

$$P_{RES}(t) = p_B(t) - P_{BSEL}(t) - P_{B\,min} \tag{2.37}$$

$$I_{BAUX} = \mathfrak{R} * \sum_{t=1}^{T} P_{RES}(t) \tag{2.38}$$

Batteries' total payoff is:

$$I_B = I_{BSEL} + I_{BD} + I_{BAUX} - C_{BINV} - C_{BOM} - C_{BENS} - C_{BPUR} \tag{2.39}$$

2.4 Design of the Game Model

In the proposed model, all three players will either compete with one another or will establish a coalition to gain maximum value of profit.

2.4.1 Non-Cooperative Game Model

All three players will compete with one another in the case of a non-cooperative game. In the non-cooperative game the strategic model will have:

Players: W, S, B

Strategic-set: $\varphi_W = \left[P_W^{min}, P_W^{max}\right], \varphi_S = \left[P_S^{min}, P_S^{max}\right], \varphi_B = [P_B^{min}, P_B^{max}]$

Payoff: $I_W(P_W, P_S, P_B)$, $I_S(P_W, P_S, P_B)$, $I_B(P_W, P_S, P_B)$

In the case of the above game model has achieved the Nash equilibrium (P_W^*, P_S^*, P_B^*), it must fulfil the following criteria:

$P_W^* = arg \max\limits_{P_W} I_W\ (P_W, P_S^*, P_B^*)$, $P_S^* = arg \max\limits_{P_S} I_S\ (P_W^*, P_S, P_B^*)$

$P_B^* = arg \max\limits_{P_B} I_B\ (P_W^*, P_S^*, P_B)$

It indicates that strategy of each player is the best, only when all other players will achieve their strategies in the Nash equilibriums.

2.4.2 Cooperative Game Model

In this model, players cooperate with one another through different combinations of coalitions to gain maximum profit by selecting the right coalition value. For this game of three players, four different types of coalitions are possible. As an example, consider when wind and PV generation are in coalition and batteries are independent.

Player: {W, S}, B.

Strategic set: $\varphi_{WS} = \left[P_W^{min}, P_W^{max}, P_S^{min}, P_S^{max}\right], \varphi_B = [P_B^{min}, P_B^{max}]$

Payoff: $I_{WS}(P_W, P_S, P_B), I_B(P_W, P_S, P_B)$

If the above game model is under the Nash equilibrium, it must fulfil:

$(P_W^*, P_S^*) = arg \max\limits_{P_W P_S} I_{WS}\ (P_W, P_S, P_B^*)$, $P_B^* = arg \max\limits_{P_B} I_B\ (P_W^*, P_S^*, P_B)$

It indicates that for coalition {W, S}, the optimum value of the Nash equilibrium (P_W^*, P_S^*) is achieved only when the capacity of batteries will also reach Nash equilibrium value P_B^*, when (P_W, P_S)=(P_W^*, P_S^*). In the same way, all the other remaining cooperative game models are developed.

2.5 Algorithm to Achieve the Nash Equilibrium

There are various techniques to find the optimum value of the Nash equilibrium. In this section, it is found through an iterative search procedure for the proposed hybrid system. The details of this algorithm are given in Figure 2.5, and the steps are as follows:

1. Define the essential parameters such as solar irradiance, wind speed, price of electricity and discount rate and so on.
2. Develop a model for the proposed hybrid system model.
3. Randomly select the initial Nash equilibrium (P_W^0, P_S^0, P_B^0) values from the strategic set. The case of a non-cooperative model is considered to explain the process of decision-making. The jth round the strategy is ($\mathrm{P}_\mathrm{W}^\mathrm{j}, \mathrm{P}_\mathrm{S}^\mathrm{j}, \mathrm{P}_\mathrm{B}^\mathrm{j}$), which depends on the previous round ($\mathrm{P}_\mathrm{W}^{\mathrm{j}-1}, \mathrm{P}_\mathrm{S}^{\mathrm{j}-1}, \mathrm{P}_\mathrm{B}^{\mathrm{j}-1}$), as:

   $\mathrm{P}_\mathrm{W}^\mathrm{j} = \arg\max_{\mathrm{P}_\mathrm{W}} \mathrm{I}_\mathrm{W} (\mathrm{P}_\mathrm{W}, \mathrm{P}_\mathrm{S}^{\mathrm{j}-1}, \mathrm{P}_\mathrm{B}^{\mathrm{j}-1})$,

   $\mathrm{P}_\mathrm{S}^\mathrm{j} = \arg\max_{\mathrm{P}_\mathrm{S}} \mathrm{I}_\mathrm{S} (\mathrm{P}_\mathrm{W}^{\mathrm{j}-1}, \mathrm{P}_\mathrm{S}, \mathrm{P}_\mathrm{B}^{\mathrm{j}-1})$,

   $\mathrm{P}_\mathrm{B}^\mathrm{j} = \arg\max_{\mathrm{P}_\mathrm{B}} \mathrm{I}_\mathrm{B} (\mathrm{P}_\mathrm{W}^{\mathrm{j}-1}, \mathrm{P}_\mathrm{S}^{\mathrm{j}-1}, \mathrm{P}_\mathrm{B})$

   The particle swarm optimisation (PSO) algorithm [25-26] is used to find the most optimised results. In the simulation, 50 iterations and 100 particles are considered.

4. In this step, advise every player about the selected strategic values in the fourth step.
5. Check whether the optimum Nash equilibriums values are achieved and if none of the players changes their capacity during the whole round of the simulation, (P_W^j, P_S^j, P_B^j) = ($P_W^{j-1}, P_S^{j-1}, P_B^{j-1}$) = ($P_W^*, P_S^*, P_B^*$).

   If the above criteria are achieved and none of the players can improve their profits by changing their capacity within the strategic set, the Nash equilibrium is found. In case the Nash equilibrium is not achieved, move back to Step 4 to calculate again.

6. Optimised results of the Nash equilibrium are achieved for the proposed hybrid system model.

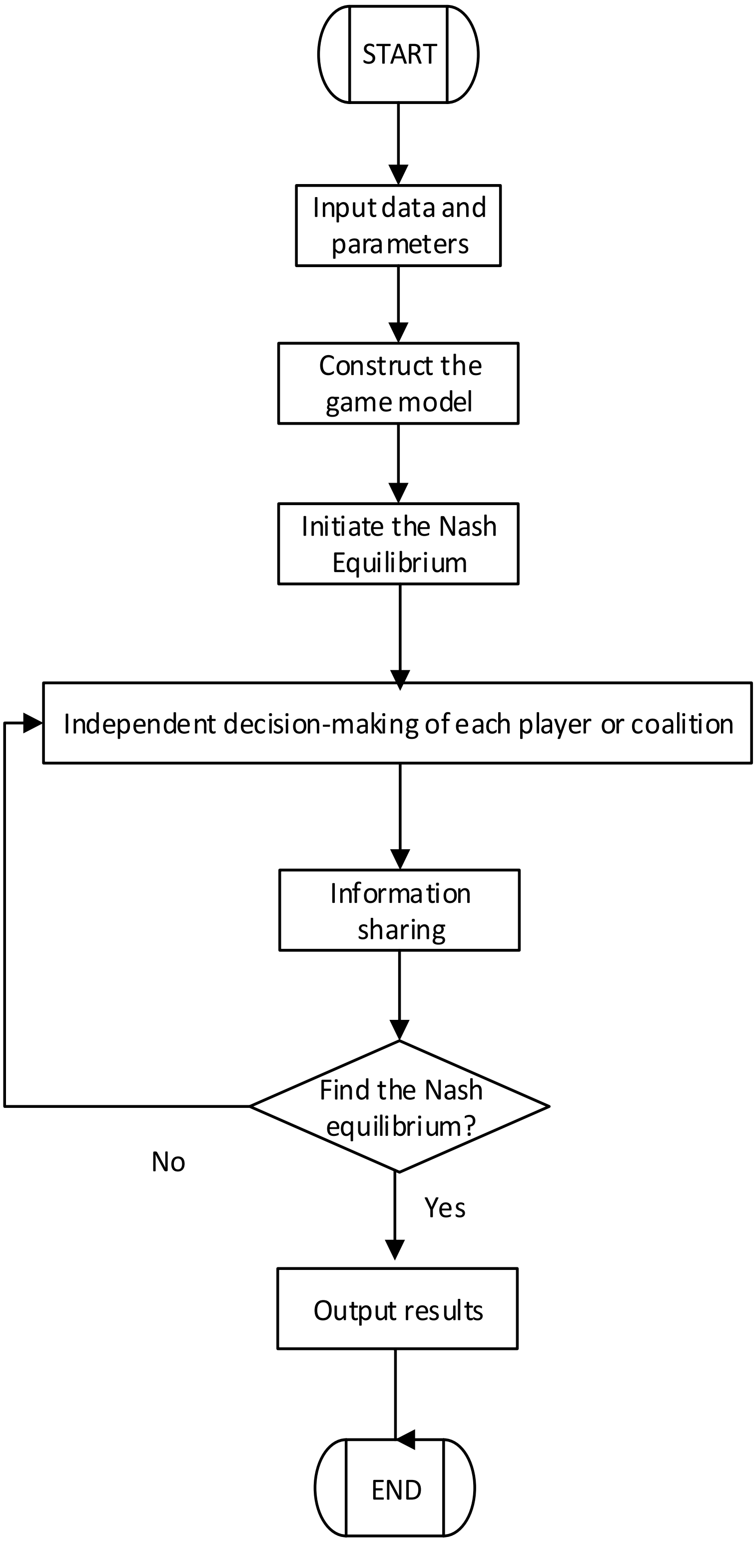


Figure 2.5 Algorithm to achieve optimum Nash equilibriums

2.6 Results and Analysis

To analyse the proposed hybrid power system, The known technical data is listed in Appendix A Table A.1 [17] used in the simulation. The simulation model is made in MATLAB software using an approach of PSO.

2.6.1 Non-Cooperative Model

The case of competition among all the players is illustrated in Table 2.1 and Figure 6.2, where the capacity of all three players is represented by $P_{total} = P_W^* + P_S^* + P_B^*$; and the profit of all players is $I_{total} = I_W + I_S + I_B$. Table 2.1 shows that in the case of a non-cooperative game model, the optimum values of Nash equilibriums are 30,008 kW, 15,021 kW and 8032 kW, which clearly show that P_W^* accounts for the highest 57% and P_B^* contributes smallest 15% only. Similarly, wind generation has the highest ratio of profit at 63%. The profit ratios of PV and batteries are 18.8% and 18.1% respectively, despite the higher capacity of PV panels.

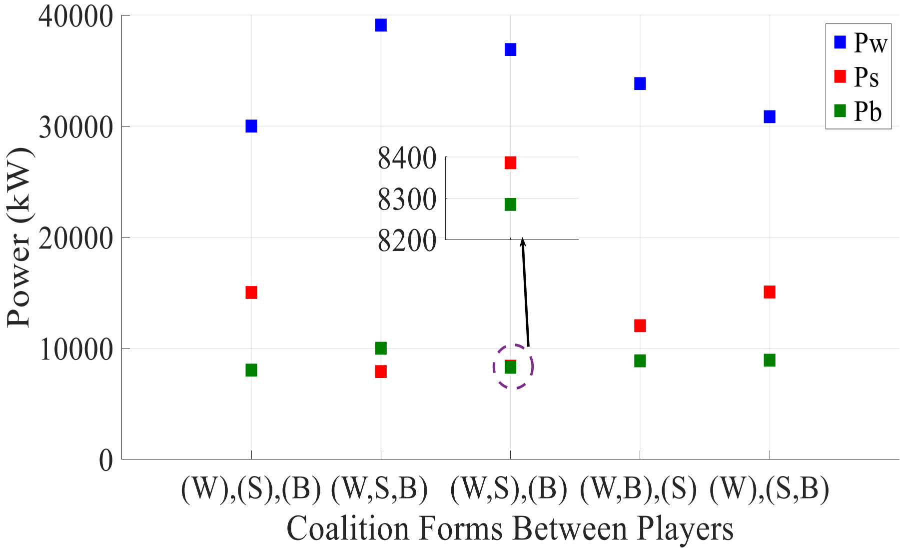


Figure 2.6 Power capacity of the players in hybrid power system

Table 2.1 Results for a Non-Cooperative model

		Strategy (kW)				Payoff ($/year)	
No.	Coalition forms	P_W^*	P_S^*	P_B^*	P_{total}	Payoff of each player	I_{total}
1	{W}, {S}, {B}	30,008	15,021	8032	53,061	I_W=3.592E+07, I_S=1.071E+07, I_B=1.031E+07	5.693E+07

Table 2.2 Results for a Cooperative model

		Strategy (kW)				Payoff ($/year)	
No.	Coalition forms	P_W^*	P_S^*	P_B^*	P_{total}	Payoff of each player	I_{total}
2	{W, S, B}	39,101	7899	10,000	57,000	I_{WSB}=6.507E+07	6.507E+07
3	{W, S}, {B}	36,897	8386	8285	53,568	I_{WS}=4.958E+07, I_B=1.056E+07	6.014E+07
4	{W, B}, {S}	33,832	12,032	8869	54,733	I_{WB}=5.084E+07, I_S=8.646E+06	5.948E+07
5	{W}, {S, B}	30,853	15,066	8923	54,842	I_W=3.550E+07, I_{SB}=2.157E+07	5.707E+07

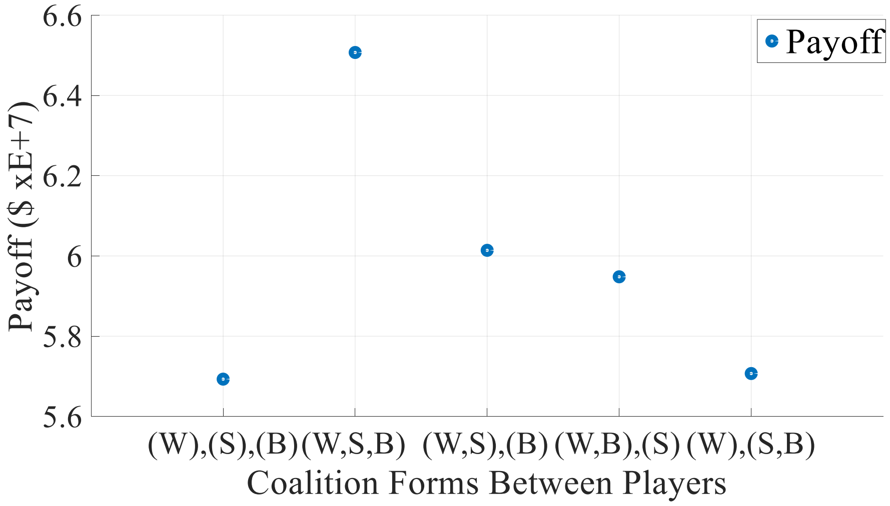


Figure 2.7 Payoff values for coalition forms

2.6.2 Cooperative Game Model

In the case of four cooperative games, the optimum values of the Nash equilibrium are illustrated in Table 2.2. The similarity in the Nash equilibrium results other than game 2, is $P_W^* > P_S^* > P_B^*$. However, we can also see the difference with regards to players' capacity and total profits. This is evident in the case of game-3, where the coalition between wind and PV results in smaller players' capacity and greater profit, and the total payoff is highest in the case of game-2 when a coalition is found among all the players. If Table 2.1, Table 2.2 and Figure 2.7 are compared, this illustrates that cooperative games have the highest total profit than the case of non-cooperative ones. The coalition of game-2 and game-3 has the highest profit, which means that the coalition between wind and PV generation can achieve the highest profit value.

2.6.3 Sensitivity Analysis

Sensitivity analysis is performed to validate the payoff values of proposed hybrid power systems.

A. Electricity Price

Electricity price influences the payoff of a proposed hybrid system. The comparative change with respect to Table 2.1 and Table 2.2 are illustrated in Table 2.3. Table 2.3 shows that as the electricity price decreases $0.11/kWh, the total profit of the proposed hybrid power system also decreases, and vice versa.

Table 2.3 Change in Payoff values for different electricity prices

Electricity Price ($/kWh)	No.	$\Delta \mathrm{I}_{\mathrm{total}}$(%)
0.11	1	−9.485
	2	−9.242
	3	−9.291
	4	−9.392
	5	−9.578
0.13	1	9.488
	2	9.242
	3	9.293
	4	9.391
	5	9.413

B. Discount Rate

The discount rate can also influence the payoff of the proposed hybrid power system, and the comparisons with the discount rate being 11% and 13% are illustrated in Table 2.4. It can be seen from Table 2.4 that at a higher discount rate, the payoff of the proposed hybrid power system decreases and vice versa.

2.7 Comparative Analysis

In this section, the results of the proposed hybrid power system are compared and analysed with a similar kind of game model designed in [58] and use the game theory technique Nash equilibrium. However, the proposed hybrid power system is different in design, and accordingly, an objective function is formulated and also modelled for a typical residential load and weather data.

Table 2.4 Change in Payoff values for different discount rates

Discount Rates (%)	No.	$\Delta \mathrm{I}_{\mathrm{total}}$(%)
11	1	0.778
	2	0.596
	3	0.634
	4	0.706
	5	0.704
13	1	−0.789
	2	−0.609
	3	−0.645
	4	−0.718
	5	−0.883

The number of players among both game models are wind turbines, photovoltaic panels and batteries. The main objective of this optimisation based on a game theory is the correct sizing of each player and maximisation of the annual profit. The maximum load requirement for both models is approximately 10 MW, but the load distribution throughout the year is different. The average electrical load profile of the proposed hybrid power system is higher. The annual electrical load, wind speed and solar radiation data are considered, and the prices of the system components are mentioned in Table 2.1.

The results of the proposed hybrid power system and of the model in [58] are listed in Table 2.5. First, if we compare the sizing of the players, the contribution of wind turbines is the highest in all type of coalitions, and battery contribution is at minimum in most cases. There is a similarity among most coalition types, as $P_W^* > P_S^* > P_B^*$. The total capacity P_{Total} of each coalition for a proposed hybrid power system are closer, but not the same, as in model [58], because the selected load profile is different. The annual per-unit payoff values for both models are compared in Figure 2.8, and this shows that its value is at maximum when all the players are in a single coalition and cooperating with one another, and its value is at a minimum when the players make a non-cooperative game model.

Table 2.5 Results after the comparative analysis between the game models

Sl#	Coalition forms among the players	Results for proposed hybrid power system (HPS)					Results for the model in [58]				
		Sizing of the Players (kW)				Payoff ($/Year)	Sizing of the Players (kW)				Payoff ($/Year)
		$\mathrm{P}_{\mathrm{W}}^{*}$	$\mathrm{P}_{\mathrm{S}}^{*}$	$\mathrm{P}_{\mathrm{B}}^{*}$	$\mathrm{P}_{\mathrm{total}}$	$\mathrm{I}_{\mathrm{total}}$	P_{W}^{*}	P_{S}^{*}	P_{B}^{*}	P_{total}	I_{total}
1	{W}, {S}, {B}	30,008	15,021	8032	53,061	5.6931E+07	40,622	15,760	6250	62,632	2.2885E+07
2	{W, S, B}	39,101	7899	10,000	57,000	6.5072E+07	33,255	6820	8510	48,585	2.4174E+07
3	{W, S}, {B}	36,897	8386	8285	53,568	6.0141E+07	33,184	6996	6250	46,430	2.4129E+07
4	{W, B}, {S}	33,832	12,032	8869	54,733	5.9484E+07	42,079	15,775	7920	65,774	2.3064E+07
5	{W}, {S, B}	30,853	15,066	8923	54,842	5.7075E+07	42,064	15,697	6250	64,011	2.2977E+07

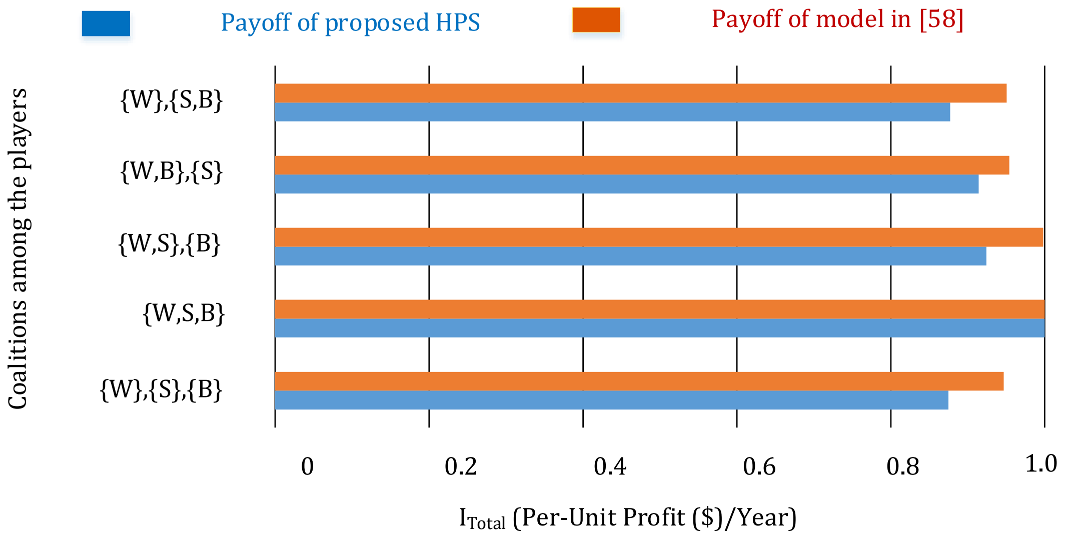


Figure 2.8 Payoff results for both game models

2.8 Summary

In this chapter, an approach of game theory is used to model the proposed hybrid power system which consists of wind turbines, photovoltaic panels and battery in a grid-connected mode to meet the electrical load requirements. The main objective of this work is the capacity allocation of the proposed model, and the findings are in maximum payoff values. Cooperative and non-cooperative game models are designed, and the results are compared. The findings are that the payoff values are optimum when all the players are in a single coalition and cooperating with one another. The results are validated through sensitivity analysis for electricity price and discount rate. In the end, the results of the proposed hybrid power system are compared with one of the models in [58], and this confirms the feasibility of the proposed hybrid power system.

The proposed model of this chapter consists of a single-microgrid, and two game theory techniques cooperative and non-cooperative are analysed and compared. At the end, the most feasible approach is explained to find the suitable sizes and maximum output values. This research is extended in next chapter and a typical networked microgrid is considered that consist of two different microgrids who are analysed to meet a load requirement of an Australia remote town. Networked microgrid is modelled based on a cooperative game theory technique Shapely values is used for the correct sizing the system components and to find maximum profit values.

Chapter 3 Economic Analysis and Sizing of a Networked Microgrid

This chapter focuses on the design of the capacity allocation of generation resources and on finding the maximum value of payoff for a networked microgrid in the planning stage using two game-theoretic approaches. In the networked microgrid, each of the microgrids consists of different combinations of generation resources and batteries. The game-theoretic technique called the Nash equilibrium is used for the optimisation purpose through an iterative search procedure. To meet the load requirements, generation resources such as wind turbines, photovoltaic panels and batteries are considered players. In order to find the maximum annual profit of networked microgrids, two different techniques of game theory, Nash equilibrium and Shapely values are used, and the most efficient one is identified comparing the results.

To keep the selected networked microgrid simple, two different microgrids are considered for this study. An imperialistic competition algorithm is used to design the model for the networked microgrid in MATLAB to achieve the most suitable sizing of generation resources and the maximum annual profit. To ensure the effectiveness of the networked microgrid, sensitivity analysis is performed for electricity price and discount rate.

This chapter is based on the research papers “Comparative Study on Game Theoretic Optimum Sizing and Economical Analysis of a Networked Microgrid”, published in *Energies* 2019, and “Optimal sizing of a networked microgrid using Nash equilibrium for mount magnet”, published in *International Journal of Smart Grid and Clean Energy*, 2020.

3.1 Statement of Contribution

The authors listed below have certified that:

- They meet the criteria for authorship in that they have participated in the conception, execution or interpretation, of at least that part of the publication in their field of expertise.
- There are NO conflicts of interest. They agree to the use of the publication in the student's thesis and its publication on the Curtin University online database.

Papers:

1. "Comparative Study on Game-Theoretic Optimum Sizing and Economical Analysis of a Networked Microgrid", published in *Energies* 2019, Vol. 12, No. 20, 4004. DOI: 10.3390/en12204004.
2. "Optimal sizing of a networked microgrid using Nash equilibrium for mount magnet", published in *International Journal of Smart Grid and Clean Energy*, Vol. 9, No. 1, January 2020, pp 82–90. DOI: 10.12720/sgce.9.1.82-90.

Contributors	Statement of contribution	Total Contribution
Liaqat Ali	Conceptualisation, visualisation, methodology, simulation validation, data analysis and drafting the manuscript.	80%
S.M. Muyeen	Conceptualisation, supervision and critical revision of the paper.	10%
Hamid Bizhani	Simulation validation, and critical revision of the paper.	5%
Arindam Ghosh	Supervision and critical revision of the paper.	5%

Principle Supervisor Confirmation

I have sighted email or other correspondence from the co-authors confirming their certifying authorship.

Associate Professor S.M. Muyeen

____________________ 1st April 2021

Figure 3.1 Mount Magnet in Western Australia

3.2 Design of the Networked Microgrid

The design of the networked microgrid is based on the input data, such as the wind speed, solar radiation, electrical load and other information. As shown in Figure 3.1, a town in Western Australia named Mount Magnet is considered to achieve optimum sizing of generation resources and maximum profit of the selected architecture. The feasibility of the proposed architecture is checked, and Mount Magnet’s real-time weather profile and load data are illustrated in Section 1.5 and Figure 1.3.

The networked microgrid can be a combination of a number of microgrids; however, the selected system consists of two microgrids with different combinations of generation resources and batteries. The block diagram of the proposed networked microgrid is shown in Figure 3.2, for a remote town, which consists of generation resources, batteries, electrical load and the main grid. Wind turbines, photovoltaic panels and storage batteries are considered as the sources of power generation, depending on the weather forecast. For the proposed power system, both microgrids are connected with the main grid and common electrical load; therefore, if they fail to meet the load requirements, they have the option to purchase power from the main grid, and in the case of large generation, they can sell the excess power to the main grid. The goal of this research is to find the optimum sizes of generation resources and battery to meet the load requirements and achieve maximum annual profit for the networked microgrid.

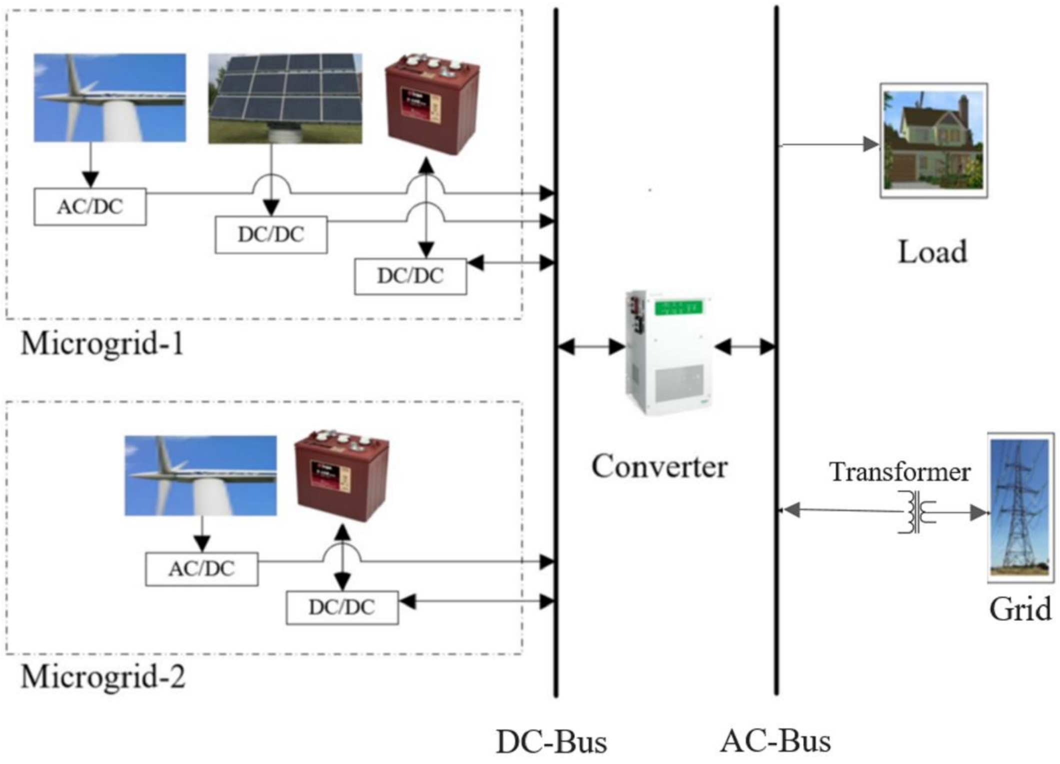


Figure 3.2 Block diagram of a networked microgrid

3.3 Problem Formulation

Game theory is a scientific field dealing with the study and analysis of strategic, rational decision process of individuals and their interactions in the environment. In other words, it is a decision-making process that can resolve different kinds of conflicts between the decision-makers and find the maximum payoff [61]. A model of game theory is the combination of autonomous decision-makers known as players, and they should be two or more in quantity to play a game. Besides this, every player should have more than one choice to achieve a payoff from a game; otherwise, one is not able to adopt a strategy. This means that a model of game theory is the combination of different players, strategies and payoff functions [28]. Game theory is a wonderful way to deal with various decision-making problems in microgrids, where different renewable resources and batteries are used for generation purpose. Game theory techniques have been used in different research areas to solve various technical problems [25, 27, 30], which confirms the solid basis for the market contributions to achieve their optimum payoff.

The main element of any game model are the decision variables known as the players, and each one must have more than one option to make their strategies to find the required payoff. In the networked architecture, $m, n,\ i,\ P_i$ and I_i represent the number of microgrids, number of game players, generation resources, decision variables or capacity of players, and payoff or annual profit respectively. The maximum and minimum power values of the players are the constraints in a selected game model and are represented as strategic space $SS_i\ = \left[P_i^{min}, P_i^{max}\right]$. The total annual profit for a single microgrid MG is:

$$I_{MG\_m} = \sum_{1}^{n} I_i \tag{3.1}$$

Similarly, the annual profit for networked microgrid NMG that is the combination of m number of microgrids can be found as:

$$I_{NMG} = I_{MG\_1} + I_{MG\_2} \dots\dots + I_{MG\_m} = \sum_{1}^{m}(\sum_{1}^{n} I_i) \tag{3.2}$$

3.3.1 Payoff for Microgrid 1

In microgrid 1, three-generation resources i wind turbines WT, solar panels SP and batteries BT are considered, and their decision variables or players are represented by P_{WT}, P_{SP}, and P_{BT}, respectively. Similarly, the maximum payoff or profit for the WT, SP and BT are I_{WT}, I_{SP}, and I_{BT}, respectively. The total annual profit for microgrid-1 is:

$$I_{MG\_1} = \sum_{1}^{n=3} I_i \tag{3.3}$$

In grid-connected mode, to achieve the maximum annual profit for the generation resource i different parameters are considered, such as power selling income I_{i_SE}, salvage value I_{i_SV}, income from ancillary services I_{i_AS}, initial investment cost C_{i_IN}, compensation cost from energy cannot be supplied C_{i_ES}, purchasing power from the grid C_{i_PR}, and operation and maintenance cost C_{i_OM} and so on. The annual profit for each of the generation resource can be found using the below equation:

$$I_i = I_{i\_SE} + I_{i\_SV} + I_{i\_AS} - C_{i\_IN} - C_{i\_OM} - C_{i\_ES} - C_{i\_PR} \qquad (3.4)$$

In comparison with wind turbines and solar panels, batteries normally do the activities of smoothing power generation, filling valleys and reducing peak, so the payoff mainly comes from ancillary services. For simplicity, in this analysis, only I_{i_AS} of batteries are considered; however, for wind turbines and solar panels, it is taken as zero. When the storage batteries are out of service, their I_{i_SV} is zero. C_{i_OM} is calculated by multiplying the per unit operation and maintenance cost of the player $\mathcal{U}_{i\_OM}$ by the generation capacity of the decision variable. I_{i_SV}, C_{i_IN}, and C_{i_PR} for each of the player i can be calculated as follows:

$$I_{i\_SV} = P_i * \mathcal{U}_{i\_SV} * \mathfrak{D}/((1+\mathfrak{D})^{\mathbb{L}_i} - 1) \qquad (3.5)$$

$$C_{i\_IN} = \mathcal{U}_i * P_i * \mathfrak{D}(1+\mathfrak{D})^{\mathbb{L}_i}/((1+\mathfrak{D})^{\mathbb{L}_i} - 1) \qquad (3.6)$$

$$C_{i\_PR} = \frac{C_{GR} * P_i}{(\sum_1^{n=3} P_i)} \qquad (3.7)$$

where $\mathcal{U}_{i\_SV}$, $\mathbb{L}_i$, and $\mathcal{U}_i$ are per unit salvage value, life span and per-unit cost for each player i. C_{GR} is the annual cost of each player for purchasing power from a large grid, and can be found by multiplying the per hour result of power purchased from the grid $P_{GR}(t)$ and the grid power price, for a year.

The annual compensation cost for energy not supplied C_{i_ES} in a networked microgrid is:

$$C_{i\_ES} = C_{ES} * P_i/(\sum_1^{n=3} P_i) \qquad (3.8)$$

$$C_{ES} = \sum_{t=1}^{8784} * 1.5 * \mathbb{E}(t) * \{DP(t) - P_{GR}(t)\} \qquad (3.9)$$

$$DP(t) = P_L(t) - p_{WT}(t) - p_{SP}(t) - (p_{BT}(t) - P_{BT\_min}) \qquad (3.10)$$

$$P_{GR}(t) = \begin{cases} 0 & DP(t) \leq 0 \\ DP(t) & 0 < DP(t) \leq P_{TL}^{max} \\ P_{TL}^{max} & DP(t) > P_{TL}^{max} \end{cases} \qquad (3.11)$$

where C_{ES}, $DP(t)$, $P_L(t)$ and P_{TL}^{max} are the total annual cost of energy not supplied, unbalanced power in the microgrid, load demand and transmission capacity of the tie-line between the networked microgrid and main grid, in hour t, respectively.

The output power of the wind turbine $p_{WT}(t)$ and storage battery $p_{BT}(t)$ can be found as:

$$p_{WT}(t) = \begin{cases} 0 & V(t) < v_c \; or \; V(t) \geq v_o \\ \dfrac{P_{WT} * (V(t) - v_c)}{v_r - v_c} & v_c \leq V(t) < v_r \\ P_{WT} & v_r \leq V(t) < v_o \end{cases} \tag{3.12}$$

$$p_{BT}(t) = \begin{cases} p_{BT}(t-1) + \xi_c * \Delta(t-1) & \Delta(t-1) \geq 0 \\ p_{BT}(t-1) + \Delta(t-1) & \Delta(t-1) < 0 \end{cases} \tag{3.13}$$

$$\Delta(t-1) = p_{WT}(t-1) + p_{SP}(t-1) - p_L(t-1) \tag{3.14}$$

where $V(t)$ is the wind speed in hour t. The batteries are charged with respect to the power difference $\Delta(t)$ between the electrical load and the total generation capacities in hour t.

The annual income from power selling I_{i_SE}, can be calculated from the following:

$$I_{i\_SE}(t) = \sum_{t=1}^{8784} (1+\propto) * \mathbb{E}(t) * P_{i\_SE}(t) \tag{3.15}$$

$$P_{i\_SE}(t) = \begin{cases} p_i(t) & P_{SU}(t) \leq 0 \\ \dfrac{p_i(t) * P_{mx}(t)}{(\sum_1^{n=2} P_i)} & P_{SU}(t) > 0 \end{cases} \tag{3.16}$$

$$P_{mx}(t) = P_L(t) + P_{TL}^{max} + (P_{BT} - p_{BT}(t)) \tag{3.17}$$

$$P_{SU}(t) = p_{WT}(t) + p_{SP}(t) - P_{mx}(t) \tag{3.18}$$

where $P_{i\_SE}(t)$, $P_{SU}(t)$, and $P_{mx}(t)$ are the power selling, surplus power and maximum power that can be consumed, respectively.

The annual selling power $P_{BT\_SE}(t)$ and ancillary income for storage battery I_{BT_AS} can be found as:

$$P_{BT\_SE}(t) = \begin{cases} Dp_{BT}(t) & Dp_{BT}(t) > 0 \\ 0 & Dp_{BT}(t) \leq 0 \end{cases} \tag{3.19}$$

$$Dp_{BT}(t) = p_{BT}(t) - p_{BT}(t+1) \tag{3.20}$$

$$I_{BT\_AS} = \Re * \sum_{t=1}^{8760} \left(p_{BT}(t) - P_{BT\_SE}(t) - P_{B\_min} \right) \tag{3.21}$$

where $Dp_{BT}(t)$ and I_{pu_RP} represent the change in battery capacity in hour t.

3.3.2 Payoff for Microgrid 2

In microgrid 2, two-generation resources i wind turbine WT and batteries BT are considered to design a model, and their decision variables are P_{WT} and P_{BT}, respectively. I_{WT} and I_{BT} represents the annual profit for each of the players. The total annual profit for microgrid 2 is:

$$I_{MG\_2} = \sum_{1}^{n=2} I_i \tag{3.22}$$

To achieve the maximum annual profit for microgrid-2, the technical parameters and Equation 4 are used for wind turbine WT and batteries BT. Last, the total annual profit of the networked architecture including microgrid-1 and microgrid-2 are calculated as follows:

$$I_{NMG} = \sum_{1}^{m=2} \left(\sum_{1}^{n} I_i \right) = I_{MG\_1} + I_{MG\_2} \tag{3.23}$$

3.4 Game Theory Technique

Game theory is an advanced type of multi-objective optimisation that has been applied for many years to solve different decision-making problems. To design cooperative and non-cooperative game models, various kinds of solution concepts or techniques are used, such as the Nash equilibrium, Pareto optimality, Shapley values, Nash bargaining solutions and so on. In-game theory, the Nash equilibrium is a fundamental concept and the most widely used technique for cooperative and non-cooperative game models to find the sizing and outcome of decision variables [62]. Shapley values is a technique mostly used for cooperative game models to fairly allocate the benefits among the independent power producers for the success of cooperation [63, 64]. In this research, cooperative game models are designed and use a technique of Nash equilibrium for optimum sizing of the capacities of generation resources and batteries. The maximum profit from networked microgrid is obtained based on the optimum sizes of the players, and Shapley values are also used to fairly allocate the profit among the players based on their contribution to the game model.

In order to explain the Nash equilibrium, consider microgrid 1, which consists of three players as generation resources wind turbines WT, solar panels SP and batteries BT. Therefore, the cooperative game model can have four different possible coalitions for the planning problem of a three-player game. The optimum values of decision variables are found through Nash equilibrium using an iterative procedure, and illustrated below when WT, SP are cooperating with each other and BT is working as self-sufficient:

1. Input the parameters such as wind speed, solar radiation, electricity price and discount rate and so on.
2. For the selected microgrid, randomly choose initial values of decision variables (P_{WT}^{0}, P_{SP}^{0}, P_{BT}^{0}) from a strategic space.
3. In the case of generation resources, WT and SP are cooperating with each other and BT is self-sufficient. To explain, consider a j^{th} iteration (P_{WT}^{j}, P_{SP}^{j}) (P_{BT}^{j}), which depend on the previous iteration $(P_{WT}^{j-1}, P_{SP}^{j-1})$ (P_{BT}^{j-1}), as:

$$(P_{WT}^{j-1}, P_{SP}^{j-1}) = arg \max_{P_{WT}P_{SP}} I_{WT\,SP}\,(P_{WT}, P_{SP}, P_{BT}^{j-1})$$

$$P_{BT}^{j-1} = arg \max_{P_{BT}} I_{BT}\,(P_{WT}^{j-1}, P_{SP}^{j-1}, P_{BT})$$

4. In this step, share with every player in the coalition strategic values of the third step.
5. Check the condition of the Nash equilibrium, if none of the players changes its value during the whole round of iteration, which means (P_{WT}, P_{SP})=(P_{WT}^{*}, P_{SP}^{*}), and $P_{BT} = P_{BT}^{*}$, the Nash equilibrium is found. In this case, the results are not achieved, so move back to Step 3.

To find the maximum value of annual profit from a networked microgrid a cooperative game theory technique, Shapely values are introduced based on the optimum sizing of generation resources and batteries. It is a widely used solution concept in coalition-type games, and its main advantage is the fair distribution of profit among the players depending on their marginal contribution in the architecture [65, 66]. Shapely values is a very simple and straightforward way to distribute the payoff or profit among the players of a game model in a collaborative way [61]. In Shapley values, Φ_i represents for each player, and the game model is defined by (n, f) for each of the player $n \in N$ and is expressed as:

$$\Phi_i = \sum_{S \in N} [f(S) - f(S - i)] * \frac{(\mid S \mid -1)!\,(n - \mid S \mid)!}{n!} \qquad (3.24)$$

where N is the total number of players in the coalition, $\mid S \mid$ is the number of players in set S, $v(S)$ is the payoff or profit when all players of set S are in coalition, and $v(S - i)$ is the profit when all players except i are in coalition. Through this game technique, the players who contribute the most in the networked microgrid is rewarded the most, and the one who contributes the least is rewarded the least.

To design and simulate the proposed networked architecture in MATLAB, an imperialistic competition algorithm is used. The main operators of this algorithm are assimilation, revolution and imperialistic competition, as shown in Figure 3.3. It is a modern population-based algorithm and is used in various research areas to solve many optimisation problems [67, 68]. In this research, to find the most feasible sizes of decision variables, 50 populations or countries, five imperials, and a maximum of 50 years are considered. Besides this, one-year realistic input data of residential load, wind speed, and solar radiation of a remote town in Western Australia are considered in designing and simulation to find optimum sizes of generation resources and maximum profit of a networked microgrid.

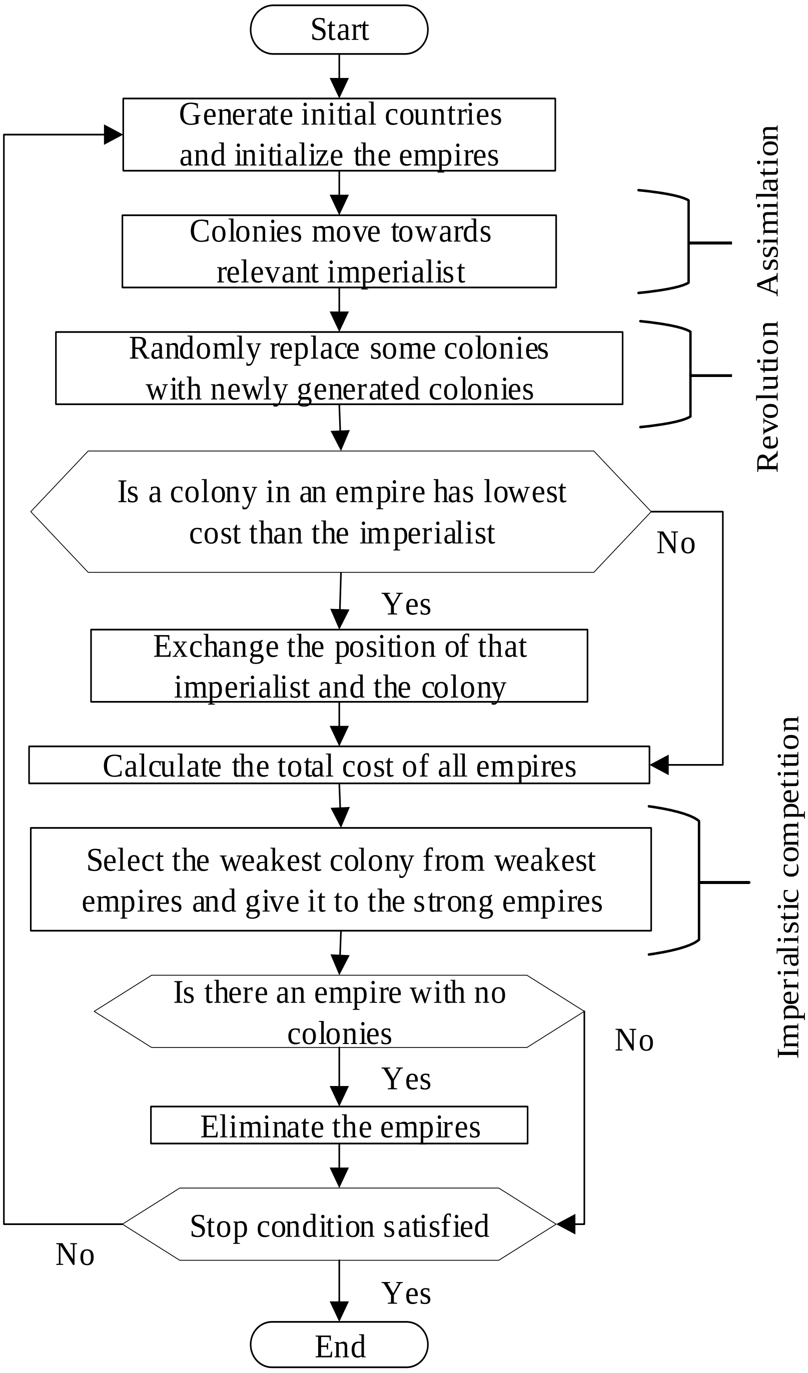


Figure 3.3 Imperialistic competition algorithm

3.5 Results and Analysis

The optimum sizing of the networked microgrid is carried out with the help of the game-theoretic technique called the Nash equilibrium and all possible combinations of the cooperative game model are considered. The annual profit of each microgrid is found using the Nash equilibrium and Shapely values, and a comparative analysis is carried among the game-theoretic techniques to identify the maximum profit of networked microgrid. A simulation model is made in MATLAB software and used a population-based imperialistic competition algorithm. To optimise the objective function and to find suitable sizes of decision variables, input parameters, as listed in Appendix A Table A.1 [58] are considered for each of the generation resource and batteries.

In the case of microgrid 1 three-generation resources wind turbines WT, solar panels SP and batteries BT are considered players, and therefore, for the cooperative game model, four different kinds of coalitions are possible. However, microgrid 2 consists of two players wind turbines WT and batteries BT, and therefore, only one coalition is possible among them. To find the cooperative game model with maximum profit and the most suitable generation sizes, all possible coalitions are considered and simulated. The optimum sizes of decision variables and maximum annual profit are found using the Nash equilibrium technique for each combination and are listed in Table 3.2 for both microgrids. It is evident from the results that the power capacity of WT is higher than SP and BT; however, SP capacity is smaller than BT in all cases except case 3.

Table 3.1 Nash equilibrium results for networked microgrid

	Game Model		Capacity Allocation of the Players (kW)			Total Profit ($\$/year$)
MG 1	Case#	Coalition	P_{WT}	P_{SP}	P_{BT}	I_{MG_1}
	1	{WT, SP, BT}	44,876	8007	9294	2.48E+7
	2	{WT, SP}, {BT}	44,979	8541	9999	2.47E+7
	3	{WT, BT}, {SP}	44,952	15,020	9304	2.29E+7
	4	{WT}, {SP, BT}	32,482	8032	9756	2.06E+7
MG 2	Case#	Coalition	P_{WT}		P_{BT}	I_{MG_1}
	5	{WT, BT}	44,903		8752	2.50E+7

Table 3.2 illustrates that annual profit is higher when wind turbines WT make a coalition with any of other players, and it reaches maximum values when all other players use solar panels SP and batteries BT are in coalition with wind turbines WT. Therefore, case 1 is the most suitable coalition for microgrid 1 with sizes of 44,876 kW, 8007 kW and 9294 kW for WT, SP and BT, respectively, and maximum profit is 2.48E+7 \$/year using the Nash equilibrium. Besides this, for microgrid 2, the maximum profit is 2.50E+7 \$/year and optimum sizes of WT and BT are 44,903 kW and 8952 kW, respectively. The cooperative game models also show that if larger sizes of generation resources are considered in a microgrid, the value of annual profit is higher. As the microgrid achieves the opportunity to sell additional power to the main grid, it is easier for the networked architecture to meet load requirements in any emergency.

Table 3.2 Shapley values result for networked microgrid

	Game Model		Profit Using Shapley Values ($\$/year$)			
	Case#	Coalition	Φ_{WT}	Φ_{SP}	Φ_{BT}	Φ_{MG_1}
MG 1	1	{WT, SP, BT}	1.63E+7	8.24E+6	1.09E+7	3.54E+7
	2	{WT, SP}, {BT}	1.60E+7	8.11E+6	1.09E+7	3.50E+7
	3	{WT, BT}, {SP}	1.47E+7	7.59E+6	1.00E+7	3.23E+7
	4	{WT}, {SP, BT}	1.19E+7	6.12E+6	8.80E+6	2.68E+7
MG 2	Case#	Coalition	Φ_{WT}		Φ_{BT}	Φ_{MG-2}
	5	{WT, BT}	1.74E+7		1.25E+7	2.99E+7

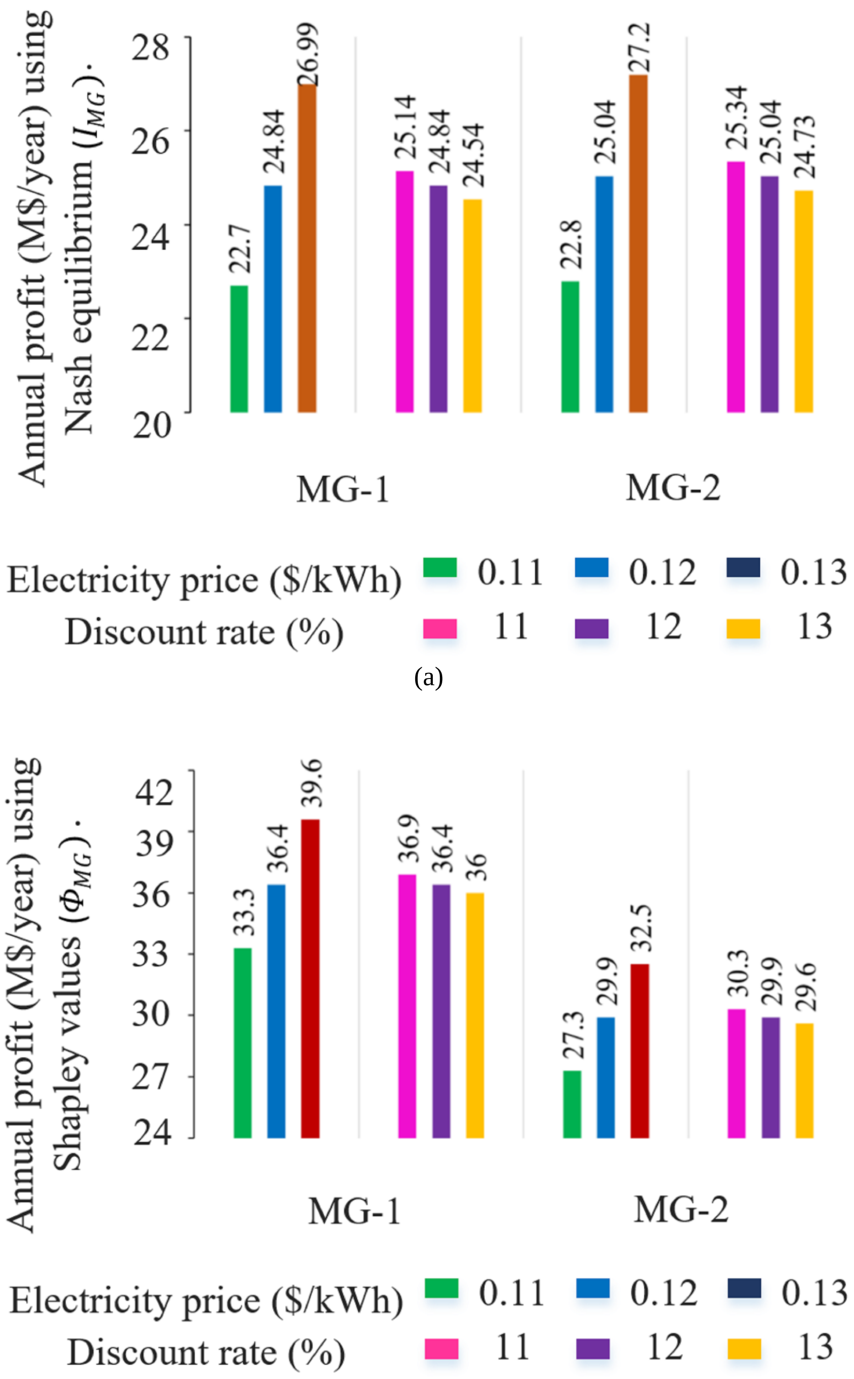
In this analysis, to achieve the maximum value of annual profit from the networked microgrid, two different game theory techniques: the Nash equilibrium and Shapley values are used, and the results are compared to identify the most feasible solution. The annual profit of the Nash equilibrium and Shapley values are shown in

Table 3.2 and Table 3.3, respectively for each microgrid. If the annual profit for each possible coalition is compared between both game-theoretic techniques, the results are found to be maximum for Shapley values compared to the Nash equilibrium. It is also illustrated in Table 3 that the distribution of the annual profit among the players is fair in each coalition with respect to the players' contribution. Therefore, the technique of Shapley values is proposed for the maximisation of the annual profit of the networked microgrid, and optimum sizing of generation resources and batteries are found through the Nash equilibrium.

In the end, sensitivity analysis is performed for both techniques of game theory to analyse the impact of changing the values of the electricity price R and discount rate Dr for the proposed networked architecture. These parameters are considered to validate the results and observe the variations in the value of the annual profit from microgrid 1 and microgrid 2. The influence of changing the electricity price and discount rate are shown in Figure 3.4 (a) and 3.4 (b), respectively, and in Table 3.4. The results for both microgrids show that, as the electricity price decreases, the total annual profit decreases too. However, in the case of high electricity prices, generation resources are earning more profit by selling power to the load and main grid. On the other hand, as the value of the discount rate increases, the value of profit is increasing sequentially, and vice versa. It is also evident from both parameters that the influence of the electricity price is more sensitive than the discount rate. Therefore, a small increase in electricity price produces a rapid increase in profit value.

Table 3.3 Sensitivity analysis of networked microgrid for game theory techniques

Game Model		Profit (M$/year) Using a Nash Equilibrium (I_{MG})						Profit (M$/year) Using Shapley Values (Φ_{MG})					
		Electricity Price ($/kWh)			Discount Rate (%)			Electricity Price ($/kWh)			Discount Rate (%)		
		0.11	0.12	0.13	11	12	13	0.11	0.12	0.13	11	12	13
MG 1	{WT, SP, BT}	22.7	24.8	26.9	25.1	24.8	24.5	33.3	36.4	39.6	36.9	36.4	36.0
MG 2	{WT, BT}	22.8	25.0	27.2	25.3	25.0	24.7	27.3	29.9	32.5	30.3	29.9	29.6



(a)

(b)

Figure 3.4 Sensitivity analysis for game theory techniques: (a) Nash equilibrium; (b) Shapley values

3.6 Summary

In this chapter, two techniques of game theory are considered for sizing and comparative analysis of grid-connected networked microgrid, based on a multi-objective imperialistic competition algorithm ICA for system optimisation. The selected networked microgrid, which consists of two different grid-connected microgrids with common electrical load and main grid, might have different combinations of generation resources including wind turbine, photovoltaic panels and batteries. The game theory technique Nash equilibrium is developed to perform the effective sizing of a networked microgrid in which capacities of the generation resources and batteries are considered as players and annual profit as the payoff. In order to meet the equilibrium point and the optimum sizes of generation resources, all possible coalitions between the players are considered, ICA, which is frequently used in optimisation applications, is implemented using MATLAB software. Both techniques of the game theory Shapley values and Nash equilibrium are used to find the annual profit of each microgrid, and the results are compared based on optimum sizing, and maximum values of annual profit are identified. Finally, in order to validate the results of the networked microgrid, the sensitivity analysis is studied to examine the impact of electricity price and discount rates on maximum values of profit for both game theory techniques.

The proposed model of this chapter consists of a networked microgrid that consist of two different microgrids. Networked microgrid is modelled based on a techniques Nash Equilibrium and Shapely values to find the correct sizing and achieve the maximum profit values. In the next chapter similar architecture is considered but two microgrids are considered with different combinations of generation resources. Microgrid clustering is introduced to design a network and different cooperative game theory technique Nash bargain solution is used to find suitable sizes of each player and maximum payoff values. The results are further verified and validated with help of sensitivity analysis.

Chapter 4 Optimal Planning of a Clustered Microgrid Based on a Nash Bargaining Solution

In this chapter, in order to show the capability of the game theory, methods in the optimisation of multi-players objectives, the planning procedure of a clustered microgrid including two independent microgrids are analysed. In addition, despite most research work that uses a non-cooperative type of game theory techniques, which are constrained when addressing fairness in conjunction with efficiency, a cooperative approach is utilised here in order to satisfy all players in terms of fairness and efficiency. This also reduces the intermittency effect of generated power by solar and wind systems. The electrical load profile and weather forecast data of a town of Western Australia, Mount Magnet, as shown in Figure 4.1, is taken to achieve the most realistic and optimum results. The state of Western Australia has generous conditions for renewable energy resources by world standards, especially for wind speed and solar radiation [69, 70].

This chapter is based on the research papers “Optimal planning of Clustered Microgrid using a Technique of Cooperative Game Theory”, published in *Electric Power Systems Research* 2020, and “Optimal Sizing and Profit Maximization of Clustered Microgrid using Game Theory Techniques”, published in 2019 from the 9th IEEE International Conference on Power and Energy Systems (ICPES).

4.1 Statement of Contribution

The authors listed below have certified that:

- They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise.
- There are NO conflicts of interest. They agree to the use of the publication in the student’s thesis and its publication on the Curtin University online database.

Papers:

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2. “Optimal Sizing and Profit Maximization of Clustered Microgrid using Game Theory Techniques”, 2019 from the 9th IEEE International Conference on Power and Energy Systems (ICPES), Perth, Australia, 2019, pp. 1–6, DOI: 10.1109/ICPES47639.2019.9105648.

Contributors	**Statement of contribution**	**% Total Contribution**
Liaqat Ali	Conceptualisation, visualisation, methodology, simulation validation, data analysis and drafting the manuscript.	80
S.M. Muyeen	Conceptualisation, supervision and critical revision of paper.	10
Hamed Bizhani	Simulation validation, and critical revision of paper.	5
Arindam Ghosh	Supervision and critical revision of paper.	5

Principle Supervisor Confirmation

I have sighted email or other correspondence from the co-authors confirming their certifying authorship.

Associate Professor S.M. Muyeen

____________________ 1st April 2021

Figure 4.1 Town of Mount Magnet in Western Australia

4.2 Problem Formulation

The clustered microgrid can consist of n number microgrids in a grid-connected mode, as shown in Figure 4.2, to avoid the complexity of work and reduce computation time. The proposed system consists of two microgrids with various combinations of renewable resources. To meet the load requirements in the clustered microgrid, the selected components are wind turbines, solar panels and batteries, but the combination in each microgrid is kept different. As shown in Figure 4.3, the first microgrid contains wind turbines, solar panels and batteries as the generation components, while the second microgrid has only wind turbines and solar panels as generation resources. The individual microgrids keeping at certain distances are connected and controlled to exchange power to various loads.

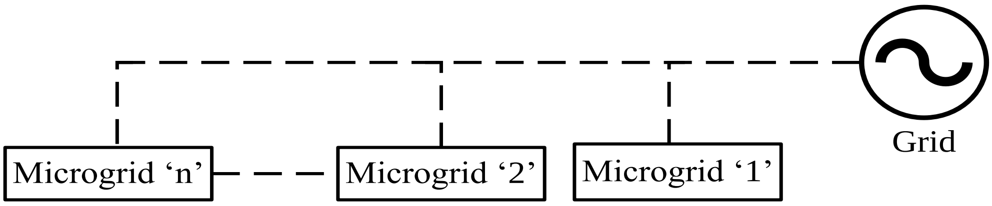


Figure 4.2 Grid-connected clustered microgrid

The main objective of this research is to allocate the most suitable capacities of generation resources and batteries for the clustered microgrid to meet the electrical load requirements of Mount Magnet and ensure its smooth operation and maximum profitability. Because the clustered microgrid are connected with the main grid, if any of the microgrid cannot meet the load requirements, it can purchase power from the main grid, and in case of large power generation from any microgrid, it can sell surplus power to the main grid. For the selected clustered microgrid, the power generation is through wind turbines, solar panels and storage batteries, depending on the weather forecast and load.

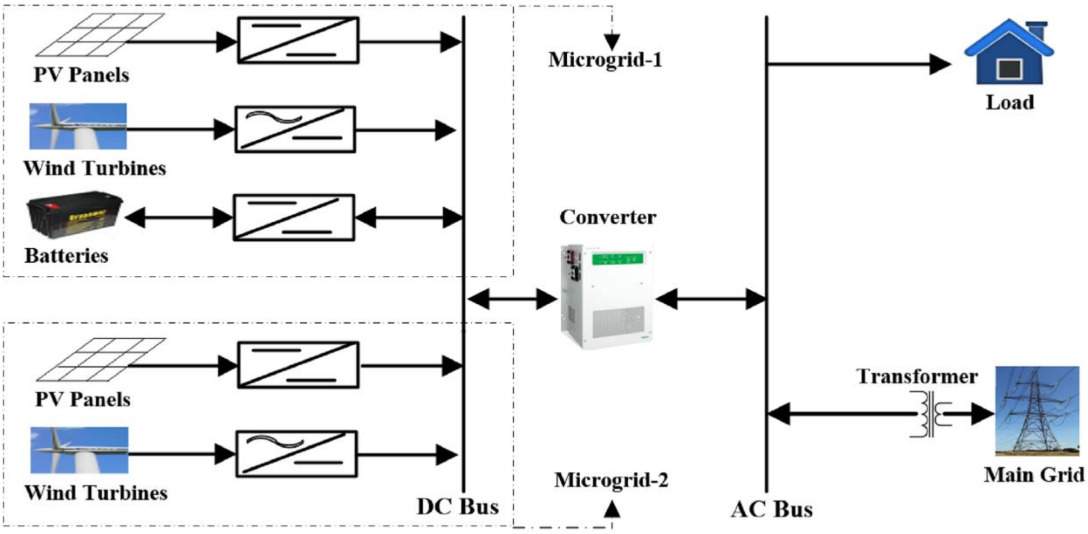


Figure 4.3 Block diagram of clustered microgrid

4.2.1 Elements of the Game Model

In the clustered microgrid, three different players are involved in power generation and are expressed as $\mathcal{W}$ for wind turbines, $\mathcal{SP}$ for solar panels and $\mathcal{B}$ for batteries. The decision variable $\mathcal{P}_j$ for each player is represented by their power capacities, such as $\mathcal{P}_{\mathcal{W}}$, $\mathcal{P}_{\mathcal{SP}}$ and $\mathcal{P}_{\mathcal{B}}$ for wind turbines, solar panels and batteries, respectively, within their boundary limits or strategic spaces. The strategic set $\mathfrak{S}_j$ for the wind turbine, solar panel and wind turbine are $\mathfrak{S}_{\mathcal{W}} = \left(\mathcal{P}_{\mathcal{W}}^{min}, \mathcal{P}_{\mathcal{W}}^{max}\right)$, $\mathfrak{S}_{\mathcal{SP}} = \left(\mathcal{P}_{\mathcal{SP}}^{min}, \mathcal{P}_{\mathcal{SP}}^{max}\right)$, and $\mathfrak{S}_{\mathcal{B}} = \left(\mathcal{P}_{\mathcal{B}}^{min}, \mathcal{P}_{\mathcal{B}}^{max}\right)$, respectively.

4.2.2 Payoff for Each Microgrid

In this case, microgrid 1 is considered as a combination of three different generation resources, including wind turbine $\mathcal{W}$, solar panels $\mathcal{SP}$ and batteries $\mathcal{B}$ in a grid-connected mode to meet the load requirements. To achieve the maximum payoff or profit for the proposed microgrid, various factors such as power selling income, the subsidy from the government, cost of initial investment, cost of energy that cannot be served, operation and maintenance cost and so on, are taken into account [58]. From each player, its income and cost are also taken into consideration to find the profit, where $\mathcal{PR}$, $\mathcal{I}$ and $\mathcal{C}$ represent the annual profit, annual income and annual cost, respectively.

A. Wind Turbines

Maximum profit for wind turbines is calculated as follows:

$$\mathcal{PR}_{\mathcal{W}} = \mathcal{I}_{\mathcal{W}\_\mathcal{SE}} + \mathcal{I}_{\mathcal{W}\_\mathcal{SL}} + \mathcal{I}_{\mathcal{W}\_\mathcal{AS}} - \mathcal{C}_{\mathcal{W}\_\mathcal{IN}} - \mathcal{C}_{\mathcal{W}\_\mathcal{OM}} - \mathcal{C}_{\mathcal{W}\_\mathcal{ES}} - \mathcal{C}_{\mathcal{W}\_\mathcal{PC}} \tag{4.1}$$

The fluctuation in the wind power is found in terms of wind speed $v(t)$. The wind power generated $p_{\mathcal{W}}(t)$ in hour t is calculated as follows:

$$Dp_{BT}(t) = p_{BT}(t) - p_{BT}(t+1) \tag{4.2}$$

Maximum power consumed $\mathcal{P}_{\mathcal{CN}}(t)$ in hour t is:

$$\mathcal{P}_{\mathcal{CN}}(t) = \mathcal{P}_{\mathcal{D}}(t) + \mathcal{P}_{\mathcal{TC}} + (\mathcal{P}_{\mathcal{B}} - p_{\mathcal{B}}(t)) \tag{4.3}$$

where t=1, 2, …, 8784 hours, $\mathcal{P}_{\mathcal{D}}(t)$, $p_{\mathcal{B}}(t)$ and $\mathcal{P}_{\mathcal{TC}}$ represent the electrical load demand, power of storage battery in hour t and maximum tie line transmission capacity between the main grid and clustered microgrid, respectively. The excess generation from a wind turbine or surplus power $\mathcal{P}_{\mathcal{SR}}(t)$ in hour t is:

$$\mathcal{P}_{\mathcal{SR}}(t) = p_{\mathcal{W}}(t) + p_{\mathcal{SP}}(t) - \mathcal{P}_{\mathcal{CN}}(t) \tag{4.4}$$

Wind turbine annual income $\mathcal{I}_{\mathcal{W}\_\mathcal{SE}}$ from power selling $\mathcal{P}_{\mathcal{W}\_\mathcal{SE}}(t)$ to main grid in hour t is as follows:

$$\mathcal{P}_{\mathcal{W}\_\mathcal{SE}}(t) = \begin{cases} p_{\mathcal{W}}(t) & \mathcal{P}_{\mathcal{SR}}(t) \leq 0 \\ \dfrac{p_{\mathcal{W}}(t) * \mathcal{P}_{\mathcal{CN}}(t)}{(p_{\mathcal{W}}(t) + p_{\mathcal{SP}}(t))} & \mathcal{P}_{\mathcal{SR}}(t) > 0 \end{cases} \tag{4.5}$$

$$\mathcal{I}_{\mathcal{W}\_\mathcal{SE}} = (1+\propto) * \sum_{t=1}^{8784} \mathbb{E}(t) * \mathcal{P}_{\mathcal{W}\_\mathcal{SE}}(t) \tag{4.6}$$

where $\mathcal{F}$ and $\mathbb{E}(t)$ shows the coefficient of subsidy from the government and price of electricity in hour t. Wind turbine annual salvage value $\mathcal{I}_{\mathcal{W}\_\mathcal{SL}}$ and annual investment cost $\mathcal{C}_{\mathcal{W}\_\mathcal{IN}}$ are calculated as:

$$\mathcal{I}_{\mathcal{W}\_\mathcal{SL}} = \mathcal{P}_{\mathcal{W}} * \mathcal{U}_{\mathcal{W}\_\mathcal{SV}} * \mathfrak{D}/((1+\mathfrak{D})^{\mathbb{L}_{\mathcal{W}}} - 1) \tag{4.7}$$

$$\mathcal{C}_{\mathcal{W}\_\mathcal{IN}} = \mathcal{P}_{\mathcal{W}} * \mathcal{U}_{\mathcal{W}} * \mathfrak{D}(1+\mathfrak{D})^{\mathbb{L}_{\mathcal{W}}}/((1+\mathfrak{D})^{\mathbb{L}_{\mathcal{W}}} - 1) \tag{4.8}$$

where $\mathcal{U}_{\mathcal{W}\_\mathcal{SV}}$, $\mathfrak{D}$, $\mathcal{U}_{\mathcal{W}}$ and $\mathbb{L}_{\mathcal{W}}$ are per unit wind turbine salvage value, electricity discount rate, per unit cost of wind turbine and the life span of the wind turbine, respectively.

The annual operation and maintenance cost of the wind turbine $\mathcal{C}_{\mathcal{W}\_\mathcal{OM}}$ is calculated by multiplying its per unit operation and maintenance cost $\mathcal{U}_{\mathcal{W}\_OM}$ by the capacity of wind turbine $\mathcal{P}_{\mathcal{W}}$; however, annual ancillary service benefits of the wind turbine $\mathcal{I}_{\mathcal{W}\_\mathcal{AS}}$ is considered zero.

The annual cost of energy not served $\mathcal{C}_{\mathcal{W}\_\mathcal{ES}}$ in a clustered microgrid is calculated as follows:

$$\mathcal{C}_{\mathcal{W}\_\mathcal{ES}} = \mathcal{C}_{\mathcal{ES}} * \mathcal{P}_{\mathcal{W}}/(\mathcal{P}_{\mathcal{W}} + \mathcal{P}_{\mathcal{SP}} + \mathcal{P}_{\mathcal{B}}) \tag{4.9}$$

Annual compensation cost of total energy not served $\mathcal{C}_{\mathcal{ES}}$ is:

$$\mathcal{C}_{\mathcal{ES}} = \sum_{t=1}^{8784} 1.5 * \mathbb{E}(t) * (\mathcal{P}_{\mathcal{UB}}(t) - \mathcal{P}_{\mathcal{PG}}(t)) \tag{4.10}$$

In the above equation unbalanced power $\mathcal{P}_{\mathcal{UB}}(t)$ in a clustered microgrid and power purchased from the main grid $\mathcal{P}_{\mathcal{PG}}(t)$ during hour t is:

$$\mathcal{P}_{\mathcal{UB}}(t) = \mathcal{P}_{\mathcal{D}}(t) - p_{\mathcal{W}}(t) - p_{\mathcal{SP}}(t) - (p_{\mathcal{B}}(t) - \mathcal{P}_{\mathcal{B}\_min}) \tag{4.11}$$

$$\mathcal{P}_{\mathcal{PG}}(t) = \begin{cases} 0 & \mathcal{P}_{\mathcal{UB}}(t) \leq 0 \\ \mathcal{P}_{\mathcal{UB}}(t) & 0 < \mathcal{P}_{\mathcal{UB}}(t) \leq \mathcal{P}_{\mathcal{TC}} \\ \mathcal{P}_{\mathcal{TC}} & \mathcal{P}_{\mathcal{UB}}(t) > \mathcal{P}_{\mathcal{TC}} \end{cases} \tag{4.12}$$

where the available power in the batteries in hour t is expressed as $(p_{\mathcal{B}}(t) - \mathcal{P}_{\mathcal{B}\_min})$.

Wind turbine annual cost to purchase power from the main grid is as below:

$$\mathcal{C}_{\mathcal{W}\_\mathcal{PC}} = \mathcal{C}_{\mathcal{PC}} * \mathcal{P}_{\mathcal{W}}/(\mathcal{P}_{\mathcal{W}} + \mathcal{P}_{\mathcal{SP}} + \mathcal{P}_{\mathcal{B}}) \tag{4.13}$$

The total annual cost to purchase power from the grid $\mathcal{C}_{\mathcal{PR}}$ is:

$$\mathcal{C}_{\mathcal{PC}} = \sum_{t=1}^{8784} \mathbb{E}(t) * \mathcal{P}_{\mathcal{PG}}(t) \tag{4.14}$$

B. Solar Panels

Solar panels are not developed in detail for this research, and per unit hourly solar power $\wp_{\mathcal{SP}}(t)$ is used to define the variations in solar radiation for one year. The annual profit of solar panels can be written as follows:

$$\mathcal{PR}_{\mathcal{SP}} = \mathcal{I}_{\mathcal{SP}\_\mathcal{SE}} + \mathcal{I}_{\mathcal{SP}\_\mathcal{SL}} + \mathcal{I}_{\mathcal{SP}\_\mathcal{AS}} - \mathcal{C}_{\mathcal{SP}\_\mathcal{IN}} - \mathcal{C}_{\mathcal{SP}\_\mathcal{OM}} - \mathcal{C}_{\mathcal{SP}\_\mathcal{ES}} - \mathcal{C}_{\mathcal{SP}\_\mathcal{PC}} \tag{4.15}$$

Annual ancillary income benefits for solar panels $\mathcal{I}_{\mathcal{SP}\_\mathcal{AS}}$ is defined as zero, and annual income of solar panels for power selling to the main grid $\mathcal{I}_{\mathcal{SP}\_\mathcal{SE}}$ is calculated as follows:

$$\mathcal{P}_{\mathcal{SP}\_\mathcal{SE}}(t) = \begin{cases} \wp_{\mathcal{SP}}(t) & \mathcal{P}_{\mathcal{SR}}(t) \le 0 \\ \dfrac{\wp_{\mathcal{SP}}(t) * \mathcal{P}_{\mathcal{CN}}(t)}{(\wp_{\mathcal{W}}(t) + \wp_{\mathcal{SP}}(t))} & \mathcal{P}_{\mathcal{SR}}(t) > 0 \end{cases} \tag{4.16}$$

$$\mathcal{I}_{\mathcal{SP}\_\mathcal{SE}} = (1+\propto) * \sum_{t=1}^{8784} \mathbb{E}(t) * \mathcal{P}_{\mathcal{SP}\_\mathcal{SE}}(t) \tag{4.17}$$

Solar panels annual income from the salvage value $\mathcal{I}_{\mathcal{SP}\_\mathcal{SL}}$, annual investment cost $\mathcal{C}_{\mathcal{SP}\_\mathcal{IN}}$, annual operation and maintenance cost $\mathcal{C}_{\mathcal{SP}\_\mathcal{OM}}$, the annual cost of due to energy not served $\mathcal{C}_{\mathcal{SP}\_\mathcal{ES}}$ and the annual cost of power purchased from the grid $\mathcal{C}_{\mathcal{SP}\_\mathcal{PC}}$ are calculated in a similar way, as defined for wind turbines.

C. Batteries

The annual profit for batteries can be obtained as follows:

$$\mathcal{PR}_{\mathcal{B}} = \mathcal{I}_{\mathcal{B}\_\mathcal{SE}} + \mathcal{I}_{\mathcal{B}\_\mathcal{SL}} + \mathcal{I}_{\mathcal{B}\_\mathcal{AS}} - \mathcal{C}_{\mathcal{B}\_\mathcal{IN}} - \mathcal{C}_{\mathcal{B}\_\mathcal{OM}} - \mathcal{C}_{\mathcal{B}\_\mathcal{ES}} - \mathcal{C}_{\mathcal{B}\_\mathcal{PC}} \tag{4.18}$$

The batteries are charged with respect to the power difference between generation resources and the electrical load. For microgrid 1, the generation resources are wind turbines and solar panels, and electrical load performs the power consumption. The difference between the generation resources and load in hour t is represented as $\Delta(t)$. If excessive power is in the generation resources, then the batteries are charged with efficiency ξ_c. The power of the batteries $\mathscr{p}_{\mathcal{B}}(t)$ and changes in batteries' power $\Delta\mathscr{p}_{\mathcal{B}}(t)$ in hour t are expressed as the following:

$$\mathscr{p}_{\mathcal{B}}(t) = \begin{cases} \mathscr{p}_{\mathcal{B}}(t-1) + \xi_c * \Delta(t-1) & \Delta(t-1) \geq 0 \\ \mathscr{p}_{\mathcal{B}}(t-1) + \Delta(t-1) & \Delta(t-1) < 0 \end{cases} \tag{4.19}$$

$$\Delta\mathscr{p}_{\mathcal{B}}(t) = \mathscr{p}_{\mathcal{B}}(t) - \mathscr{p}_{\mathcal{B}}(t+1) \tag{4.20}$$

Batteries' annual income through power selling to the main grid is calculated as below:

$$\mathcal{P}_{\mathcal{B}\_\mathcal{SE}}(t) = \begin{cases} \Delta\mathscr{p}_{\mathcal{B}}(t) & \Delta\mathscr{p}_{\mathcal{B}}(t) > 0 \\ 0 & \Delta\mathscr{p}_{\mathcal{B}}(t) \leq 0 \end{cases} \tag{4.21}$$

$$\mathcal{I}_{\mathcal{B}\_\mathcal{SE}} = (1+\propto) * \sum_{t=1}^{8784} \mathbb{E}(t) * \mathcal{P}_{\mathcal{B}\_\mathcal{SE}}(t) \tag{4.22}$$

The annual ancillary income of batteries $\mathcal{I}_{\mathcal{B}\_\mathcal{AS}}$ depends on the supplied reserve power, and is:

$$\mathcal{I}_{\mathcal{B}\_\mathcal{AS}} = \Re \sum_{t=1}^{8784} \left(\mathscr{p}_{\mathcal{B}}(t) - \mathcal{P}_{\mathcal{B}\_\mathcal{SE}}(t) - \mathcal{P}_{\mathcal{B}\_min}\right) \tag{4.23}$$

where $\Re$ represents the per unit income ($/(kWh) from reserve power. Annual income from the batteries' salvage value $\mathcal{I}_{\mathcal{B}\_\mathcal{SL}}$ is zero if the batteries are out of service. Batteries' annual investment cost $\mathcal{C}_{\mathcal{B}\_\mathcal{IN}}$, operation and maintenance cost $\mathcal{C}_{\mathcal{B}\_\mathcal{OM}}$, cost of power not served $\mathcal{C}_{\mathcal{B}\_\mathcal{ES}}$ and cost of power purchased from the grid $\mathcal{C}_{\mathcal{B}\_\mathcal{PC}}$ can be calculated in a similar way as for wind turbine and solar panels.

It is evident from the above calculations that profit maximisation of each player not only depends on its own parameters, but also on other players' too. For microgrid 1, the maximum profit for each player is calculated by using its own equation, and the maximum profit for microgrid 1 $\mathcal{PR}_{MG-1}$ in grid-connected mode can be found as follows:

$$\mathcal{PR}_{MG-1} = \mathcal{PR}_{\mathcal{W}} + \mathcal{PR}_{\mathcal{SP}} + \mathcal{PR}_{\mathcal{B}} \tag{4.24}$$

Figure. 4.3 shows that microgrid 2 consists of two generations of resources of wind turbines $\mathcal{W}$ and solar panels $\mathcal{SP}$ in grid-connected mode, and contributing to microgrid 1 to meet the load requirements of the selected town. Considering all the technical parameters, the maximum profit for both players $\mathcal{P}_{\mathcal{W}}$ and $\mathcal{P}_{\mathcal{SP}}$ are calculated in the same way as calculated for microgrid 1, and the maximum profit for microgrid 2 is obtained as:

$$\mathcal{PR}_{MG-2} = \mathcal{PR}_{\mathcal{W}} + \mathcal{PR}_{\mathcal{SP}} \tag{4.25}$$

4.2.3 Payoff for Clustered Microgrid

In this paper, the concept of a single microgrid is adopted to meet the requirements of clustered architecture, and two microgrids are considered in grid-connected mode. Therefore, the maximum profit for a clustered microgrid CMG can be found as follows:

$$D\mathcal{PR}_{CMG} = \mathcal{PR}_{MG-1} + \mathcal{PR}_{MG-2} \tag{4.26}$$

In the clustered system, different microgrids with various combinations of generation resources can be connected in parallel. If n number of microgrids are connected in clustered architecture are shown in Figure 2, then the maximum profit of clustered microgrid can be written as follows:

$$\mathcal{PR}_{CMG} = \mathcal{PR}_{MG-1} + \mathcal{PR}_{MG-2} + \cdots + \mathcal{PR}_{MG-n} = \sum_{1}^{n} \mathcal{PR}_{MG-n} \tag{4.27}$$

4.3 The Nash Bargaining Solution

In microgrid, game theory can be a wonderful way to deal with various decision-making problems where multiple renewable resources are used for generation. From many years, the game theory techniques are used to solve various technical problems in different research areas, which yields a strong basis for the market participants to achieve their optimum results [25, 27, 71]. In a game model, the components of a microgrid may belong to different owners, but to get feasible sizing of generation capacities, each of the components prefers to collaborate for maximization of their profits. The Nash bargaining solution is a cooperative game model of the negotiation process, which can be effectively used to meet the basic fair and efficient requirements that are important in real-world bargaining solution [37]. The Nash bargaining solution is a bilateral negotiation process between the players to achieve maximum values of payoff, when decision variables reach their optimal values within set space [38]. Therefore, in this chapter a modern game theory approach of Nash bargaining solution is used for the suitable sizing and to achieve optimum payoff values.

In this section, the basic idea of the Nash bargaining solution is first explained, and then the technique of cooperative game theory is discussed to organise the proposed game model. For the Nash bargaining solution, two players, which can cooperate along with a set of agreements in terms of their payoff, are considered. A game model can have the Nash bargaining solution and in details shown in [72, 73] and it fulfils the following axioms:

1. Pareto Optimality

In a game model, none of the players can be better off until and unless at least one player is worse off, at the same point. To fulfil this requirement of Pareto Optimality (PO), there should not be any other point in the whole research limit where two players can achieve more. It can be expresses as:

$$\emptyset(U, \boldsymbol{u}^0) \in PO(U) \tag{4.288}$$

2. Independence of Irrelevant Alternatives

If (U, V) is the payoff for both players from a possible set A, and is an element of subset B, then (U, V) must be selected from B. If $\boldsymbol{u}' \in V \subset U$ and

$$\boldsymbol{u}' = \emptyset(U, \boldsymbol{u}^0) \tag{4.299}$$

then

$$\emptyset(V, \boldsymbol{u}^0) = \boldsymbol{u}' \qquad (4.30)$$

3. Symmetry

If the players are interchanged between them, they are still supposed to achieve a similar payoff. It means that players are indistinguishable and the payoff will not discriminate between them. If the utility space *U* is symmetric with respect to *i* and *j*,

$$u_i^0 = u_j^0 \, , u \in U \; and \; u^0 < u \qquad (4.31)$$

and

$$\boldsymbol{u}' = \emptyset(U, \boldsymbol{u}^0) \qquad (4.3230)$$

then,

$$u'_i = u'_j \qquad (4.3331)$$

where U, u, u^0 and $\emptyset(U, \boldsymbol{u}^0)$ are utility space, utility vector in U, utility at disagreement point and bargaining solution, respectively.

4. Invariance to Affine Transformation

The solution of a game model should not depend on scales or units. This means that if a positive constant is added or multiplies, the solution should not be affected for both or either of the players. If $\psi: \mathbb{R}^N \to \mathbb{R}^N$,

$$\psi(\boldsymbol{u}) = \boldsymbol{u}' \qquad (4.3432)$$

with $u'_i = c_i u_i + d_i$ and $c_i, d_i \in \mathbb{R}, c_i > 0, \forall i,$ then

$$\emptyset(\psi(U), \psi(\boldsymbol{u}^0)) = \psi(\emptyset(U, \boldsymbol{u}^0)) \tag{4.3533}$$

The second axiom says that if the players are bargaining for a feasible payoff, normalisation should be finished before the end of the bargaining solution. In addition, the second, third and fourth axioms are called axioms of fairness. The fourth axiom states that a game elimination of non-feasible solutions should not affect the bargaining process.

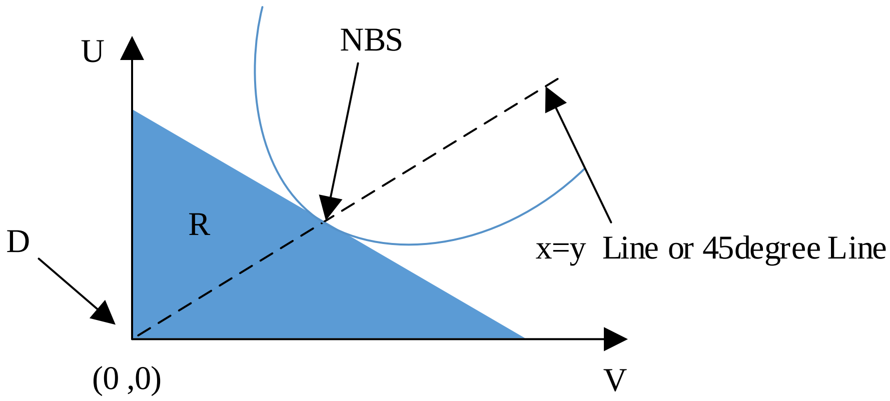


Figure 4.4 Nash bargaining solution between two players

For a cooperative game of two players, the payoff is represented by (U, V), and R represents the complete region for bargaining. Figure 4.4 shows the bargaining solution among two players with payoff (U, V), where D represents the disagreement point in the region. If the bargaining takes place between the players, this means that they agree on a different solution within the region R, which shows the feasible Nash bargaining solution.

Figure. 4.5 shows the algorithm to find the Nash bargaining solution in multiple steps. Here, inputs of the algorithm are the weather forecast and load profiles. In the process of designing a cooperative game, the players and marginal spaces for implementation of the selected technique of game theory are defined. Then the bargaining between the players is initiated, and if the players satisfy the conditions of the Nash bargaining process, the payoff is achieved. Otherwise, they need to repeat the bargaining process to find the optimum Nash bargaining solution.

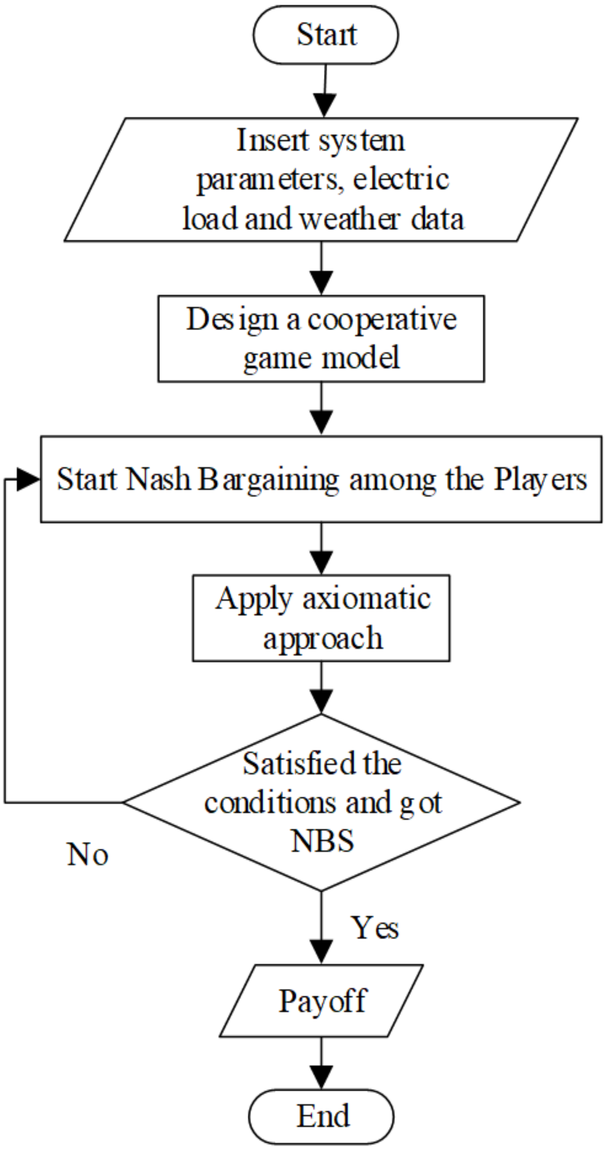


Figure 4.5 Algorithm to find Nash bargaining solution

In order to perform the optimisation of the cooperative game model and for verification of the algorithm, the well-known particle swarm optimisation (PSO) algorithm is utilised, which is frequently adopted in different research areas to resolve the optimisation problem [74, 75]. In this paper, to find the most feasible Nash bargaining solution, 50 iterations and 100 particles are selected. The algorithm for the Nash bargaining solution is implemented in MATLAB software to find the optimal values of decision variables and maximum payoff.

4.4 Results and Analysis

In order to design a model for the proposed clustered microgrid, the Mount Magnet data for electrical load, wind speed and solar radiation are taken, and a time interval from 1 June 2015 to 31 May 2016 is considered as shown in Section 1.5 Figure 1.3 [56]. The known input parameters for the proposed model are given in Appendix A Table A.1 [58].

Table 4.1 illustrates the most suitable power capacity of each player, along with the maximum annual profit of the first microgrid using the Nash bargaining solution to fulfil the requirements of the load. As can be seen, different valid combinations from case 1 to case 3 have been considered. For example, as shown in case 1, the wind turbine and the solar panel are chosen as two players to achieve the optimum value of bargaining solutions, and the battery selects random values within its strategic space until the solution reaches the maximum profit. It is apparent from the results that the profit is fairly high in all cases, and any combinations can be selected to find the optimum solution for Nash bargaining. However, the profit is relatively higher in case 1 compared to the others, where wind turbines and solar panels are taken as players for the bargaining solution.

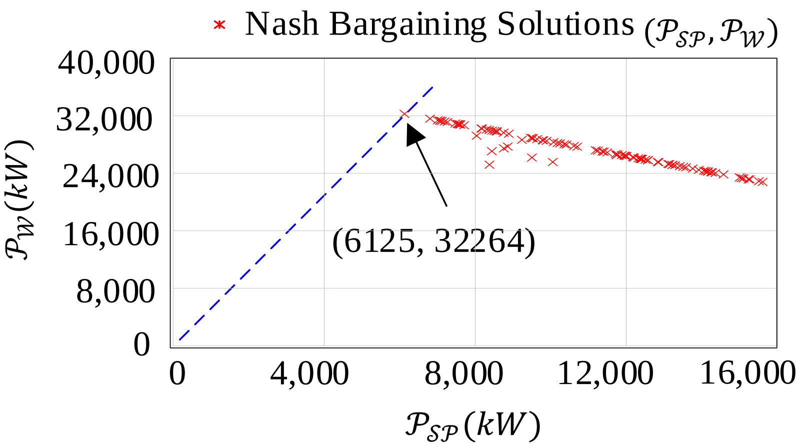
For microgrid 2 in clustered architecture, as shown in Table 4.2, the wind turbines and the solar panels are selected as players. Table 4.2 illustrates the most suitable generation capacities for wind turbines and solar panels, along with the maximum profit. It is obvious from Table 4.1 and Table 4.2 that the annual profit will go higher if greater numbers of generation resources are chosen in the microgrid to fulfil the requirements of the attached load. This is because the involvement of more generation resources in the microgrid creates more options to sell extra power to the main grid, and also creates an easier way to meet the load requirements in worse weather conditions.

Table 4.1 Nash bargaining solution for grid-connected microgrid 1

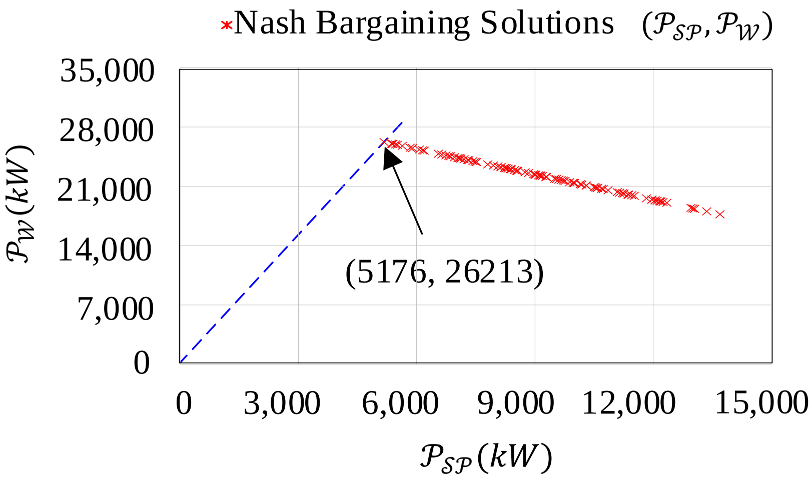
Game Models			Nash Bargaining Solutions (kW)		Profit ($/year)
Case	Coalitions	$\mathcal{P}_{\mathcal{W}}$	$\mathcal{P}_{\mathcal{SP}}$	$\mathcal{P}_{\mathcal{B}}$	$\mathcal{PR}_{MG-1}$
1	$\{\mathcal{W}, \mathcal{SP}\}$, $\{\mathcal{B}\}$	32,264	6125	10,000	2.1058E+7
2	$\{\mathcal{W}, \mathcal{B}\}$, $\{\mathcal{SP}\}$	32,380	6995	9985	2.0505E+7
3	$\{\mathcal{W}\}$, $\{\mathcal{SP}, \mathcal{B}\}$	33,128	8000	10,000	2.1007E+7

Table 4.2 Nash bargaining solution for grid-connected microgrid 2

Game Models		Nash Bargaining Solutions (kW)		Profit ($/year)
Case	Coalitions	$\mathcal{P}_{\mathcal{W}}$	$\mathcal{P}_{\mathcal{SP}}$	$\mathcal{PR}_{MG-2}$
1	$\{\mathcal{W}, \mathcal{SP}\}$	26,213	5176	5.8463E+6



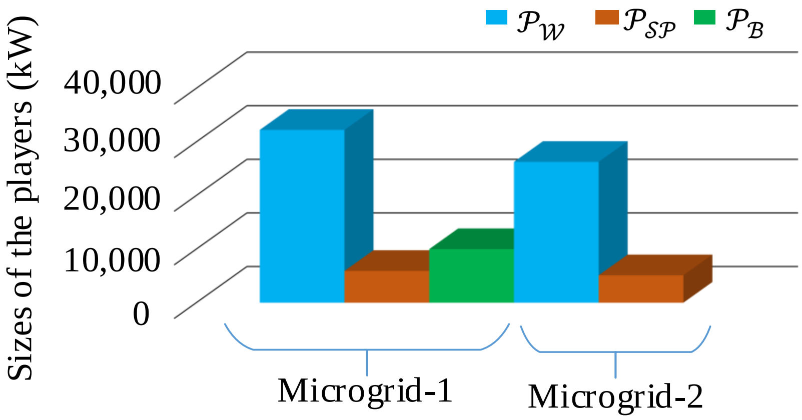
(a)



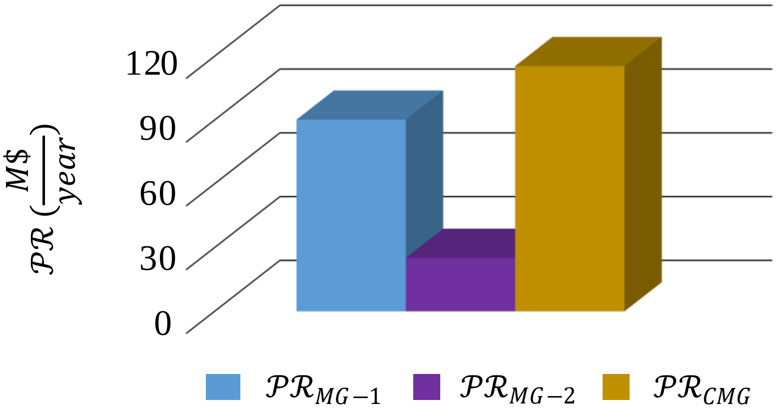
(b)

Figure 4.6 Nash bargaining solutions for (a) microgrid 1, and (b) microgrid 2

To reach the optimum values of a Nash bargaining solution and maximum profit, the algorithm has performed the simulation for 100 possible bargaining solutions (particles). The different bargaining solutions are shown in Figure 4.6 (a) and Figure 4.6 (b) for microgrid 1 and microgrid 2, respectively. As can be seen, for both individual microgrids, after trying different solutions, an optimum point is found. Figure 4.7 (a) shows the optimum values of generation resources for microgrid 1 and microgrid 2 in clustered architecture in grid-connected mode. Figure 4.7 (b) illustrates the maximum value of profit at the point of the Nash bargaining solution for microgrid 1, microgrid 2 and total profit for the clustered microgrid.



(a)



(b)

Figure 4.7 (a) Optimum sizes of the players, and (b) maximum profit for clustered microgrid

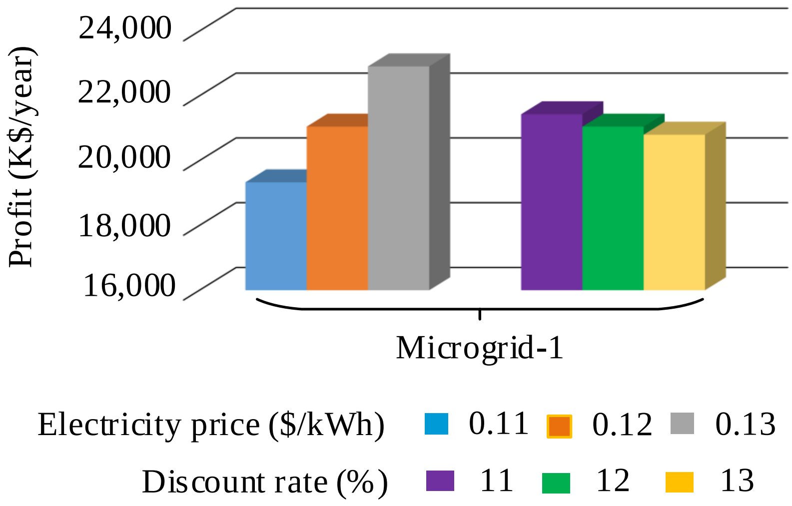
4.4.1 Sensitivity Analysis

To confirm the feasibility of the Nash bargaining results, and to analyse the effect of uncertainties, a sensitivity analysis was conducted. For this purpose, the electricity prices and the discount rates were taken into consideration to perform the analysis, for cooperative game models microgrid 1 (case 1) and microgrid 2 (case 1). The selected electricity sensitivity analyses are \$0.11/kWh, 0.12 \$/kWh, and \$0.13/kWh. For both microgrids, it can be seen in Table 4.3 and Figure 4.8, that as the electricity price decreases, the annual profit of clustered microgrid also reduces, and vice versa.

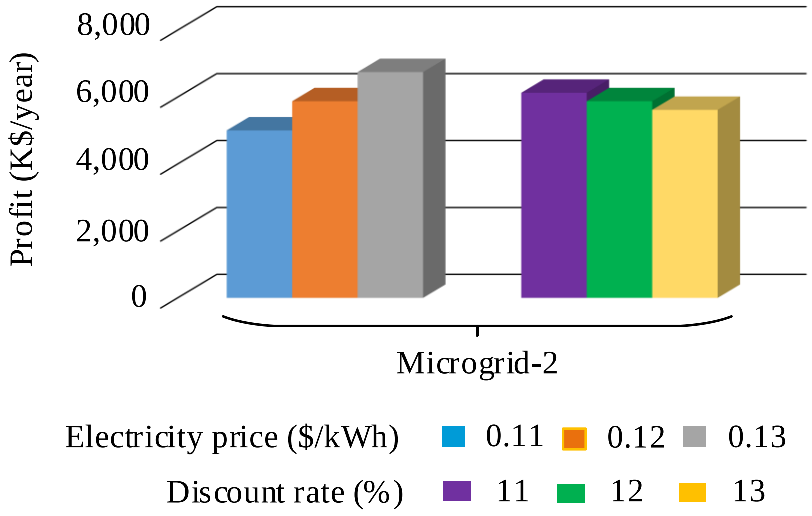
Table 4.3 Sensitivity analysis for microgrid 1 and microgrid 2

Microgrid#	Electricity Price ($/kWh)	Profit (K$/year)	Discount Rate (%)	Profit (K$/year)
1	0.11	19,330	11	21,431
	0.12	21,049	12	21,049
	0.13	22,907	13	20,800
2	0.11	5004	11	6129
	0.12	5876	12	5876
	0.13	6748	13	5618

Figure 4.8 also shows the effect of the discount rate on the annual profit of the clustered microgrid. It can be deduced that for discount rates of 11%, 12% and 13% the change in the profit is tangible. As the discount rates decrease, the annual profit values are increasing, and vice versa. It is also evident from the sensitivity analysis of both parameters that the electricity price has more impact on the payoff than the discount rate. Consequently, even small changes in the electricity price significantly increase or decrease the values of annual profit.



(a)



(b)

Figure 4.8 Results of sensitivity analysis for (a) microgrid 1 and (b) microgrid 2

4.5 Summary

In this chapter, a cooperative type of game theoretical technique is proposed at the planning stage to model a grid-connected clustered microgrid. In order to make it more applicable, the selected microgrid consists of different combinations of generation resources such as wind turbines, solar cells and batteries. In the game model, generation resources are considered to be players and their profit is the payoff. The technique of the Nash bargaining solution is adopted in this study for capacity allocation of generation resources and batteries, and also to maximise the annual profit of individual microgrids and its cluster. As a cooperative game model, all possible coalitions are discussed between the players to find their optimum sizes, and the most suitable one is selected based on the game theory technique and maximum payoff value. For this purpose, a particle swarm optimisation algorithm is developed to find the most feasible Nash bargaining solution using MATLAB software. In the simulations and for the system analysis, the realistic electrical load data and weather forecast is taken for a remote town Mount Magnet in Western Australia. Finally, a sensitivity analysis is performed to validate and show the reasonableness of the optimised results concerning the proposed clustered system.

The proposed model of this chapter consists of a clustered microgrid that consist of two microgrids and single objective optimization with respect to annual profit is performed to achieve the results. The load data and weather profiles of a single town are considered to perform the analysis based on Bash bargaining solution. In the next chapter multi-microgrid system is considered with three microgrids who are connected with three different Australian towns in grid-connected mode. A multi-objective optimization is performed based on LCOE and reliability index, and architecture is designed based on Nash equilibrium to find suitable sizes of the players and optimum payoff values.

Chapter 5 Multi-Objective Optimisation and Sizing of Multi-Microgrids Using a Game Theory Technique

In this chapter, a multi-microgrids system consisting of three different microgrids in grid-connected mode is considered. Multi-objective optimisation is performed for the sizing of generation resources and storage batteries in order to achieve optimum payoff values. Microgrids in the system architecture have different combinations of wind turbines, photovoltaic panels, batteries and residential loads. The technical criteria for the multi-objective function are selected as the levelised cost of energy and reliability index. The multi-microgrids system is modelled with respect to a cooperative game theory technique called the Nash equilibrium. The real-time weather data and load profiles of three different remote towns in Australia are taken to perform the analysis and validate the results. The simulation model is MATLAB software and the particle swarm optimisation algorithm is used for the simulation of the multi-microgrid system.

This chapter is based on the research paper “Game Approach for Sizing and Cost Minimization of a Multi-microgrids using a Multi-objective Optimization”, published in *2021 IEEE Green Technologies Conference (GreenTech)*, 2021, and “Peer-to-Peer Energy Trading and Planning of Multi-microgrid System using a Multi-Objective Optimization" submitted in the *IEEE Transactions on Industry Applications*, 2021.

5.1 Statement of Contribution

The authors listed below have certified that:

- They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise.
- There are NO conflicts of interest. They agree to the use of the publication in the student's thesis and its publication on the Curtin University online database.

Paper:

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2. "Peer-to-Peer Energy Trading and Planning of Multi-microgrid System using a Multi-Objective Optimization," submitted in the *IEEE Transactions on Industry Applications*, 2021, Manuscript ID: 2021-IACC-0551.

Contributors	**Statement of contribution**	**% Total Contribution**
Liaqat Ali	Conceptualisation, visualisation, methodology, simulation validation, data analysis and drafting the manuscript.	80
S.M. Muyeen	Conceptualisation, supervision and critical revision of the paper.	10
Hamed Bizhani	Simulation validation, and critical revision of the paper.	5
Marcelo G. Simoes	Critical revision of the paper.	5

Principle Supervisor Confirmation

I have sighted email or other correspondence from the co-authors confirming their certifying authorship.

Associate Professor S.M. Muyeen

____________________ 1st April 2021

5.2 The Multi-Microgrid System

The schematic diagram of the grid-connected multi-microgrid system is shown in Figure 5.1. Multiple combinations of wind turbines, photovoltaic panels and batteries are considered within each microgrid to meet its electrical load requirement. Multi-microgrid systems meet both stability and economical requirements more comfortably in the joint presence of wind turbines, solar panels and batteries.

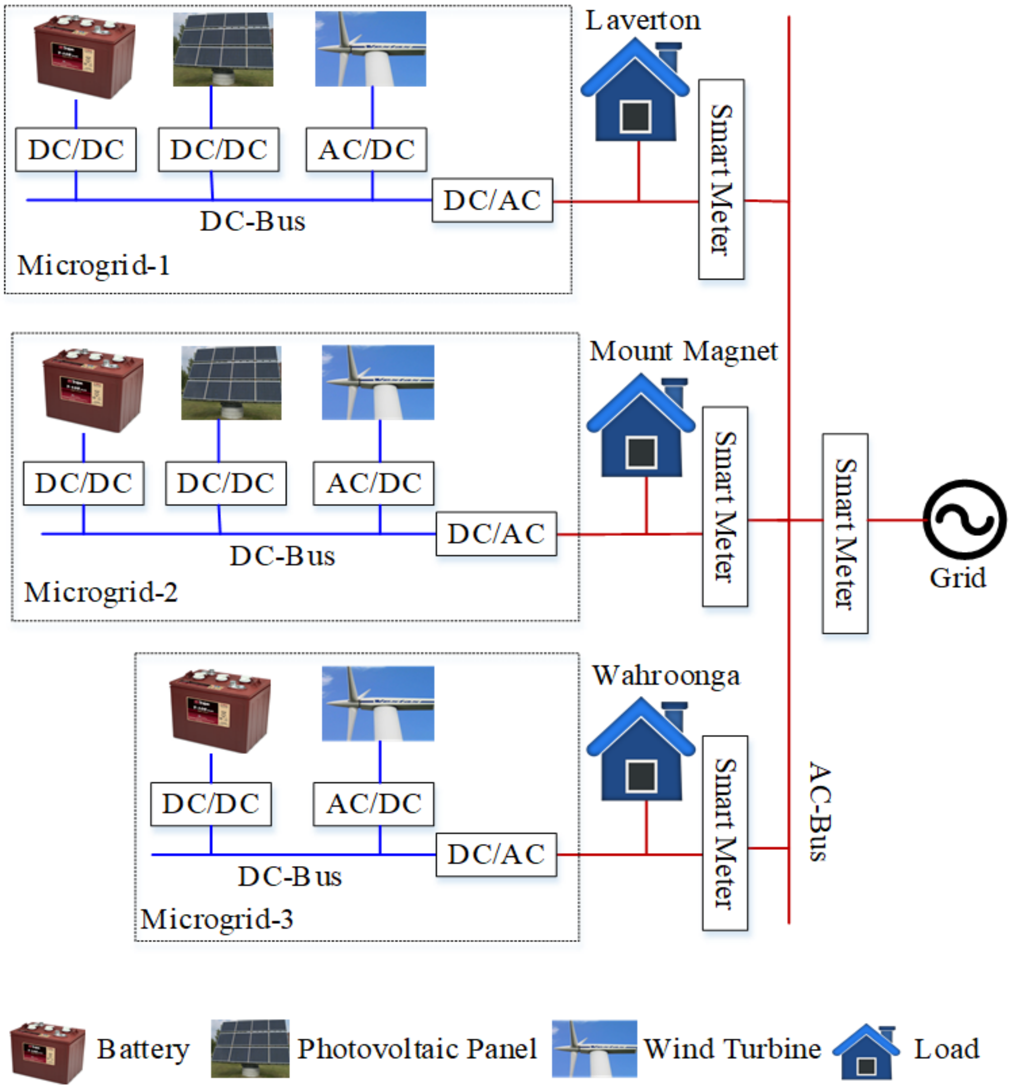


Figure 5.1 Schematic diagram of multi-microgrids system

To analyse the power exchange within the system, smart meters are positioned at both sides of transmission and distribution lines. Wind turbines and photovoltaic panels are connected with a DC-bus through unidirectional AC/DC and DC/DC converters. However, storage batteries are connected with a DC-bus via bidirectional converters. In all microgrids, to connect the DC-bus with AC-bus a DC/AC converter is placed. All grid-connected microgrids are integrated together in the system and complement one another to serve the loads while meeting specific economic and reliability standards. To find optimum results and the accurate sizes of the system components, the real-time data of wind speed, solar radiation and residential loads of three towns in Australia were considered. In the multi-microgrid model, the data of Laverton, Mount Magnet and Wahroonga are illustrated in Section 1.5 and Figure 1.3 from July 2014 to June 2015, June 2015 to May 2016, and July 2012 to June 2013, respectively [50-54].

5.3 Problem Formulation

To achieve the main objective of this study, a multi-objective function is formulated based on the criteria of the levelized cost of energy $(LCOE)$, and the reliability index (I_R). Furthermore, a cooperative game theory technique is used, players are defined, and strategic spaces are set to find the optimum payoff values and for suitable sizing. Wind turbines WT, photovoltaic panels PP and storage batteries SB are the players i for each microgrid. The sizes of players are P_{WT}, P_{SP} and P_{SB}, and the strategic spaces are set as $\left(P_{WT}^{min}, P_{WT}^{max}\right)$, $\left(P_{PP}^{min}, P_{PP}^{max}\right)$, and $\left(P_{SB}^{min}, P_{SB}^{max}\right)$ for wind turbines, photovoltaic panels, and storage batteries, respectively.

5.3.1 Levelized Cost of Energy

On the commercial and residential level, more priority is given to lower the energy cost of the overall system and minimise the electricity bills. Therefore, in this study, the first criteria for optimisation is selected as $LCOE$. For the selected model, the $LCOE$ is defined as the sum of the total cost of the multi-microgrids system divided by the total annual energy supplied E_{an} [15]. In the architecture, the $LCOE$ for microgrid 1 is expressed as follows:

$$LCOE_1 = \sum_{1}^{3} (CO_i / E_{an}) \; i \in \{WT, PP, SB\} \tag{5.1}$$

The total cost for each player is the sum of its annual investment cost $\mathrm{CO_{INV}}$ and operation and maintenance cost $\mathrm{C_{O\&M}}$ is calculated as follows:

$$CO_i = CO_{i\_INV} + C_{i\_O\&M} \tag{5.2}$$

Annual investment cost: If the $\mathcal{U}_i$ is the per-unit cost of the player i, then the annual investment cost for each player is found as follows:

$$CO_{i.INV} = \mathcal{U}_i * P_i * \mathfrak{D}(1+\mathfrak{D})^{\mathbb{L}_i}/((1+\mathfrak{D})^{\mathbb{L}_i} - 1) \tag{5.3}$$

Annual operation and maintenance cost: If the $\mathcal{U}_{i\_OM}$ is the per-unit operation and maintenance cost of the player i, then the operation and maintenance cost for each player is found as follows:

$$CO_{i\_O\&M} = \mathcal{U}_{i\_OM} * P_i \tag{5.4}$$

The $LCOE$ for the multi-microgrids system with n number of microgrids is shown as follows:

$$\mathscr{f}(LCOE_{MMG}) = min\ (\sum_{n=1}^{N} (LCOE_n)) \tag{5.5}$$

5.3.2 Reliability Index

The second criterion to design a multi-microgrids system is the reliability index I_R, which aims to minimise the cost of power loss. The two parameters including the cost of energy not supplied CO_{ENS} and cost of power purchased from the grid CO_{PUR} are minimised for the architecture. For microgrid 1, the I_R is expressed as follows:

$$I_{R\_1} = \sum_{1}^{3} (CO_{i\_ENS} + C_{i\_PUR})\ i \in \{WT, PP, SB\} \tag{5.6}$$

In the multi-microgrids system, three players WT, PP, and SB are considered. The generated power through a wind turbine $p_{WT}(t)$ is found as:

$$p_{WT}(t) = \begin{cases} 0 & \mathscr{v}(t) < \mathscr{v}_c \ or\ \mathscr{v}(t) \geq \mathscr{v}_o \\ \dfrac{P_{WT} * (\mathscr{v}(t) - \mathscr{v}_c)}{\mathscr{v}_r - \mathscr{v}_c} & \mathscr{v}_c \leq \mathscr{v}(t) < \mathscr{v}_r \\ P_{WT} & \mathscr{v}_r \leq \mathscr{v}(t) < \mathscr{v}_o \end{cases} \tag{5.7}$$

The power generated by the storage battery $p_{SB}(t)$ is shown as follows:

$$p_{SB}(t) = \begin{cases} p_{SB}(t-1) + \xi_c * \varDelta(t-1) & \varDelta(t-1) \geq 0 \\ p_{SB}(t-1) + \varDelta(t-1) & \varDelta(t-1) < 0 \end{cases} \quad (5.8)$$

$$\varDelta(t-1) = p_{WT}(t-1) + p_{PP}(t-1) - P_L(t-1) \quad (5.9)$$

In the study, the detailed design of photovoltaic panels are not calculated, but its solar power $p_{SB}(t)$ is represented by the sunlight radiation.

The annual cost for energy not supplied: In order to calculate the cost of energy not supplied for the player i, the unbalanced power $DP(t)$ in the multi-microgrids system during hour t is first calculated by:

$$DP(t) = P_L(t) - p_{WT}(t) - p_{PP}(t) - p_{SB}(t) \quad (5.10)$$

where $p_{SB}(t)$ is the difference between the battery charge level $p_{SB\_SOC}(t)$ in hour t and the P_{SB_min}. The power purchased from the main grid $P_g(t)$ is found as:

$$P_g(t) = \begin{cases} 0 & DP(t) \leq 0 \\ DP(t) & 0 < DP(t) \leq P_{T\_max} \\ P_{T\_max} & DP(t) > P_{T\_max} \end{cases} \quad (5.11)$$

The energy not supplied ENS in hour t is then written as:

$$P_{ENS}(t) = U(t) * (DP(t) - P_g(t)) \quad (5.12)$$

where $U(t)$ is the step function, which is zero when the $DP(t)$ is smaller than $P_g(t)$, and equals one if the $DP(t)$ is larger than $P_g(t)$. The total annual cost of ENS for player i is:

$$CO_{i\_ENS} = \sum_{t=1}^{T} k(t) * P_{ENS}(t) \quad (5.13)$$

where $k(t) = 1.5\mathbb{E}(t)$ and $T = 8760$ hours.

The annual cost for purchasing power from the grid: The total cost of purchasing power from the main grid C_{i_PUR} for the player i is found as:

$$C_{i\_PUR} = \sum_{t=1}^{T} \mathbb{E}(t) * P_g(t) \qquad (5.14)$$

The I_R for the multi-microgrids system with n number of microgrids is obtained as follows:

$$f(I_{R\_MMG}) = min\,(\sum_{n=1}^{N} (I_{R\_n})) \qquad (5.15)$$

5.3.3 Multi-Objective Function

In the multi-objective function, several criteria can be considered to meet the requirements of optimisation [17]. The levelised cost of energy $LCOE$ and the reliability index I_R are the criteria to formulate the multi-objective function in this paper. The designed multi-objective function is a minimising function, because both criteria are minimising. If n number of microgrids are connected in the multi-microgrids system, the value of multi-objective MO function is obtained as:

$$f(MO_{MMG}) = \min\,(K_1 * \sum_{1}^{n} LCOE_n + K_2 * \sum_{1}^{n} I_{R_n}) \qquad (5.16)$$

where the constant-coefficients K_1 and K_2 are represented for the levelised cost of energy, and the reliability index, respectively. The ranges of K_1 and K_2 are set $0 < K_1 < 1$ and $0 < K_2 < 1$, respectively.

5.4 The Nash Equilibrium

Game theory has different cooperative and non-cooperative techniques to optimise the various type of game models. It is confirmed through the studies [58, 62] that cooperative types of game models are more profitable and efficient than non-cooperative models. Therefore, in this research, the cooperative game theory model is considered, where wind turbines, photovoltaic panels and storage batteries are used as players. The game model has three players for microgrid 1 and microgrid 2; therefore, among the players, four ways of coalitions are possible. In the analysis, one type of coalition is considered where all three players $\{(WT, PP, SB)\}$ are cooperating with one another. Similarly, for microgrid 3, wind turbine and storage batteries are used as the players, therefore, it has one way of coalition $\{(WT, SB)\}$ where both players are cooperating with each other. To illustrate the Nash equilibrium technique, one coalition $\{(WT, PP, SB)\}$ is considered, and explained in Figure 5.3 for the sizing of the players and to achieve optimum payoff values.

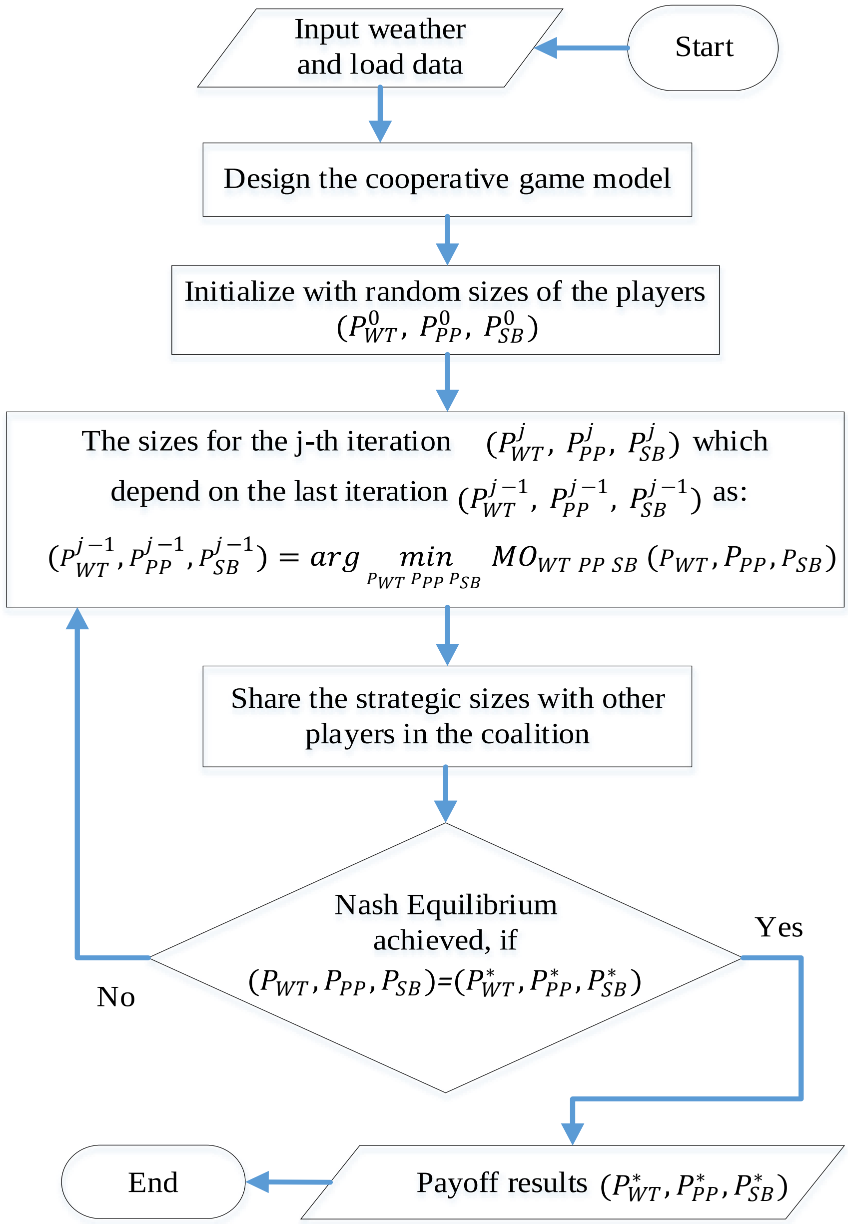


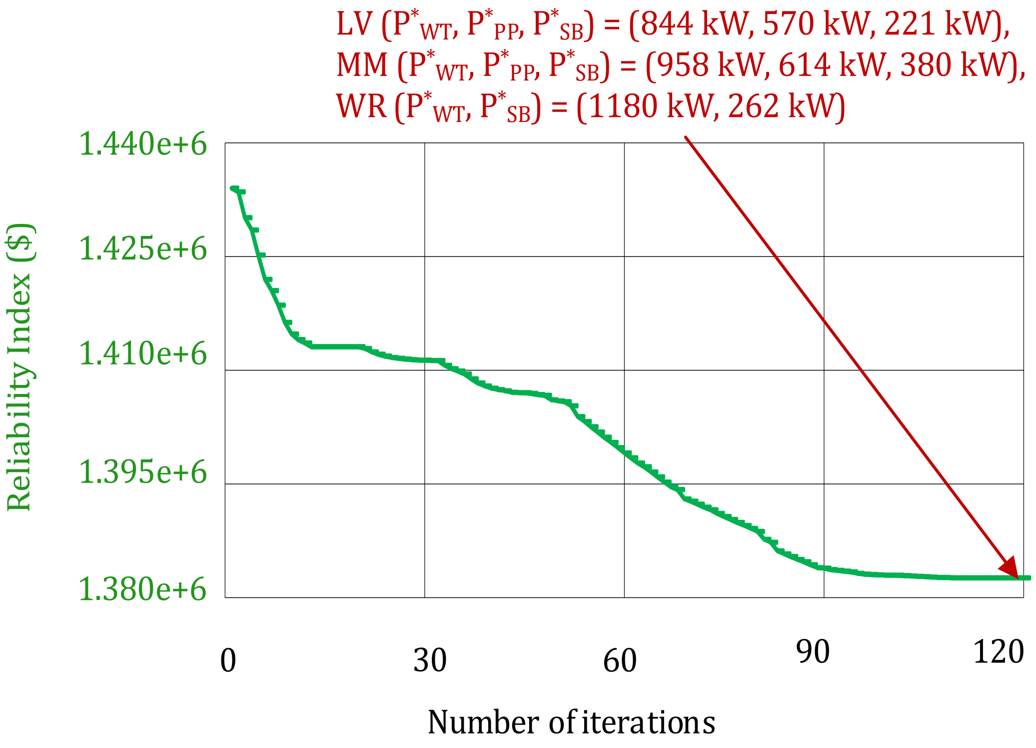
Figure 5.2 Flow chart for a game theory technique

The proposed model is simulated in MATLAB software based on game theory technique, and the particle swarm optimisation (PSO) algorithm with a population of

100 is used to perform the multi-objective optimisation. A PSO algorithm is used in various research areas, and their different optimisation problems are solved [74, 76]. In order to reach the suitable sizes of the players, and optimum payoff values, the simulation model is run for 120 iterations.

5.5 Results and Analysis

To analyse the multi-microgrids system, the realistic weather data and residential load profiles of three towns in Australia are considered. The simulation model is made in MATLAB software using a PSO algorithm with technical parameters summarised in Appendix A Table A.1 [77].



LV (P^*_{WT}, P^*_{PP}, P^*_{SB}) = (844 kW, 570 kW, 221 kW),
MM (P^*_{WT}, P^*_{PP}, P^*_{SB}) = (958 kW, 614 kW, 380 kW),
WR (P^*_{WT}, P^*_{SB}) = (1180 kW, 262 kW)

Figure 5.3 Sizes of the players for the optimisation I_R

Figure 5.3 illustrates the sizes of the players for the three towns in Australia at the Nash equilibrium point ($P^*_{WT}, P^*_{PP}, P^*_{SB}$) when the single-object optimisation is performed for the I_R. The objective function I_R is minimised in a way that its minimum values are stable after the 90th iteration and achieved the optimised result as 1.3826e+6 $. At the Nash equilibrium point, the value of the second objective function LCOE is calculated as 11.261¢/kWh. Similarly, Figure 5.4 shows the sizes of the players at the Nash equilibrium when the second objective function LCOE is only optimised. As can be seen, the values of LCOE become stable after the 110th iteration, and the optimised value is 9.794¢/kWh. At the Nash equilibrium point of LCOE, the values of the second objective function I_R is calculated as 1.4520e+6 $. It is evident from the results that in the case of a single-objective function, only one objective function reaches its optimum minimum values.

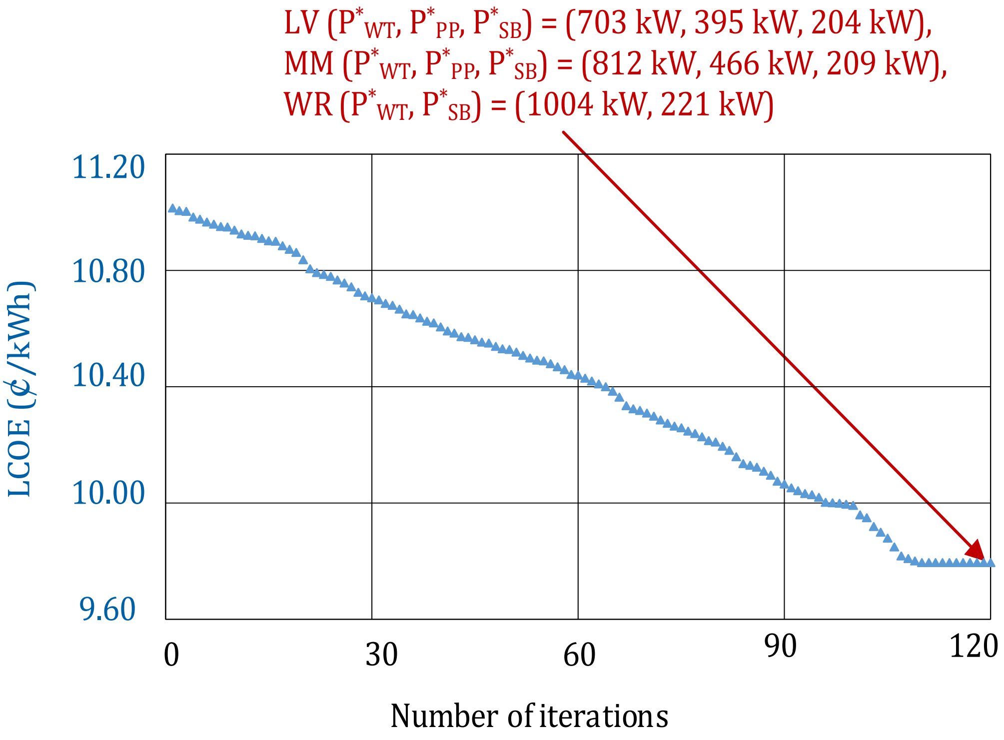


Figure 5.4 Sizes of the players for the optimisation of LCOE

Figure 5.5 shows the values of the multi-objective function, where both criteria including LCOE and I_R are optimised simultaneously to reach their optimum values. The value of the multi-objective (MO) function becomes stable after 100 iterations and reaches its minimum value of 0.34904 p.u. The optimum sizes of the players and payoff values of the objective functions LCOE and I_R are given in Table 5.2. As can be seen, the payoff values for LCOE and I_R are 9.928¢/kWh, and 1.3962e+6 $, respectively. Since both objective functions are optimised simultaneously using the MO function, the payoff values are minimum, and therefore, the sizes of the players are correct and suitable for the multi-microgrid system.

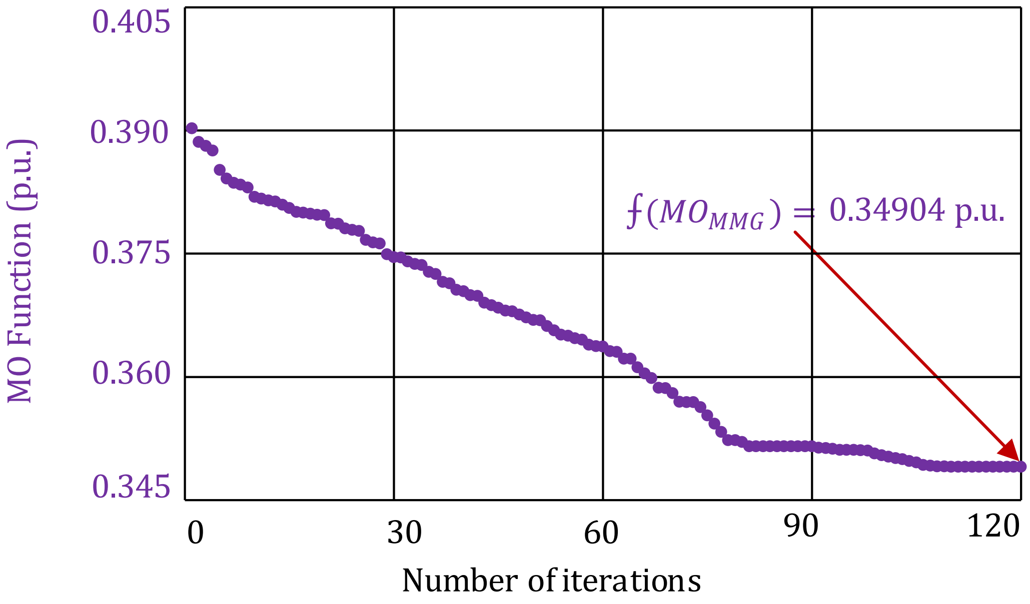


Figure 5.5 MO optimisation results for the multi-microgrids system

The results are validated considering the distribution of the players' size within microgrids. Since Mount Magnet has the largest residential load, therefore, the total size of the players is 1631 kW. Laverton has the second-largest residential load, and the total size of the players is 1422 kW. Wahroonga has the smallest residential load compared to other towns, and its total size of the players is 1399 kW. The sizes of the players are further verified as both single-object and MO optimisations and follow the same trend for the players sizes so that $P^*_{WT} > P^*_{PP} > P^*_{SB}$ [58].

Table 5.1 Results of multi-objective optimisation

<table>
<tr><th colspan="9">Optimum Payoff values and Sizes of the players at Nash equilibrium</th></tr>
<tr><td rowspan="3">Sizes of the players (kW)</td><td colspan="3">Laverton</td><td colspan="3">Mount Magnet</td><td colspan="2">Wahroonga</td></tr>
<tr><td>P^*_{WT}</td><td>P^*_{PP}</td><td>P^*_{SB}</td><td>P^*_{WT}</td><td>P^*_{PP}</td><td>P^*_{SB}</td><td>P^*_{WT}</td><td>P^*_{SB}</td></tr>
<tr><td>812</td><td>382</td><td>228</td><td>946</td><td>448</td><td>237</td><td>1083</td><td>316</td></tr>
<tr><td rowspan="2" colspan="2">Payoff values</td><td colspan="3">$\mathrm{MO_{MMG}}$ function (p.u.)</td><td colspan="2">$\mathrm{I_{R\_MMG}}$ ($)</td><td colspan="2">$\mathrm{LCOE_{MMG}}$ (¢/kWh)</td></tr>
<tr><td colspan="3">0.34904</td><td colspan="2">1.3962e+6</td><td colspan="2">9.928</td></tr>
</table>

5.6 Summary

This chapter introduces a multi-objective optimisation based on a game theory technique for sizing and cost minimisation of grid-connected multi-microgrids. The multi-microgrid system comprised three microgrids with various combinations of wind turbines, photovoltaic panels and storage batteries to meet the load requirement. Due to the variability of generation resources, and to maintain a lower energy cost, the benchmarks considered for multi-objective optimisation are reliability and a levelised cost of energy. The architecture is designed based on the Nash equilibrium game theory technique in which the generation resources and storage batteries are selected as three players. The simulation model is built in MATLAB software, and a particle swarm optimisation algorithm is used for the optimisation of the multi-microgrids. The benchmarks of the multi-objective function are minimised to achieve suitable sizes of the players in a way that the optimum payoff values for the system are achieved. The feasibility of the game-theoretic model is tested based on the real-time residential load, and weather data from three towns of Australia.

The proposed model of this chapter consists of three microgrids who are connected with three different Australian towns and only peer-grid energy trading is considered to perform the analysis. In the next chapter, three microgrids in grid-connected mode are considered and a multi-objective optimization is performed based of different technical criteria. The proposed model is designed based on Nash equilibrium, and P2P energy trading scheme is illustrated and compared with traditional P2G energy trading scheme to find best solution and optimum payoff results to meet load requirements.

Chapter 6 P2P Energy Trading in a Networked Microgrid Based on a Multi-Objective Optimisation and Game Theory

In this chapter, a multi-objective optimisation is proposed for a networked microgrid based on a P2P energy trading scheme. The networked architecture is designed via a cooperative type of game theory technique to achieve the optimum sizes of the players and payoff value from the proposed multi-objective function. For the networked microgrid, the multi-objective function is based on different criteria including annual profit, energy index of reliability and loss of power supply probability. 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 excellence of the work, as shown in Figure 6.1. Sensitivity analysis is performed based on technical parameters to verify the stability of the proposed system and validate the results.

This chapter is based on the research papers “Optimal Sizing of Networked Microgrid using Game Theory considering the Peer-to-Peer Energy Trading”, published in 2020 at the 2nd IEEE International Conference on Smart Power & Internet Energy Systems (SPIES), “A Multi-objective Optimisation for Planning of Networked Microgrid using a Game Theory for P2P Energy Trading Scheme”, submitted in 2021 to the *Journal IET Generation, Transmission & Distribution*, and “A Peer-to-peer Energy Trading for a Clustered Microgrid – Game Theoretical Approach”, published in 2021 to the *International Journal of Electrical Power and Energy Systems.*

6.1 Statement of Contribution

The authors listed below have certified that:

- They meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise.
- There are NO conflicts of interest. They agree to the use of the publication in the student's thesis and its publication on the Curtin University online database.

Papers:

1. "Optimal Sizing of Networked Microgrid using Game Theory considering the Peer-to-Peer Energy Trading", in 2020 2nd International Conference on Smart Power & Internet Energy Systems (SPIES), pp. 322–326. IEEE, 2020.
2. "A Multi-objective Optimization for Planning of Networked Microgrid using a Game Theory for P2P Energy Trading Scheme", peer-reviewed in the *Journal IET Generation, Transmission & Distribution*, 2021, GTD-2021-01-36.
3. "A Peer-to-peer Energy Trading for a Clustered Microgrid – Game Theoretical Approach", *International Journal of Electrical Power and Energy Systems,* Vol. 133, 2021, 107307, DOI: 10.1016/j.ijepes.2021.107307.

Contributors	Statement of contribution	% Total Contribution
Liaqat Ali	Conceptualisation, visualisation, methodology, simulation validation, data analysis and drafting the manuscript.	80
S.M. Muyeen	Conceptualisation, supervision and critical revision of paper.	10
Hamid Bizhani	Simulation validation, and critical revision of paper.	5
Arindam Ghosh	Supervision and critical revision of paper.	5

Principle Supervisor Confirmation

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Associate Professor S.M. Muyeen

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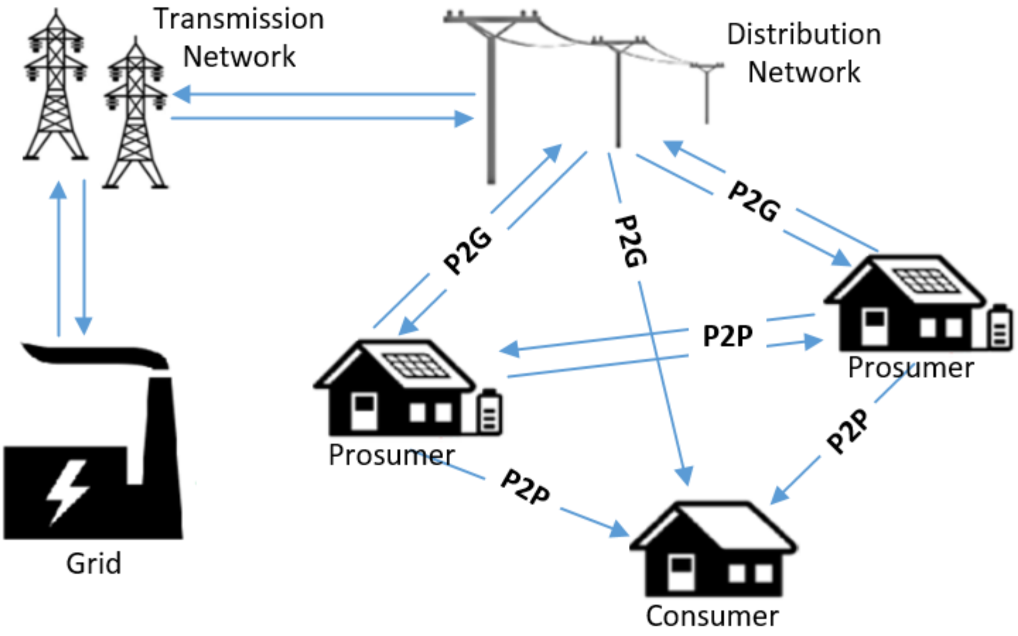


Figure 6.1 P2G and P2P types of energy trading in a network

Figure 6.2 Towns of Australia Laverton, Mount Magnet and Wahroonga

6.2 The Operation Model for Networked Microgrid

Nowadays P2P energy trading is getting very famous in worldwide and Australian electricity market, and an emerging Blockchain technology is becoming very popular to create a strong and transparent trading for P2P energy microgrids. The scheme of P2P energy trading is implemented in different energy markets to ensure maximum profit to the consumers and to increase the overall reliability of the power system. In Australia, Power Ledger has implemented P2P exchanging sites based on Blockchain technology to effectively manage the energy flow among the prosumers. The New York-based energy start-up Drift has implemented P2P energy trading and assisted buyers with saving 10 % of their power costs [78, 79].

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 one another through a bidirectional power link to perform 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 is 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. In the networked microgrid, the real-time data of three remote towns Mount Magnet, Laverton and Wahroogra are shown in Figure 6.2.

Figure 6.3 illustrates the schematic 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 first met through its own generated power. If it is not enough, then the microgrid buys the power from one of the microgrids 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.

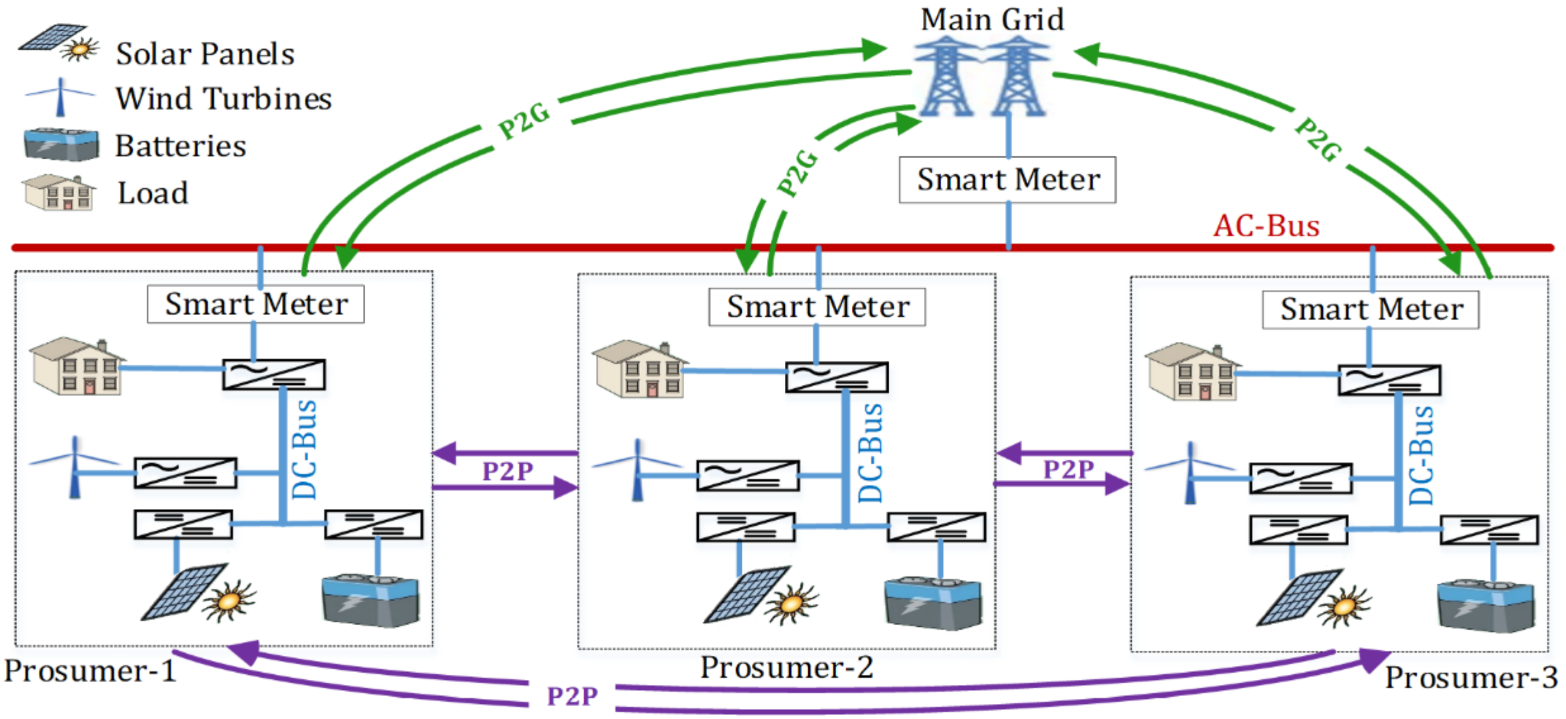


Figure 6.3 Networked microgrid for P2G and P2P energy trading

6.3 Problem Formulation and Design of Multi-Objective Function Based on *APF* and *EIR*

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 [80]. Wind turbines $\mathcal{W}$, solar panels $\mathcal{SP}$, and batteries $\mathcal{B}$ are the decision-making players for each microgrid. The sizes of the players are represented as $\mathcal{P}_{\mathcal{W}}$, $\mathcal{P}_{\mathcal{SP}}$ and $\mathcal{P}_{\mathcal{B}}$, and their strategic spaces are shown as $(\mathcal{P}_{\mathcal{W}}^{min}, \mathcal{P}_{\mathcal{W}}^{max})$, $(\mathcal{P}_{\mathcal{SP}}^{min}, \mathcal{P}_{\mathcal{SP}}^{max})$, and $\left(\mathcal{P}_{\mathcal{B}}^{min}, \mathcal{P}_{\mathcal{B}}^{max}\right)$ for wind turbines, solar panels and batteries, 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.

6.3.1 Design of Multi-Objective Function

A. Annual Profit

To calculate the annual profit of the networked microgrid for P2G and P2P energy trading schemes, important technical parameters including power selling income $I_{i_{\mathcal{SE}}}$, salvage value $I_{i_{\mathcal{SL}}}$, income from ancillary services $I_{i_{\mathcal{AS}}}$, initial investment cost $C_{i_{\mathcal{IN}}}$, compensation cost from energy cannot be supplied $C_{i_{\mathcal{ES}}}$, purchasing power from the grid $C_{i_{\mathcal{PC}}}$ and operation and maintenance cost $C_{i_{\mathcal{OM}}}$ are considered. The maximising objective function for APF is expressed as follows:

$$f(APF_i) = \max\left(I_{i_{\mathcal{SE}}} + I_{i_{\mathcal{SL}}} + I_{i_{\mathcal{AS}}} - C_{i_{\mathcal{IN}}} - C_{i_{\mathcal{OM}}} - C_{i_{\mathcal{ES}}} - C_{i_{\mathcal{PC}}}\right) \qquad (6.1)$$

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

$$p_{\mathcal{W}}(t) = \begin{cases} 0 & v(t) < v_c \ or \ v(t) \geq v_o \\ \dfrac{\mathcal{P}_{\mathcal{W}} * (v(t) - v_c)}{v_r - v_c} & v_c \leq v(t) < v_r \\ \mathcal{P}_{\mathcal{W}} & v_r \leq v(t) < v_o \end{cases} \qquad (6.2)$$

$$\mathscr{p}_{\mathcal{B}}(t) = \begin{cases} \mathscr{p}_{\mathcal{B}}(t-1) + \xi_c * \Delta(t-1) & \Delta(t-1) \geq 0 \\ \mathscr{p}_{\mathcal{B}}(t-1) + \Delta(t-1) & \Delta(t-1) < 0 \end{cases} \tag{6.3}$$

$$\Delta(t-1) = \mathscr{p}_{\mathcal{W}}(t-1) + \mathscr{p}_{\mathcal{SP}}(t-1) - \mathcal{P}_{\mathcal{D}}(t-1) \tag{6.4}$$

where $t = 1, 2, 3, \dots, 8760\ hours. \mathcal{P}_{\mathcal{D}}(t-1)$, and $\Delta(t-1)$ denotes the electrical load $\mathcal{P}_{\mathcal{D}}(t)$, 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 $\mathscr{p}_{\mathcal{SP}}(t)$ is used to define the sunlight fluctuant nature. The annual $C_{i\_\mathcal{OM}}$ of each player, is found by multiplying its per unit operation and maintenance cost $\mathcal{U}_{i\_OM}$ by its generation capacity. The $I_{i\_\mathcal{AS}}$ of the storage, batteries is calculated, and for the wind turbines and the solar panels, its value is zero. The annual $C_{i\_\mathcal{IN}}$, $I_{i\_\mathcal{SL}}$, and $C_{i\_\mathcal{PC}}$ for the players is:

$$C_{i\_\mathcal{IN}} = \mathcal{P}_i * \mathcal{U}_i * \mathfrak{D}(1+\mathfrak{D})^{\mathbb{L}_i}/((1+\mathfrak{D})^{\mathbb{L}_i} - 1) \tag{6.5}$$

$$I_{i\_\mathcal{SL}} = \mathcal{P}_i * \mathcal{U}_{i\_\mathcal{S}V} * \mathfrak{D}/((1+\mathfrak{D})^{\mathbb{L}_i} - 1) \tag{6.6}$$

$$C_{i\_\mathcal{PC}} = C_{\mathcal{PC}} * \mathcal{P}_i/(\mathcal{P}_{\mathcal{W}} + \mathcal{P}_{\mathcal{SP}} + \mathcal{P}_{\mathcal{B}}) \tag{6.7}$$

where$\mathcal{U}_{i_\mathcal{S}V}$, $\mathfrak{D}$, $\mathbb{L}_i$, $\mathcal{U}_i$, and $C_{\mathcal{PC}}$ are per unit salvage value, discount rate, life span, per unit cost for each player, and total annual cost for purchasing power from the main grid, respectively.

The value of $I_{i\_\mathcal{SL}}$ will become zero when storage batteries are outdated. The annual $C_{i\_\mathcal{ES}}$ and $C_{\mathcal{PC}}$ for the players can be found as follows:

$$C_{i\_\mathcal{ES}} = \sum_{t=1}^{T} 1.5 * \mathbb{E}(t) * (\mathcal{P}_{\mathcal{UB}}(t) - \mathcal{P}_{\mathcal{PG}}(t)) \tag{6.8}$$

$$C_{\mathcal{PC}} = \sum_{t=1}^{T} \mathbb{E}(t) * \ \mathcal{P}_{\mathcal{PG}}(t) \tag{6.9}$$

$$\mathcal{P}_{\mathcal{UB}}(t) = \mathcal{P}_{\mathcal{D}}(t) - \mathscr{p}_{\mathcal{W}}(t) - \mathscr{p}_{\mathcal{SP}}(t) - (\mathscr{p}_{\mathcal{B}\_SOC}(t) - \mathcal{P}_{\mathcal{B}}\_min) \tag{6.10}$$

where T, $\mathbb{E}(t)$, $\mathcal{P}_{\mathcal{PG}}(t)$, $\mathcal{P}_{\mathcal{UB}}(t)$, and $\mathcal{P}_{\mathcal{B}\_min}$ are the total number of hours in a year, electricity price in hour t, purchased power from the main grid in hour t, unbalanced power in a microgrid in hour t and battery minimum state of charge, respectively.

In the same way the annual $I_{i\_\mathcal{SE}}$ for the solar panels and the wind turbines is calculated as:

$$I_{i\_\mathcal{SE}} = (1+\propto)\sum_{t=1}^{T}\mathbb{E}(t) * \mathcal{P}_{i\_\mathcal{SE}}(t) \qquad (6.11)$$

$$\mathcal{P}_{i\_\mathcal{SE}}(t) = \begin{cases} p_i(t) & \mathcal{P}_{\mathcal{SR}}(t) \le 0 \\ \dfrac{p_i(t) * \mathcal{P}_{\mathcal{CN}}(t)}{(p_{\mathcal{W}}(t) + p_{\mathcal{SP}}(t))} & \mathcal{P}_{\mathcal{SR}}(t) > 0 \end{cases} \qquad (6.12)$$

$$\mathcal{P}_{\mathcal{SR}}(t) = p_{\mathcal{W}}(t) + p_{\mathcal{SP}}(t) - (\mathcal{P}_{\mathcal{D}}(t) + \mathcal{P}_{\mathcal{TC}} + (\mathcal{P}_{\mathcal{B}} - p_{\mathcal{B}\_SOC}(t)) \qquad (6.13)$$

where $\propto$, $\mathcal{P}_{i\_\mathcal{SE}}(t)$, $\mathcal{P}_{\mathcal{CN}}(t)$, $\mathcal{P}_{\mathcal{SR}}(t)$, $\mathcal{P}_{\mathcal{TC}}$, and $p_{\mathcal{B}\_SOC}(t)$ are subsidy coefficient, players' power capacity selling in hour t, the maximum power consumed in hour t, the capacity of surplus power in hour t, the transmission line capacity between the microgrid and the main grid, and battery state of charge in hour t, respectively.

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

$$I_{\mathcal{B}\_\mathcal{AS}} = \Re * \sum_{t=1}^{T}\left(p_{\mathcal{B}\_SOC}(t) - \mathcal{P}_{\mathcal{B}\_\mathcal{SE}}(t) - \mathcal{P}_{\mathcal{B}\_min}\right) \qquad (6.14)$$

$$I_{\mathcal{B}\_\mathcal{SE}} = (1+\propto) * \sum_{t=1}^{T}\mathbb{E}(t) * \mathcal{P}_{\mathcal{B}\_\mathcal{SE}}(t) \qquad (6.15)$$

$$\mathcal{P}_{\mathcal{B}\_\mathcal{SE}}(t) = \begin{cases} \Delta p_{\mathcal{B}\_SOC}(t) & \Delta p_{\mathcal{B}\_SOC}(t) > 0 \\ 0 & \Delta p_{\mathcal{B}\_SOC}(t) \le 0 \end{cases} \qquad (6.16)$$

where $\mathcal{P}_{\mathcal{B}\_\mathcal{SE}}(t)$, and $\Delta p_{\mathcal{B}\_SOC}(t)$ represent batteries' power selling capacity in hour t, and change in battery capacity in hour t, respectively.

It is evident from the above equations that the maximisation of the annual profit not only depends on 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:

$$f(APF_{MG\_1}) = \max\,(APF_{\mathcal{W}} + APF_{\mathcal{SP}} + APF_{\mathcal{B}}) \tag{6.17}$$

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:

$$f(APF_{NMG\_P2G}) = \max\,(\sum_{1}^{n} APF_{MG\_n})\; n \in \{1, 2, 3\} \tag{6.18}$$

Microgrids act as the prosumers for the P2P energy trading and allow the networked microgrid to exchange power between the prosumer–prosumer and the prosumer–grid. The P2P energy trading scheme is becoming more popular compared with the traditional P2G energy trading scheme because prosumers have more options to buy/sell power, making them more efficient. The P2P energy trading encourages the prosumers to exchange power between one another, 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 6.4. Similar to P2G energy trading, for the P2P energy trading, most of the equations are the same except the $I_{i\_\mathcal{SE}}$ and $C_{i\_\mathcal{PC}}$ where the prosumers are selling or purchasing power either between one another or with the main grid. The architecture is designed in a way that the 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 requirements. In the second case, if prosumers are unable to meet their power requirements, then they will do so with the power exchange with the main grid. The value of APF for the first prosumer PR_1 is found as:

$$f(APF_{PR\_1}) = \max\,(APF_{\mathcal{W}} + APF_{\mathcal{SP}} + APF_{\mathcal{B}}) \tag{6.19}$$

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

$$f(APF_{NMG\_P2P}) = \max\left(\sum_{1}^{n} APF_{PR\_n}\right) \qquad n \in \{1,2,3\} \tag{6.20}$$

B. 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 [17]. For a microgrid, the EIR is found from the energy not supplied E_{NS_MG}, and is calculated as follows:

$$EIR_{MG} = \left(1 - \frac{E_{NS\_MG}}{E_{MG}}\right) \tag{6.21}$$

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:

$$E_{NS\_MG} = \sum_{t=1}^{T} \left(\mathcal{P}_{\mathcal{D}}(t) - \mathcal{P}_{Total}(t)\right) * u(t) \tag{6.22}$$

where $\mathcal{P}_{Total}$ 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 $\mathcal{P}_{Total}(t)$ is the power shortage in hour t. If the total generated power is lower than the load demand, the value of $u(t)$ is one. Otherwise, $u(t)$ is zero if the generated power is either equal or more than the load demand. The value of $\mathcal{P}_{Total}(t)$ is found as follows:

$$\mathcal{P}_{Total}(t) = p_{\mathcal{W}}(t) + p_{\mathcal{SP}}(t) + p_{\mathcal{B}}(t) + \mathcal{P}_{g}(t) \tag{6.23}$$

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:

$$f(EIR_{NMG\_P2G}) = \max\left(\sum_{1}^{n} EIR_{MG\_n}\right) n \in \{1,2,3\} \tag{6.24}$$

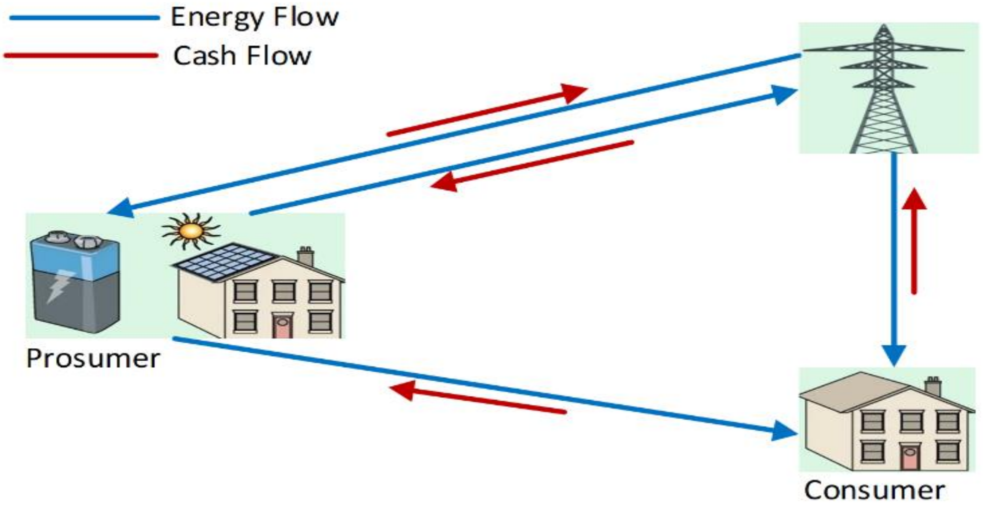


Figure 6.4 Power and cash flow for P2G and P2P energy trading

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

$$f(EIR_{NMG\_P2P}) = \max(\sum_{1}^{n} EIR_{PR\_n})\ n \in \{1,2,3\} \tag{6.25}$$

C. Multi-Objective Function

In the technique of multi-objective (MO) function, several criteria are met simultaneously to meet the requirement of the optimisation model [81]. The annual profit and energy index of reliability are the set criteria to formulate the multi-objective function. The designed multi-objective function is a maximising function because both criteria are maximising. If n number of microgrids are connected in the networked microgrid, the value of MO function is obtained as:

$$f(MO_{NMG}) = \max\,(k_1 * \sum_{1}^{n} APF_{MG_n} + k_2 * \sum_{1}^{n} EIR_{MG_n}) \tag{6.26}$$

where k_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.

6.3.2 Game Theory Technique

Usually, different methods are proposed to perform the optimisation process to achieve desired goals. Game theory is a helpful technique to solve decision-making problems and perform multi-objective optimisation. A game model can be organised in either 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 decisions in their way to optimise payoff values. However, in a cooperative game model, the players are arranged in multiple sets of coalitions and cooperate with one another to reach the optimum value of payoff [62]. The current research offers proof that cooperative types of game models are more efficient and profitable than non-cooperative ones [58]. In this paper, a cooperative game technique called the 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 sets of coalitions, where two players are cooperating and the third one is independent, such as $\{(\mathcal{W}, \mathcal{SP}), (\mathcal{B})\}$. In the fourth set, all three players are in one coalition $\{(\mathcal{W}, \mathcal{SP}, \mathcal{B})\}$ and cooperating. To explain the Nash equilibrium, one of the coalition sets $\{(\mathcal{W}, \mathcal{SP}, \mathcal{B})\}$ is considered where all the players are cooperating with one another. The optimum sizes of the players at the Nash equilibrium point$(\mathcal{P}_{\mathcal{W}}^{*}, \mathcal{P}_{\mathcal{SP}}^{*}, \mathcal{P}_{\mathcal{B}}^{*})$, and the payoff value based on iteration j are found as follows:

1. Input electrical load profile, weather forecast data solar radiation and wind speed.
2. In the networked microgrid, choose randomly the initial sizes of the players $(\mathcal{P}_{\mathcal{W}}^{0}, \mathcal{P}_{\mathcal{SP}}^{0}, \mathcal{P}_{\mathcal{B}}^{0})$ within strategic limits.
3. In the selected set of coalition $\mathcal{W}$, $\mathcal{SP}$ and $\mathcal{B}$ are cooperating with one another $\{(\mathcal{W}, \mathcal{SP}, \mathcal{B})\}$. Consider j^{th} iteration $(\mathcal{P}_{\mathcal{W}}^{j}, \mathcal{P}_{\mathcal{SP}}^{j}, \mathcal{P}_{\mathcal{B}}^{j})$, which is based on its previous iteration $(\mathcal{P}_{\mathcal{W}}^{j-1}, \mathcal{P}_{\mathcal{SP}}^{j-1}, \mathcal{P}_{\mathcal{B}}^{j-1})$ as:

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

4. Share with every player in the coalition information about the strategic sizes of the third step.
5. Check the coalition results. If none of the players changes its size during the whole iteration, this means that the Nash equilibrium is achieved $(\mathcal{P}_{\mathcal{W}}, \mathcal{P}_{\mathcal{SP}}, \mathcal{P}_{\mathcal{B}}) = (\mathcal{P}_{\mathcal{W}}^{*}, \mathcal{P}_{\mathcal{SP}}^{*}, \mathcal{P}_{\mathcal{B}}^{*})$. In that case, if the condition is not met, go back to step *3*.

In order to achieve multi-optimisation of a networked microgrid based on a P2P energy trading scheme, the game model is built and simulated in MATLAB software using a modified PSO algorithm. A PSO algorithm is a computational method to optimise different problems iteratively to improve the desired outcome and is frequently used in many research fields to solve different optimisation functions [74, 75]. 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.

6.3.3 Results and Discussions

A. 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 – Mount Magnet, Laverton, and Wahroonga in Australia are considered, as shown in Section 1.5 and Figure 1.3. It is to be noted that these towns are not contiguous and hence, in practice, cannot form networked microgrids. However, the data for these three towns are taken to consider a synthetic situation, where towns of similar capacities can be considered for energy trading. 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 [46, 47]. The technical parameters are illustrated in Appendix A Table A.1 [80].

B. Single-Objective Analysis for $\boldsymbol{f(APF)}$ and $\boldsymbol{f(EIR)}$

To evaluate and analyse the networked microgrid, the simulation model is designed in MATLAB software based on a PSO algorithm. 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 [58, 82]. If three players are making four sets of coalitions in a cooperative game model, then the payoff is optimum when all the players are working in a single coalition and cooperating with one another. In the analysis of this research, a coalition is only considered where all the three players $\mathcal{W}$, $\mathcal{SP}$, and $\mathcal{B}$ are cooperating a single coalition $\{(\mathcal{W}, \mathcal{SP}, \mathcal{B})\}$ to achieve the best value of multi-objective function and optimum sizes of the players.

Table 6.1 illustrates the results for both energy trading schemes when the optimisation is performed with respect to the single objective function $f(APF)$ for a networked microgrid so that the optimum sizes of the players ($\mathcal{P}_{\mathcal{W}}^{*}$, $\mathcal{P}_{\mathcal{SP}}^{*}$, $\mathcal{P}_{\mathcal{B}}^{*}$) at the Nash equilibrium are found. Later on, the value of the second object function EIR is calculated at the optimised values of the players. In a similar way, if the optimisation is performed for the $f(EIR)$ as a single objective function, the payoff values for both objective functions and optimised sizes of the players are shown in Table 6.2 for both energy trading schemes. Both objective functions in the simulation are maximising, and therefore, the payoff values of APF_{NMG} and EIR_{NMG} are higher in the case of the P2P energy trading scheme. The P2G energy trading energy exchange only occurs 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 APF_{NMG} is higher when $f(APF)$ is optimised as a single objective function compared to its value when $f(EIR)$ is optimised as a single objective function. Similarly, the payoff value of EIR_{NMG} is higher when the optimisation is performed with respect to $f(EIR)$, and its value drops down when $f(APF)$ is considered for single-objective optimisation.

Table 6.1 Results for optimisation of APF_{NMG} as an objective function

Coalition	Towns of Australia	Optimum Sizes of the Players				Energy Trading Schemes	Values of Objective Functions	
		$\mathcal{P}^*_{\mathcal{W}}$ (kW)	$\mathcal{P}^*_{\mathcal{SP}}$ (kW)	$\mathcal{P}^*_{\mathcal{B}}$ (kW)	$\mathcal{P}_{T}$ (kW)		APF_{NMG} ($/year)	EIR_{NMG} (p.u.)
$(\mathcal{W}, \mathcal{SP}, \mathcal{B})$	Laverton	890	531	298	1719	P2G	1.500555e+9	0.989860
	Mount Magnet	920	586	396	1902	P2P	1.501028e+9	0.995921
	Wahroonga	850	412	207	1469			

Table 6.2 Results for optimisation of EIR_{NMG} as an objective function

Coalition	Towns of Australia	Optimum Sizes of the Players				Energy Trading Schemes	Values of Objective Functions	
		$\mathcal{P}_{\mathcal{W}}^{*}$ (kW)	$\mathcal{P}_{\mathcal{SP}}^{*}$ (kW)	$\mathcal{P}_{\mathcal{B}}^{*}$ (kW)	$\mathcal{P}_{T}$ (kW)		APF_{NMG} ($/year)	EIR_{NMG} (p.u.)
$(\mathcal{W}, \mathcal{SP}, \mathcal{B})$	Laverton	883	496	309	1688	P2G	1.491103e+9	0.989957
	Mount Magnet	950	651	210	1811			
	Wahroonga	850	461	201	1512	P2P	1.491568e+9	0.995937

C. Results and Analysis of MO_{NMG} Optimisation

To perform the optimisation of a 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 6.3 shows the payoff values of APF_{NMG} and EIR_{NMG}, and suitable sizes of the players ($\mathcal{P}_{\mathcal{W}}^{*}$, $\mathcal{P}_{\mathcal{SP}}^{*}$, $\mathcal{P}_{\mathcal{B}}^{*}$) for a networked microgrid after the simulation process of $f(MO_{NMG})$ at the Nash equilibrium point for P2G and P2P. The multi-objective function is maximising; therefore, the size of the players is optimised at the maximum value of $f(MO_{NMG})$. The payoff values for P2P energy trading are higher than P2G, and as a result, the P2P scheme has a design with better reliability, more annual profit and the minimum possibility of losing power supply. For the multi-objective optimisation, the individual payoff values of APF_{NMG} and EIR_{NMG} are higher than the payoff value for the single objective optimisation, and this validates 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 6.5. The optimised sizes of the players ($\mathcal{P}_{\mathcal{W}}^{*}$, $\mathcal{P}_{\mathcal{SP}}^{*}$, $\mathcal{P}_{\mathcal{B}}^{*}$) 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. 6.3, respectively. It is also evident from Figure 6.5 that the values of $f(MO_{NMG})$ are change slightly until the 60th iteration, and then the increase is very sudden until the 100th iteration. After that, the results start getting closer to its maximum value until reaching the final values at the 125 iterations.

Figure 6.6 shows the suitable sizes of the players ($\mathcal{P}_{\mathcal{W}}^{*}$, $\mathcal{P}_{\mathcal{SP}}^{*}$, $\mathcal{P}_{\mathcal{B}}^{*}$) and total size of available power ($\mathcal{P}_{T} = \mathcal{P}_{\mathcal{W}}^{*} + \mathcal{P}_{\mathcal{SP}}^{*} + \mathcal{P}_{\mathcal{B}}^{*}$) for the three microgrids in the networked architecture. Since the residential load of microgrid 2 is the highest, it has a maximum value of $\mathcal{P}_{T}$ to meet the load requirements. Microgrid 2 has a lower capacity of $\mathcal{P}_{T}$, and microgrid 3 has the lowest value of $\mathcal{P}_{T}$ because of the lowest residential load requirements. If the sizes of the players are compared in Tables 6.1–6.3, it shows the similarity among their sizes at the Nash equilibrium points and validates the results $\mathcal{P}_{\mathcal{W}}^{*} > \mathcal{P}_{\mathcal{SP}}^{*} > \mathcal{P}_{\mathcal{B}}^{*}$ [58].

Table 6.3 Results for a multi-objective function $f(\boldsymbol{MO_{NMG}})$

Coalition	Towns of Australia	Optimum Sizes of the Players				Energy Trading Schemes	Values of Multi-Objective Function		
		$\mathcal{P}_{\mathcal{W}}^{*}$ (kW)	$\mathcal{P}_{\mathcal{SP}}^{*}$ (kW)	$\mathcal{P}_{\mathcal{B}}^{*}$ (kW)	$\mathcal{P}_{T}$ (kW)		$f(MO_{NMG})$ (p.u.)	APF_{NMG} ($/year)	EIR_{NMG} (p.u.)
$(\mathcal{W},\mathcal{SP},\mathcal{B})$	Laverton	900	521	264	1685	P2G	0.8968629	1.514346e+9	0.989989
	Mount Magnet	950	538	340	1828	P2P	0.9005483	1.514812e+9	0.995976
	Wahroonga	850	460	305	1615				

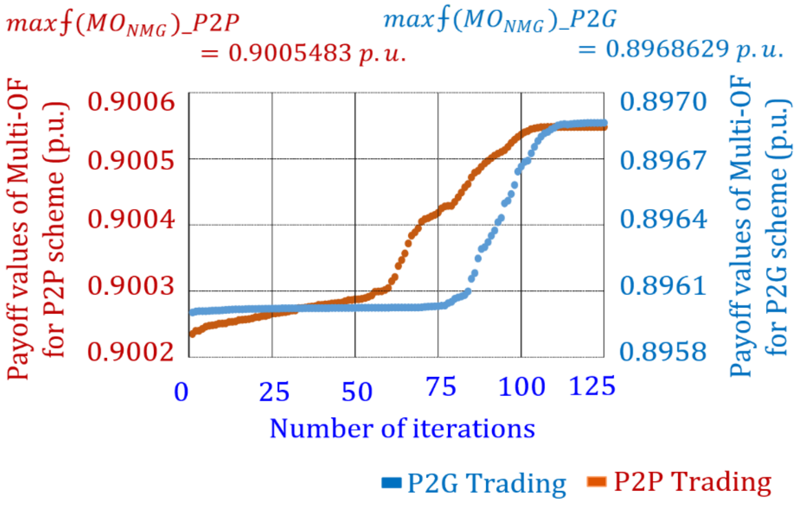


Figure 6.5 Payoff values of multi-objective function for P2G and P2P energy trading schemes

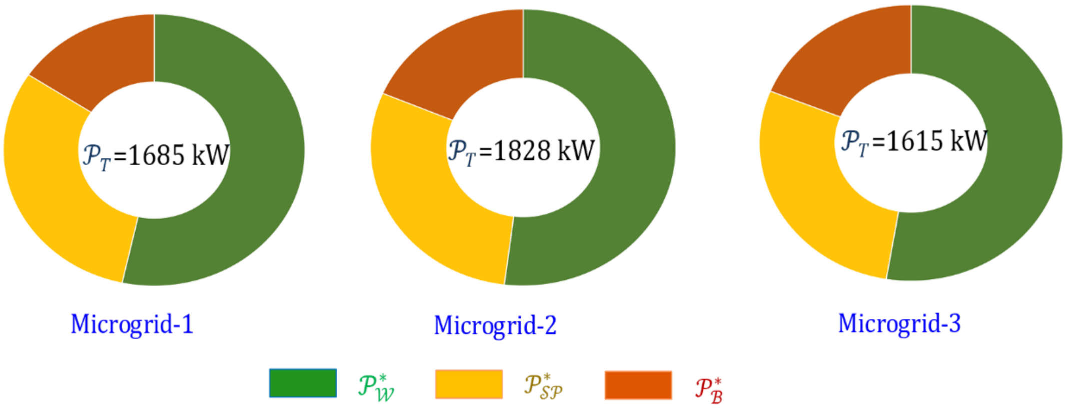
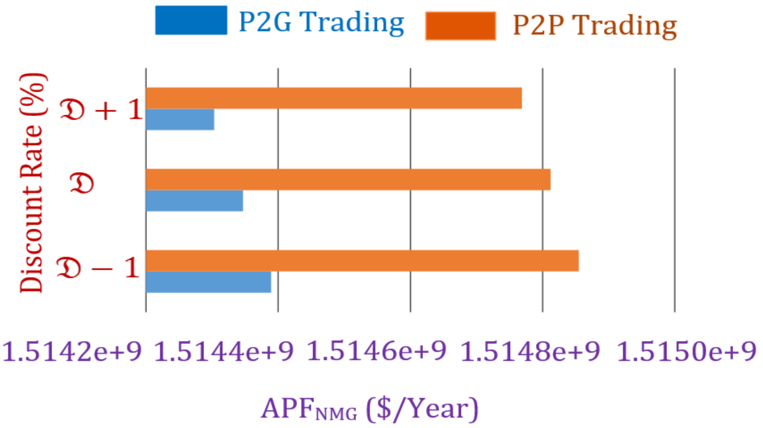


Figure 6.6 Payoff values of multi-objective function for P2G and P2P energy trading schemes

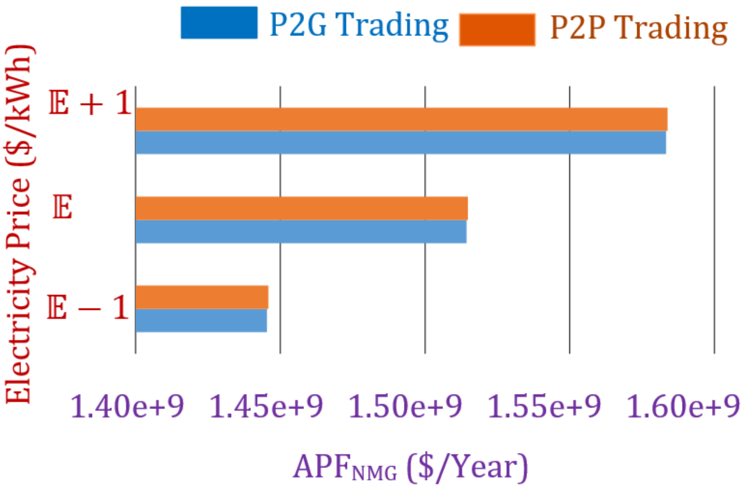
D. Sensitivity Analysis of the Model

The capacity allocation of the players to achieve maximum payoff values based on the game theory technique is performed based on input parameters in Table A.1. In this section, the effect of changing some parameters are 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 APF_{NMG} is more influenced with the selected sensitivity values; therefore, its effect is shown in Table 6.4 and Figure 6.7 to validate the payoff results. It can be seen that the percentage increase in the APF_{NMG} value is

0.003% as the discounts rate reduced 1%, and when the discount rate is increased 1%, the percentage change in APF_{NMG} value decreases 0.003%. The trend of percentage change in APF_{NMG} value is similar for discount rates for both energy trading schemes P2P and P2G energy trading that verifies the results. The influence of electricity prices is more on the APF_{NMG} value than the discount rate. Therefore, as electricity prices increase 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 the electricity prices is also validated for both energy trading schemes.



(a)



(b)

Figure 6.7 Sensitivity analysis of APF_{NMG} for P2G and P2P energy trading schemes

Table 6.4 Results of APF_{NMG} after the sensitivity analysis

Sensitivity Parameters		APF_{NMG} (\$/year)			
		P2G Trading	$\Delta APF_{\mathrm{P2G}}$ (%)	P2P Trading	$\Delta APF_{\mathrm{P2P}}$ (%)
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

6.4 Problem Formulation and Design of Multi-Objective Function Based on $\mathcal{PF}$ and $LPSP$

Renewable energy is widely used as a source in modern types of power generation, despite its unpredictable nature. The storage batteries and grid-connected networks are designed to increase the system's reliability. The selected model has a cluster of three different microgrids, which can act as prosumers to meet the requirement of P2P energy trading. One cooperative game theory technique called the Nash equilibrium is used for the sizing and payoff optimisation for the clustered microgrid. Game theory is a smart way to solve different microgrids problems, and in general, it is a combination of more than two players known as decision-makers who have their own decision-making goals with strategic space to achieve optimum payoff values [28, 61].

6.4.1 Formulation of Multi-Objective Function

The proposed architecture consists of three different microgrids, and each microgrid is a combination of generation resources including wind turbines $\mathcal{W}$, solar panels $\mathcal{SP}$ and batteries $\mathcal{B}$ to satisfy the requirement of the connected residential load. In the game model, sizes or capacities of the generation resources and batteries are taken as three players $\mathcal{P}_{\mathcal{W}}$, $\mathcal{P}_{\mathcal{SP}}$ and $\mathcal{P}_{\mathcal{B}}$ with strategic sets of $(\mathcal{P}_{\mathcal{W}}^{min}, \mathcal{P}_{\mathcal{W}}^{max})$, $(\mathcal{P}_{\mathcal{SP}}^{min}, \mathcal{P}_{\mathcal{SP}}^{max})$, and $\left(\mathcal{P}_{\mathcal{B}}^{min}, \mathcal{P}_{\mathcal{B}}^{max}\right)$, respectively. The annual profit $\mathcal{PF}_{\mathcal{j}}$ and loss of power supply probability LPS are selected as the objective functions, and then, the multi-objective optimisation is performed for the clustered microgrid to obtain the players' suitable sizes and optimised payoff value.

A. Profit as Payoff Function

In the case of a single microgrid MG, the annual profit $\mathcal{PF}_{\mathcal{j}}$ for the players is expressed as follows:

$$\mathcal{PF}_{MG\_1} = Max(\sum_{1}^{3} \mathcal{PF}_{\mathcal{j}})\ \mathcal{j} \in \{\mathcal{W}, \mathcal{SP}, \mathcal{B}\} \tag{6.27}$$

To find the annual profit for each player $\mathcal{PF}_{j}$, different parameters can be considered when clustered microgrid is working in a grid-connected mode. However, in this research, only a few parameters, including power selling income $\mathcal{I}_{j\_\mathcal{SE}}$, salvage value $\mathcal{I}_{j\_\mathcal{SL}}$, income from ancillary services $\mathcal{I}_{j\_\mathcal{AS}}$, initial investment cost $\mathcal{C}_{j\_\mathcal{IN}}$, compensation cost from energy cannot be supplied $\mathcal{C}_{j\_\mathcal{ES}}$, purchasing power from the grid $\mathcal{C}_{j\_\mathcal{PC}}$ and operation and maintenance cost $\mathcal{C}_{j\_\mathcal{OM}}$ are taken into account, as shown in Figure 6.8.

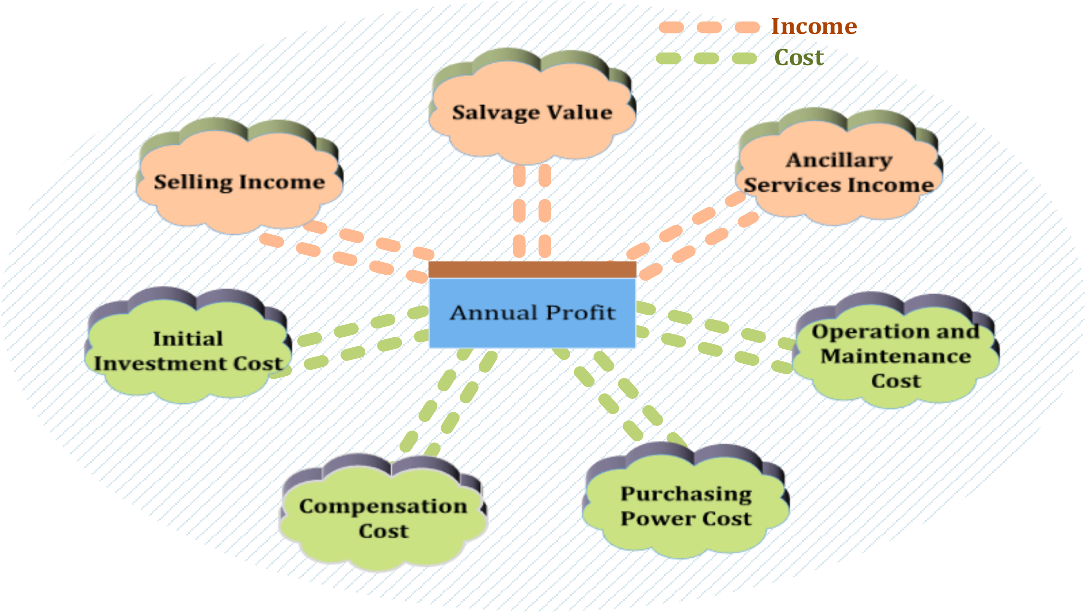


Figure 6.8 Technical parameters considered for clustered microgrid

The maximum annual profit for each player can be calculated as:

$$\mathcal{PF}_{j} = Max(\mathcal{I}_{j\_\mathcal{SE}} + \mathcal{I}_{j\_\mathcal{SL}} + \mathcal{I}_{j\_\mathcal{AS}} - \mathcal{C}_{j\_\mathcal{IN}} - \mathcal{C}_{j\_\mathcal{OM}} - \mathcal{C}_{j\_\mathcal{ES}} - \mathcal{C}_{j\_\mathcal{PC}}) \qquad (6.28)$$

If we compare the generation resources with the batteries, then usually, batteries take the tasks of power generation smoothing, valley-filling and peak-cutting. Therefore, its payoff mostly comes from ancillary services. To reduce complexity, income from ancillary services are only considered for batteries, and their value is zero for wind turbines and solar panels. In this research, hourly solar power $p_{\mathcal{SP}}(t)$ is taken to distinguish the sunlight fluctuant nature for a whole year [27]. The output power of wind turbines and batteries are obtained as follows:

$$p_{\mathcal{W}}(t) = \begin{cases} 0 & v(t) < v_c \; or \; v(t) \geq v_o \\ \dfrac{\mathcal{P}_{\mathcal{W}} * (v(t) - v_c)}{v_r - v_c} & v_c \leq v(t) < v_r \\ \mathcal{P}_{\mathcal{W}} & v_r \leq v(t) < v_o \end{cases} \tag{6.29}$$

$$p_{\mathcal{B}}(t) = \begin{cases} p_{\mathcal{B}}(t-1) + \xi_c * \Delta(t-1) & \Delta(t-1) \geq 0 \\ p_{\mathcal{B}}(t-1) + \Delta(t-1) & \Delta(t-1) < 0 \end{cases} \tag{6.30}$$

$$\Delta(t-1) = p_{\mathcal{W}}(t-1) + p_{\mathcal{SP}}(t-1) - \mathcal{P}_{\mathcal{D}}(t-1) \tag{6.31}$$

where $v(t)$ and $\mathcal{P}_{\mathcal{D}}(t-1)$ are wind speed and residential load power in the hour $(t-1)$, respectively. $\Delta(t-1)$ and $\mathcal{P}_{\mathcal{D}}(t-1)$ denotes the difference between the total generation capacity and the electrical load $\mathcal{P}_{\mathcal{D}}(t)$ in hour $t-1$.

The operation and maintenance cost for each player $\mathcal{C}_{j\_OM}$ is found by multiplying its per unit operation and maintenance cost $\mathcal{U}_{j\_OM}$ by its generation capacity $\mathcal{P}_j$. The salvage value for batteries is zero because no positive salvage value can be obtained because the storage batteries are out of work. The annual salvage value $\mathcal{J}_{j\_\mathcal{SL}}$ for generation resources, and initial investment cost $\mathcal{C}_{j\_\mathcal{IN}}$ for the players are calculated as:

$$\mathcal{J}_{j\_\mathcal{SL}} = \mathcal{P}_j * \mathcal{U}_{j\_SV} * \mathfrak{D}/((1+\mathfrak{D})^{\mathbb{L}_j} - 1) \tag{6.32}$$

$$\mathcal{C}_{j\_\mathcal{IN}} = \mathcal{P}_j * \mathcal{U}_j * \mathfrak{D}(1+\mathfrak{D})^{\mathbb{L}_j}/((1+\mathfrak{D})^{\mathbb{L}_j} - 1) \tag{6.33}$$

where $\mathcal{U}_{j\_SV}$, $\mathfrak{D}$, $\mathbb{L}_j$, and $\mathcal{U}_j$ are per unit salvage value, discount rate, life span and per-unit cost for each player, respectively.

The annual cost for purchasing power from the main grid $\mathcal{C}_{j\_\mathcal{P}C}$, and compensation cost for energy cannot be supplied $\mathcal{C}_{j\_\mathcal{ES}}$ for each player can be found using the equations below:

$$\mathcal{C}_{j\_\mathcal{P}C} = \mathcal{C}_{\mathcal{P}C} * \mathcal{P}_j/(\mathcal{P}_{\mathcal{W}} + \mathcal{P}_{\mathcal{SP}} + \mathcal{P}_{\mathcal{B}}) \tag{6.34}$$

$$\mathcal{C}_{\mathcal{PC}} = \sum_{t=1}^{T} \mathbb{E}(t) * \mathcal{P}_{\mathcal{PG}}(t) \tag{6.35}$$

$$\mathcal{C}_{j\_\mathcal{ES}} = \sum_{t=1}^{T} 1.5 * \mathbb{E}(t) * (\mathcal{P}_{\mathcal{UB}}(t) - \mathcal{P}_{\mathcal{PG}}(t)) \tag{6.36}$$

$$\mathcal{P}_{\mathcal{UB}}(t) = \mathcal{P}_{\mathcal{D}}(t) - p_{\mathcal{W}}(t) - p_{\mathcal{SP}}(t) - (p_{\mathcal{B}}(t) - \mathcal{P}_{\mathcal{B}}\_min) \tag{6.37}$$

where $\mathcal{C}_{\mathcal{PC}}$, T, $\mathbb{E}(t)$, $\mathcal{P}_{\mathcal{PG}}(t)$, $\mathcal{P}_{\mathcal{UB}}(t)$, and $\mathcal{P}_{\mathcal{B}}\_min$ total annual cost for purchasing power from the main grid, the total number of hours in a year, electricity price in hour t, purchased power from the main grid in hour t, unbalanced power in a microgrid in hour t and battery minimum state of charge, respectively.

The annual income for power selling $\mathcal{I}_{j\_\mathcal{SE}}$ for wind turbine and solar panels is then calculated as follows:

$$\mathcal{I}_{j\_\mathcal{SE}} = (1+\propto) * \sum_{t=1}^{T} \mathbb{E}(t) * \mathcal{P}_{j\_\mathcal{SE}}(t) \tag{6.38}$$

$$\mathcal{P}_{j\_\mathcal{SE}}(t) = \begin{cases} p_{j}(t) & \mathcal{P}_{\mathcal{SR}}(t) \leq 0 \\ \dfrac{p_{j}(t) * \mathcal{P}_{\mathcal{CN}}(t)}{(p_{\mathcal{W}}(t) + p_{\mathcal{SP}}(t))} & \mathcal{P}_{\mathcal{SR}}(t) > 0 \end{cases} \tag{6.39}$$

$$\mathcal{P}_{\mathcal{CN}}(t) = \mathcal{P}_{\mathcal{D}}(t) + \mathcal{P}_{\mathcal{TC}} + (\mathcal{P}_{\mathcal{B}} - p_{\mathcal{B}}(t)) \tag{6.40}$$

$$\mathcal{P}_{\mathcal{SR}}(t) = p_{\mathcal{W}}(t) + p_{\mathcal{SP}}(t) - \mathcal{P}_{\mathcal{CN}}(t) \tag{6.41}$$

where $\propto$, $\mathcal{P}_{j\_\mathcal{SE}}(t)$, $\mathcal{P}_{\mathcal{CN}}(t)$, $\mathcal{P}_{\mathcal{SR}}(t)$, and $\mathcal{P}_{\mathcal{TC}}$ are subsidy coefficient, players' power capacity selling in hour t, the maximum power consumed in hour t, the capacity of surplus power in hour t, and the transmission line capacity between the microgrid and the main grid, respectively.

The annual income from selling power $\mathcal{I}_{\mathcal{B}\_\mathcal{SE}}$ and ancillary income $\mathcal{I}_{\mathcal{B}\_\mathcal{AS}}$ for batteries are obtained as follows:

$$\mathcal{I}_{\mathcal{B}\_\mathcal{SE}} = (1+\propto) * \sum_{t=1}^{T} \mathbb{E}(t) * \mathcal{P}_{\mathcal{B}\_\mathcal{SE}}(t) \tag{6.42}$$

$$\mathcal{P}_{\mathcal{B}\_\mathcal{SE}}(t) = \begin{cases} \Delta \mathcal{p}_{\mathcal{B}}(t) & \Delta \mathcal{p}_{\mathcal{B}}(t) > 0 \\ 0 & \Delta \mathcal{p}_{\mathcal{B}}(t) \leq 0 \end{cases} \tag{6.43}$$

$$\mathcal{J}_{\mathcal{B}\_\mathcal{AS}} = \Re \sum_{t=1}^{T} \left(\mathcal{p}_{\mathcal{B}}(t) - \mathcal{P}_{\mathcal{B}\_\mathcal{SE}}(t) - \mathcal{P}_{\mathcal{B}\_min} \right) \tag{6.44}$$

where $\mathcal{P}_{\mathcal{B}\_\mathcal{SE}}(t)$, and $\Delta \mathcal{p}_{\mathcal{B}}(t)$ represent batteries' power selling capacity in hour t, and change in battery capacity in hour t, respectively.

For each player, the final value of the annual profit not only depends on the player's own parameters but on other players' too. Because three different players are involved in achieving the maximum profit, the cost allocation scheme proportional to the players' capacity is adopted to ensure fair and reasonable cost allocation among the players. Similarly, the maximum annual profit for the clustered microgrid $\mathcal{PF}_{CMG}$ consisting of three different microgrids is calculated as follows:

$$\mathcal{PF}_{CMG\_P2G} = Max\ (\mathcal{PF}_{MG\_1} + \mathcal{PF}_{MG\_2} + \mathcal{PF}_{MG\_3}) \tag{6.45}$$

where $\mathcal{PF}_{MG\_1}$, $\mathcal{PF}_{MG\_2}$, and $\mathcal{PF}_{MG\_3}$ are the annual profit values for microgrid 1, microgrid 2 and microgrid 3, in the grid-connected mode and the case of peer-to-grid (P2G) energy trading, respectively. For the P2G energy trading, the cash flow direction is in the opposite direction of the power flow.

If n is the sequence number for each microgrid, and m represents the total number of microgrids in a clustered microgrid, then its annual profit is found as:

$$\mathcal{PF}_{CMG\_P2G} = \ Max(\sum_{n=1}^{m} \mathcal{PF}_{MG\_n})\ n \in \{1, 2, 3, \dots, m\} \tag{6.46}$$

In the case of peer-to-peer (P2P) energy trading, all three microgrids work as prosumers PR, and are not only connected with one another, but are also linked with the main grid. Therefore, they not only can perform energy trading between the prosumers but also to the main grid, based on residential load requirements. Figure 6.9 illustrates the power and cash flow between two different prosumers and the grid-connected for the P2P energy trading. P2P energy trading became more popular than the traditional P2G energy trading due to its ability to buy or sell power among the prosumers and with the main grid. P2P energy trading encourages prosumers to exchange power with one another so that the players have the opportunity to achieve higher income and lower cost, which will increase the overall profit of the entire architecture.

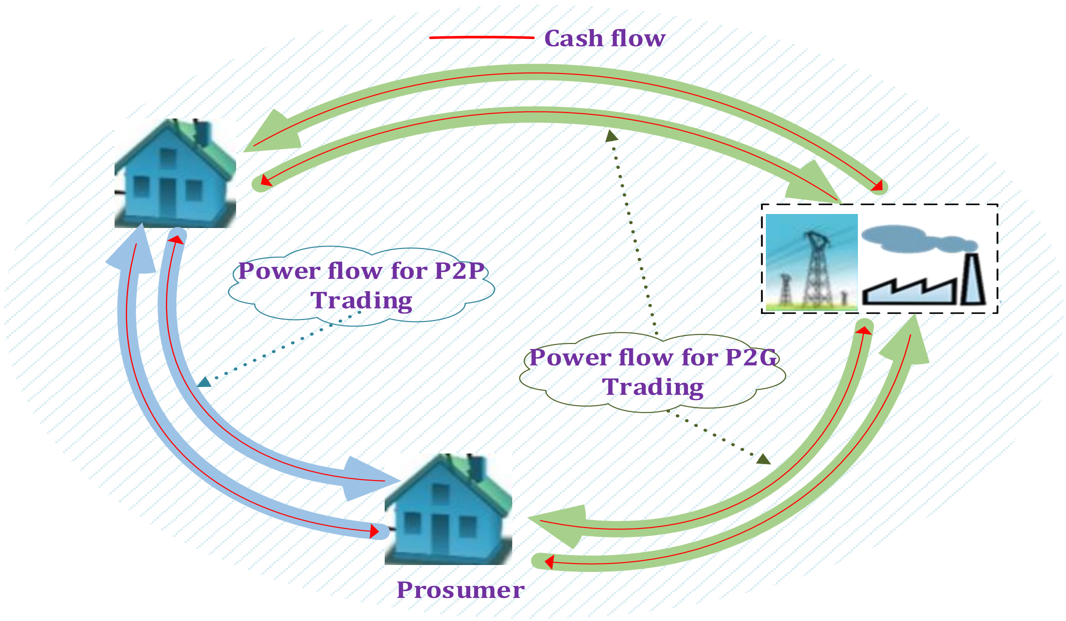


Figure 6.9 Power and cash flow for P2G and P2P energy trading between the prosumers and the main grid

The annual values of $\mathcal{I}_{j\_\mathcal{SL}}$, $\mathcal{I}_{j\_\mathcal{AS}}$, $\mathcal{C}_{j\_\mathcal{IN}}$, $\mathcal{C}_{j\_\mathcal{OM}}$, and $\mathcal{C}_{j_\mathcal{ES}}$for P2P energy trading are obtained in the same way as was calculated for P2G energy trading. However, the calculations for $\mathcal{I}_{j\_\mathcal{SE}}$ and $\mathcal{C}_{j\_\mathcal{PC}}$ is different. In P2P energy trading, the priority is to sell generated power $\mathcal{P}_{j\_\mathcal{SE}}(t)$ to the connected load; the second priority is the selling of remaining power to the nearest prosumer in the loop, on agreed P2P price $\mathbb{E}_{P}$; and last, the remaining power is sold to the main grid on P2G price $\mathbb{E}_{SG}$. On the other hand, in the case of P2P energy trading, if the generated power is not enough for a connected load, then first, power is purchased from the nearest prosumer at agreed $\mathbb{E}_{P}$. Second, if there is a shortage of generated power, then it is purchased for any other prosumer within a loop; and last, the power is purchased from the main grid at P2G price $\mathbb{E}_{PG}$ to meet the load requirements. The maximum annual profit for a clustered microgrid in the case of P2P energy trading is expressed as follows:

$$\mathcal{P}F_{CMG\_P2P} = Max\ (\mathcal{P}F_{PR\_1} + \mathcal{P}F_{PR\_2} + \mathcal{P}F_{PR\_3}) \qquad (6.47)$$

Figure 6.10 shows the architecture if n number of microgrids are connected in grid-connected mode, and the annual profit of clustered microgrid is found as:

$$\mathcal{P}F_{CMG\_P2P} = \ Max(\sum_{n=1}^{m} \mathcal{P}F_{PR\_n})\ n \in \{1, 2, 3, \dots, m\} \qquad (6.48)$$

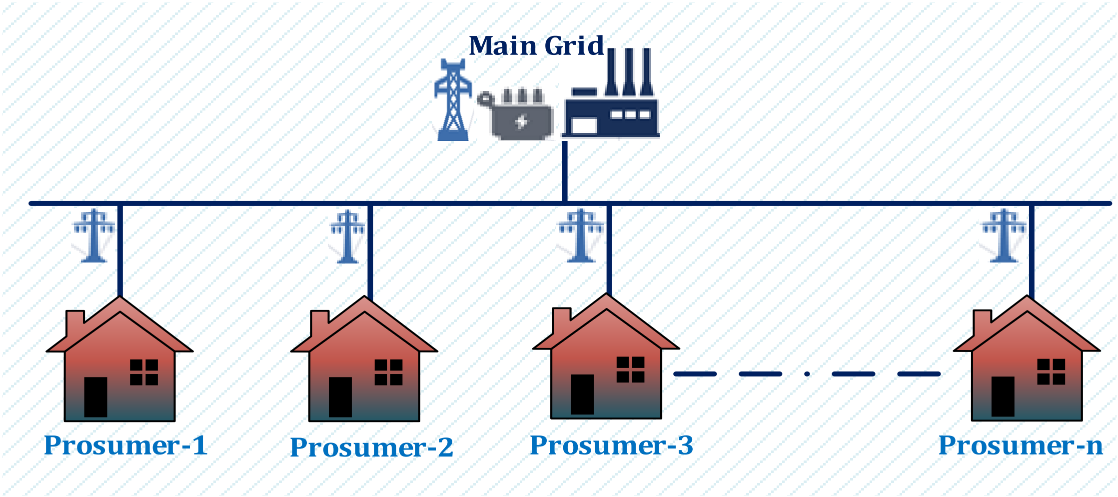


Figure 6.10 The architecture for n number of prosumers

B. LPSP as Objective Function

The idea of loss of power supply probability $LPSP$ is used in many studies to design the sizing and evaluation of hybrid power systems [83]. One of the probability definitions to illustrate system architecture's reliability is a loss of power supply probability. This is the probability that an inadequate power supply produces when the generation resources (wind turbines and solar panels) and batteries are unable to meet load requirements. The annual $LPSP$ is minimised to obtain its optimum value ($0 < LPSP < 1$) and is calculated as follows for a microgrid:

$$LPSP_{MG\_1} = Min(\sum_{t=1}^{T} H(\ \mathcal{P}_{supp}(t) < \mathcal{P}_{need}(t))/T) \qquad (6.49)$$

where $\mathcal{P}_{supp}(t)$, $\mathcal{P}_{need}(t)$, and H are the total power supplied in hour t, the total power needed in hour t, and the number of hours when $\mathcal{P}_{supp}(t) < \mathcal{P}_{need}(t)$, respectively. The $\mathcal{P}_{need}(t)$ by the load side can be calculated as:

$$\mathcal{P}_{need}(t) = \mathcal{P}_{\mathcal{D}}(t)/\mathcal{E}_{invertor} \tag{6.50}$$

where $\mathcal{E}_{invertor}(t)$ is the inverter efficiency and considered as 92% [17]. The $\mathcal{P}_{supp}(t)$ for a microgrid is found as follows:

$$\mathcal{P}_{supp\_MG}(t) = p_{\mathcal{W}}(t) + p_{\mathcal{SP}}(t) + (p_{\mathcal{B}}(t) - \mathcal{P}_{\mathcal{B}}\_min) \tag{6.51}$$

Similarly, $LPSP$ is obtained for the clustered microgrid. In the case of P2G energy trading, if the difference of supplied and needed power is positive, then additional power is sent to the main grid. Otherwise, if the difference is negative, a power shortage is provided from the main grid. The annual $LPSP$ of the clustered microgrid for P2G energy trading is expressed as:

$$LPSP_{\mathrm{CMG}\_P2G} = Min\ (\sum_{n=1}^{m} LPSP_{MG\_n})/m\ n \in \{1, 2, \dots, m\} \tag{6.52}$$

In contrast, in P2P energy trading, if the difference between supplied and needed power is positive, the additional power first is sold to any of the connected prosumers who are experiencing a power shortage. Any remaining power after selling power to the neighbouring microgrids is sent to the main grid. Otherwise, if the difference is negative, the power shortage is initially fulfilled through any connected prosumer that generates excess power. If the neighbouring microgrids are not able to provide the shortage of power, it is provided by the main grid. The annual $LPSP$ of the clustered architecture for P2P energy trading is calculated as:

$$LPSP_{\mathrm{CMG}\_P2P} = Min\ (\sum_{n=1}^{m} LPSP_{PR\_n})/m)\ n \in \{1, 2, \dots, m\} \tag{6.53}$$

C. Multi-Objective Function

Multi-objective optimisation is exploited when several objective functions need to be met simultaneously in a power system. In [17], a hybrid power system is designed based on multi-objective optimisation techniques in the grid-connected mode where the objectives are costs, reliability and pollutant emissions. In [84] the multi-objective optimisation is proposed based on environmental and economic conditions for hybrid energy systems by the genetic algorithm, and advantages of single- and multi-objective optimisation are discussed. In this research, the annual profit and loss of power supply probability are the criteria for designing a multi-objective model. For this aim, a cooperative game theory technique is used to obtain optimum values. The flow of the proposed multi-objective function is illustrated in Figure 6.11.

For the clustered microgrid as shown in Figure 6.3, the minimum payoff value of the multi-objective function MOF_{CMG} is calculated as follows:

$$MOF_{\mathrm{CMG}} = Min\ [\Psi * \mathcal{P}F_{PU} + \varpi * LPSP_{PU}] \tag{6.54}$$

where Ψ, $\mathcal{P}F_{PU}$, ϖ, and $LPSP_{PU}$ are the constant-coefficient for profit, per unit value of annual profit, constant coefficient of $LPSP$, and per unit value of $LPSP$. The range of constant coefficients Ψ and ϖ are 0< Ψ <1 and 0< ϖ <1, respectively.

The per-unit value $LPSP_{PU}$ is the same as calculated for clustered microgrid $LPSP_{\mathrm{CMG}}$. However, the per-unit value $\mathcal{P}F_{PU}$ is calculated by dividing the annual $\mathcal{P}F_{CMG}$ for the clustered microgrid by the nominal value of annual profit $\mathcal{P}F_{NOM}$. In the optimisation process, both coefficients Ψ and ϖ are used to normalise the results of the objective function.

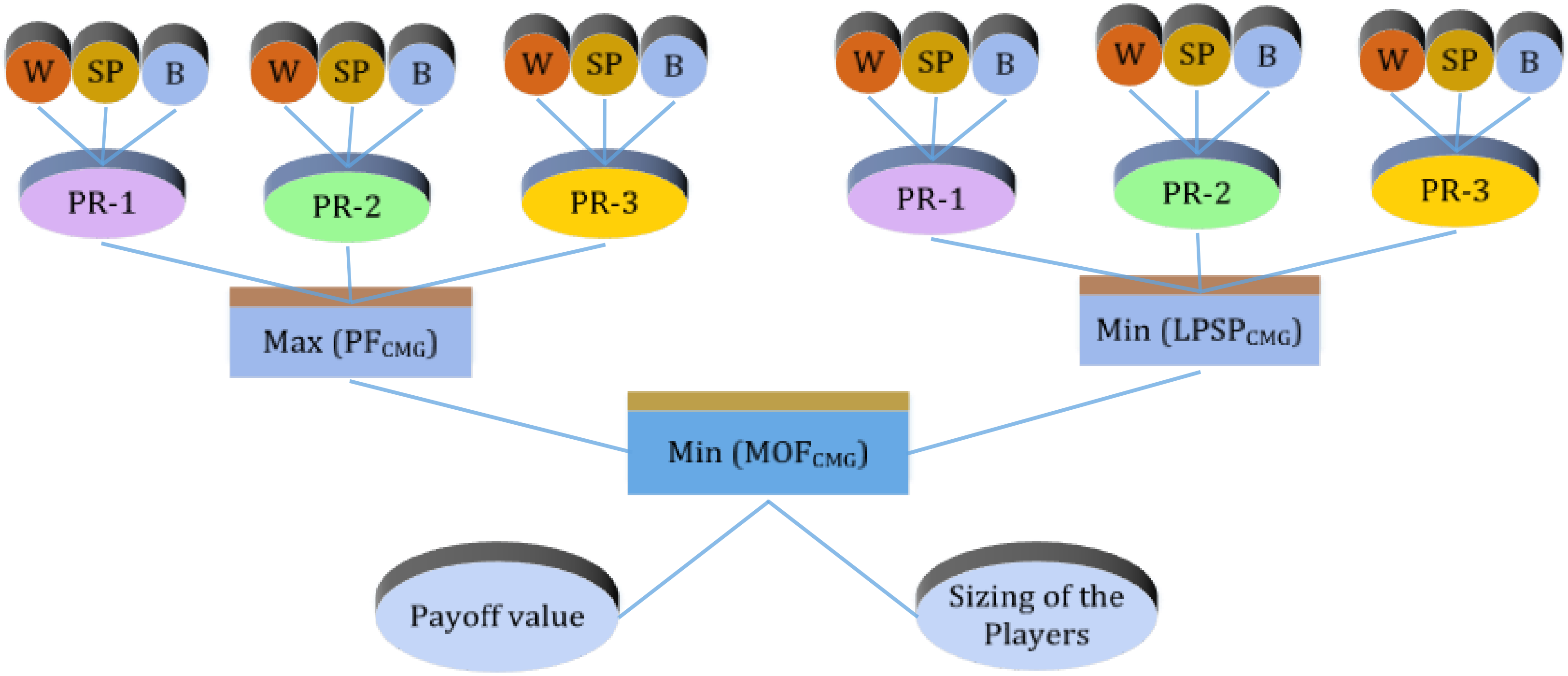


Figure 6.11 The flow for multi-objective optimisation for clustered microgrid

6.4.2 The Nash Equilibrium

In general, game theory is very useful for finding solutions to different problems and performing optimisation in modern fields. It is a decision-making approach in which multiple game players are looking for the optimum value of payoff and to fix different kinds of conflicts. The game model players can reach the optimum value of payoff either by cooperating or in a competition-based non-cooperating way. In the case of a non-cooperative game, each player decides to optimise its payoff [85]. However, in a cooperative game, the players work in different feasible coalitions and cooperate with other players in a way that the optimum value of all players' payoff is simultaneously obtained. According to [58] and [62], cooperative game models are more profitable than non-cooperative models. If the number of players is more than two, multi-coalitions can be defined. In this case, the profit occurs when all the players cooperate with other players and are in one coalition. Therefore, in this chapter, one of the cooperative game techniques, the Nash equilibrium, is used and considered only when all the players are cooperating with one another in a single coalition to achieve optimum payoff values.

If three players are cooperating, then four different kinds of coalitions are possible; that is, two players are cooperating, and the third one is self-dependent (because for three players it can occur in three different ways), and there is cooperation when all three players are in a coalition. To design a clustered microgrid, the cooperative game technique Nash equilibrium is used in each microgrid and implemented for the case where all three players, including solar panels, wind turbines and batteries are cooperating in one coalition. The Nash equilibrium technique is explained through a flow chart in Figure 6.12, to show how all the three players $\mathcal{W}$, $\mathcal{SP}$ and $\mathcal{B}$ are cooperating with one another to reach the optimum sizes of the players at the Nash equilibrium point $(\mathcal{P}_{\mathcal{W}}^{*}, \mathcal{P}_{\mathcal{SP}}^{*}, \mathcal{P}_{\mathcal{B}}^{*})$, and the final value of the payoff.

The simulation model for the clustered microgrid is designed in MATLAB software based on the Nash equilibrium technique and implemented using a modified PSO algorithm. Different optimisation algorithms are employed, such as harmony search (HS), artificial bee colony, cuckoo search (CS), imperialist competitive algorithm (ICA) [86], genetic algorithm [84] gravitational search algorithm [87] and so on. PSO is more commonly used in various research areas to solve different kinds of optimisation problems [74, 76]. In the simulation model to reach optimum sizes of generation resources and batteries, and final payoff values, the maximum number of iterations are 250 and the population size of 100, are selected. The condition for the game theory technique is also applied at the end of every optimisation to verify when the capacities of generation resources and batteries reach the Nash equilibrium and payoff meets its final value.

6.4.3 Results and Analysis

To evaluate the feasibility of the proposed game-theoretical model, the realistic weather forecast and residential load profiles are considered for three different towns: Laverton, Mount Magnet and Wahroonga, and the annual profiles of the towns are utilised for three grid-connected microgrids, respectively. The simulation model is coded in MATLAB software based on a computation method called particle swarm optimisation (PSO), and input parameters [77] are considered, as shown in Appendix A Table A.1 to optimise the objective functions. To validate the results from the proposed multi-objective function, the clustered microgrid is first analysed when the objective functions annual profit and loss of power supply probability are optimised independently. Then, both objectives are optimised under a multi-objective function. In both scenarios, the clustered architecture is simulated for energy trading schemes P2G and P2P, so that the optimum sizes of the players and their best payoff values of the objective functions are achieved.

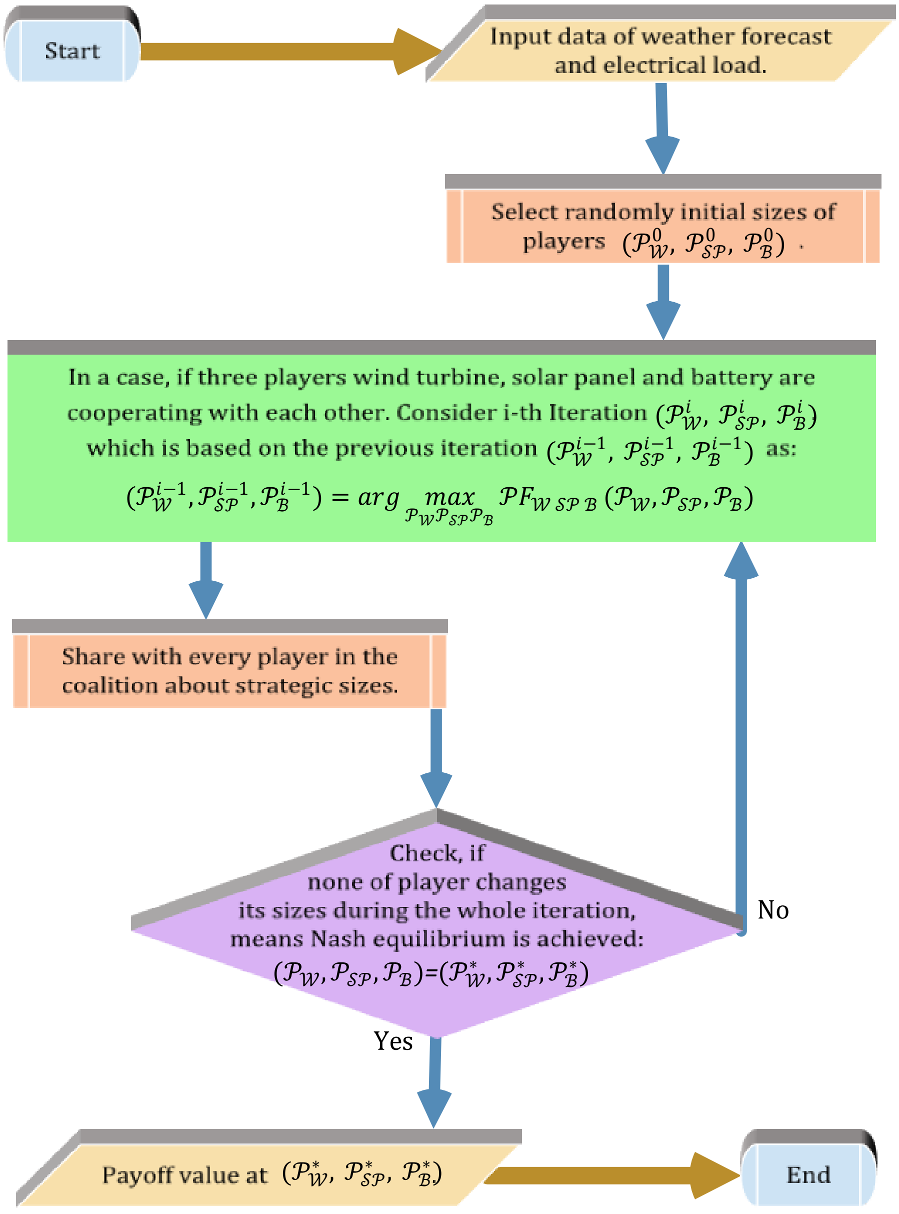


Figure 6.12 Flow chat of game theory technique Nash Equilibrium

A. Optimisation of Single Objective Functions

First, optimisation is performed with respect to the objective function $\mathcal{PF}$ of the clustered microgrid. The optimum sizes of generation resources and batteries $(\mathcal{P}_{\mathcal{W}}^{*}, \mathcal{P}_{\mathcal{SP}}^{*}, \mathcal{P}_{\mathcal{B}}^{*})$ are found for the architectures to maximise the payoff $\mathcal{PF}$ value, and then the minimum value of $LPSP$ is obtained based on the optimised sizes of the players. This simulation process is carried out for both P2G and P2P energy trading schemes, and the results are finally compared. Table 6.5 illustrates the results when optimisation is implemented to reach the Nash equilibrium point based on the objective function $\mathcal{PF}$ for both P2G and P2P energy trading schemes. As can be seen, in the case of P2P energy trading, a higher payoff is obtained due to the power exchange between the neighbouring prosumers which impose a lower purchasing cost in comparison with a P2G energy trading scheme.

Second, the $LPSP$ index is taken as an objective function to find the payoff values for both energy trading schemes. Table 6.6 shows the results when the objective function $LPSP$ is optimised, and the optimum capacities of the players ($\mathcal{P}_{\mathcal{W}}^*, \mathcal{P}_{\mathcal{SP}}^*, \mathcal{P}_{\mathcal{B}}^*$) are calculated at the Nash equilibrium point for the microgrids connected with three different towns, respectively. As can be seen, the P2P energy trading scheme enjoys better reliability and payoff in comparison to the P2G through having a multi-directional power flow in the P2P energy trading scheme that leads to a lower possibility of losing power supply.

Table 6.5 Results for optimising $\mathcal{PF}_{CMG}$ as objective function

Optimum Sizes of the Players				
Coalition	Towns	$\mathcal{P}_{\mathcal{W}}^*$ (kW)	$\mathcal{P}_{\mathcal{SP}}^*$ (kW)	$\mathcal{P}_{\mathcal{B}}^*$ (kW)
$\{\mathrm{W}, \mathrm{SP}, \mathrm{B}\}$	Laverton	880	446	340
	Mount Magnet	910	593	301
	Wahroonga	850	464	318
Payoff Values of Objection Function				
Coalition	Objective Functions		P2G Trading	P2P Trading
$\{\mathrm{W}, \mathrm{SP}, \mathrm{B}\}$	$\mathcal{PF}_{CMG}$ ($/year)		1.4869e+9	1.4873e+9
	$LPSP_{\mathrm{CMG}}$ (p.u.)		0.5135	0.4288

Table 6.6 Results for optimising $LPSP_{\mathrm{CMG}}$ as an objective function

Optimum Sizes of the Players				
Coalition	Towns	$\mathcal{P}_{\mathcal{W}}^{*}$ (kW)	$\mathcal{P}_{\mathcal{SP}}^{*}$ (kW)	$\mathcal{P}_{\mathcal{B}}^{*}$ (kW)
$\{\mathrm{W}, \mathrm{SP}, \mathrm{B}\}$	Laverton	900	525	338
	Mount Magnet	946	533	370
	Wahroonga	840	521	287
Payoff Values of Objection Function				
Coalition	Objective Functions		P2G Trading	P2P Trading
$\{\mathrm{W}, \mathrm{SP}, \mathrm{B}\}$	$\mathcal{P}F_{CMG}$ ($/year)		1.5038e+9	1.5042e+9
	$LPSP_{\mathrm{CMG}}$ (p.u.)		0.5104	0.4259

The results illustrate the players' optimum capacities at the Nash equilibrium point under the cooperative game model, which clearly indicates that the wind turbine has the most contribution; whereas batteries have the smallest capacities in the planning of the clustered microgrid. This fact, $\mathcal{P}_{\mathcal{W}}^{*} > \mathcal{P}_{\mathcal{SP}}^{*} > \mathcal{P}_{\mathcal{B}}^{*}$, is valid for all three prosumers. The selected towns in Australia have good profiles for wind speed and solar radiation; therefore, wind turbines and solar panels are larger in size and the load on batteries is at a minimum. This encourages the use of clustered microgrids to reduce the loss of power supply probability, and as a result, improve reliability. It also leads to relieving the electrical load burden on the main grid, which finally results in a better voltage profile, especially in peak times. As shown in Figure 6.13, the payoff value of the annual profit is higher when P2P energy trading is considered. The annual loss of power supply probability is also reduced for P2P energy trading for optimisation of the single objective function (SOF).

Table 6.7 **Results for the multi-objective function MOF_{CMG}**

No#	Optimum Sizes of the Players									Payoff Values				
	Prosumer 1			Prosumer 2			Prosumer 3			MOF_{CMG}		P2G Trading	P2P Trading	
	$\mathcal{P}_{\mathcal{W}}^*$ (kW)	$\mathcal{P}_{\mathcal{SP}}^*$ (kW)	$\mathcal{P}_{\mathcal{B}}^*$ (kW)	$\mathcal{P}_{\mathcal{W}}^*$ (kW)	$\mathcal{P}_{\mathcal{SP}}^*$ (kW)	$\mathcal{P}_{\mathcal{B}}^*$ (kW)	$\mathcal{P}_{\mathcal{W}}^*$ (kW)	$\mathcal{P}_{\mathcal{SP}}^*$ (kW)	$\mathcal{P}_{\mathcal{B}}^*$ (kW)	(p.u.)	$\mathcal{PF}_{CMG}$ ($/year)	$LPSP_{\text{CMG}}$ (p.u.)	$\mathcal{PF}_{CMG}$ ($/year)	$LPSP_{\text{CMG}}$ (p.u.)
1	713	577	377	930	433	217	705	324	233	0.765309	1.1327e+9	0.5308	1.3320e+9	0.4708
2	855	685	424	813	433	217	691	410	233	0.762723	1.2857e+9	0.5255	1.2868e+9	0.4517
3	701	604	425	930	433	216	706	324	233	0.765671	1.1232e+9	0.5315	1.1237e+9	0.4722
4	756	686	356	930	433	317	706	365	233	0.763845	1.1803e+9	0.5278	1.1808e+9	0.4632
5	885	634	425	912	433	299	706	324	233	0.759484	1.3436e+9	0.5191	1.3441e+9	0.4430
6	825	686	339	930	433	311	706	324	233	0.761331	1.3437e+9	0.5182	1.3441e+9	0.4430
7	766	623	424	930	433	217	707	349	233	0.763406	1.1914e+9	0.5269	1.1919e+9	0.4616
8	725	518	410	799	433	217	706	337	233	0.767594	1.2129e+9	0.5309	1.2134e+9	0.4610
9	765	686	366	743	433	293	706	324	248	0.767521	1.1897e+9	0.5352	1.1902e+9	0.4651
10	736	686	393	930	433	332	706	324	236	0.764625	1.1586e+9	0.5294	1.1591e+9	0.4663
11	725	588	424	892	516	217	706	324	233	0.765767	1.1468e+9	0.5316	1.1473e+9	0.4686
12	733	685	379	768	433	328	705	325	233	0.768282	1.1538e+9	0.5366	1.1544e+9	0.4698
13	762	537	424	782	432	342	706	341	233	0.766623	1.1865e+9	0.5333	1.1870e+9	0.4646
14	884	653	335	863	433	217	706	377	280	0.760456	1.3420e+9	0.5210	1.3425e+9	0.4442
15	885	603	392	909	433	216	738	491	308	0.758801	1.3766e+9	0.5177	1.3770e+9	0.4398
16	886	558	425	927	621	348	791	422	293	0.757203	1.4329e+9	0.5144	1.4334e+9	0.4336

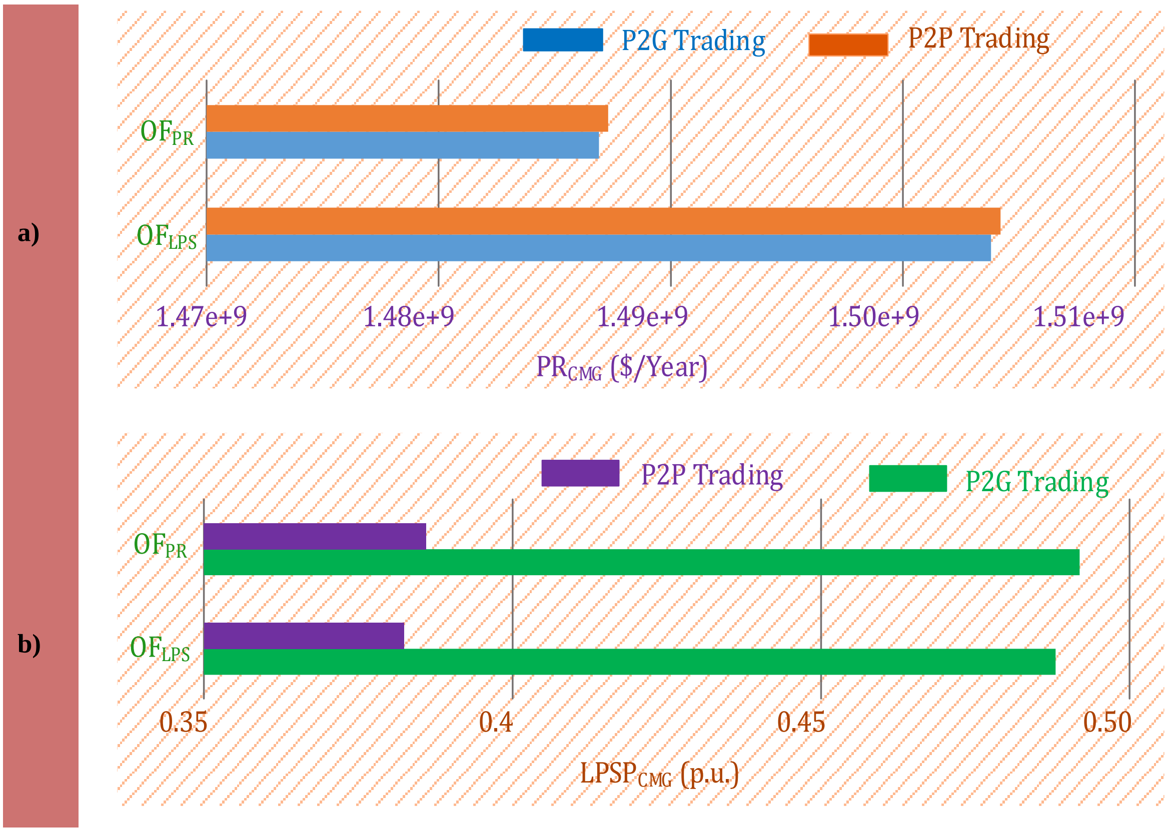


Figure 6.13 Payoff values of a) PR_{CMG}, and b) $LPSP_{CMG}$ for optimisation of *SOF* under P2G and P2P trading

B. Optimisation of the Multi-Objective Function

To improve the design for the proposed clustered microgrid, a technique of multi-objective function (MOF) is considered based on two objective functions, including $\mathcal{PF}$ and $LPSP$, respectively. In the game model, to reach the Nash equilibrium points for the players' optimum values and achieve the most feasible payoff values, both objective functions $\mathcal{PF}$ and $LPSP$ are optimised together. The simulation model is run for 250 iterations to find suitable results. The best 16 iterations, including highlighted possible optimum results at minimum values 0.757203 p.u. of MOF, are illustrated in Table 6.7 to explain multi-objective function (MOF) outcomes. In the case of multi-objective optimisation at the Nash equilibrium point, the optimised sizes of the players ($\mathcal{P}^*_{\mathcal{W}}, \mathcal{P}^*_{\mathcal{SP}}, \mathcal{P}^*_{\mathcal{B}}$) are listed for the clustered microgrid. When the system model is designed for P2G energy trading, the payoff values of objective functions $\mathcal{PF}$ and $LPSP$ are 1.4329e+9 and 0.5144, respectively, and for P2P energy trading, the outcomes of objective functions $\mathcal{PF}$ and $LPSP$ are 1.4334e+9 and 0.4336, respectively.

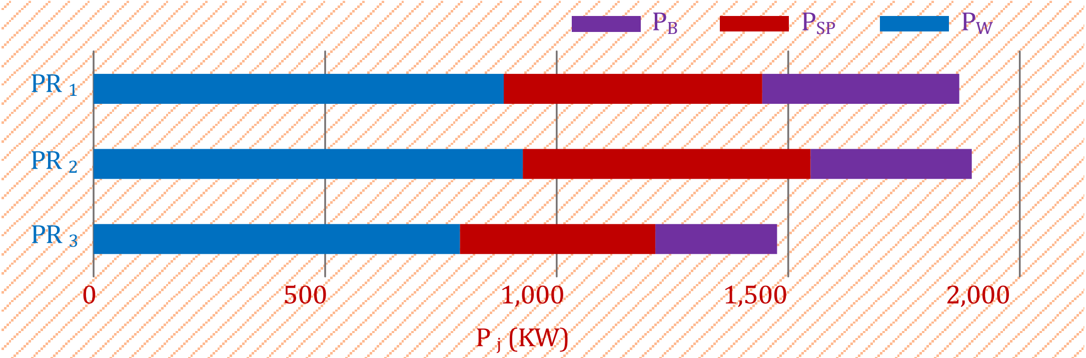


Figure 6.14 Optimum sizes of the players for multi-objective function

In the case of multi-objective optimisation, a similar trend $\mathcal{P}_{\mathcal{W}}^{*} > \mathcal{P}_{\mathcal{SP}}^{*} > \mathcal{P}_{\mathcal{B}}^{*}$ of players' sizes validate the optimum results at the Nash equilibrium point. As shown in Figure 6.14, with respect to each prosumers' residential load requirement, the total capacity of the players for prosumer 2 (PR_2) is larger than PR_1, and PR_3 is the smallest in size. Because $\mathcal{PF}$ is a maximising function and $LPSP$ is a minimising function, therefore, in the results of MOF, compared to P2G energy trading, the value of $\mathcal{PF}$ is more massive, and $LPSP$ is smaller in the case of P2P energy trading, and this justifies the economic benefit to connecting all the microgrids in a clustered architecture.

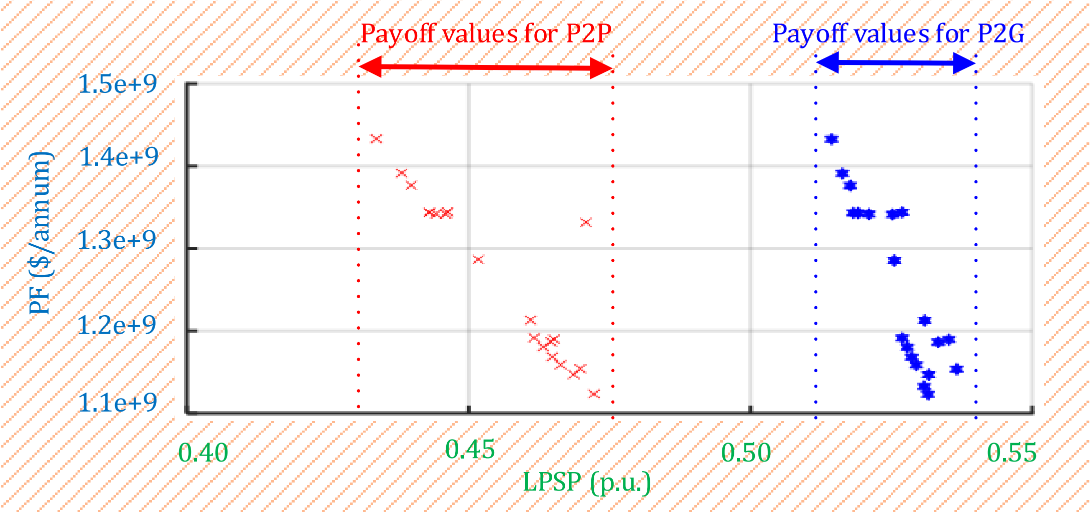


Figure 6.15 Payoff values of multi-objective function for a clustered microgrid under P2G and P2P energy trading

Figure 6.14 shows the comparative analysis of multi-objective optimisation for both objective functions $(LPSP, \mathcal{PF})$ when a clustered architecture is designed for P2G and P2P energy trading schemes. The graph illustrates the positions for objective functions $(LPSP, \mathcal{PF})$ for 16 different iterations. For the similar sizes of a clustered microgrid, the trend justifies that the values of maximising function $\mathcal{PF}$ are larger for P2P energy trading, and the values of minimising function are smaller for P2P energy trading. The results reveal that if the clustered microgrid is designed using P2P energy trading, the architecture's annual profit increases and the loss of power supply probability reduces for the selected towns of Australia.

6.5 Summary

A technique of multi-objective optimisation is used for the planning of a multiple microgrids in an architecture based on P2G and P2P energy trading schemes. Different criteria including annual profit, energy index of reliability and loss of power supply probability are considered to form a multi-objective function. 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 optimisation algorithm is used to model the networked microgrid, and to find the suitable sizes of the players that simultaneously maximise the payoff values of both objective functions. A comparative analysis is also carried out for both P2G and P2P energy trading schemes to validate the optimisation results.

The results confirm, first, the sizes of the players in each prosumer is concerning its residential load requirements; second, the capacity allocation among the players in clustered microgrid justify the trend $\mathcal{P}^*_{\mathcal{W}} > \mathcal{P}^*_{\mathcal{SP}} > \mathcal{P}^*_{\mathcal{B}}$ [58]; third, the outcomes of both objective functions have prime payoff values for P2P energy trading compare to P2G trading; and last, that the proposed multi-objective function optimise objective functions annual profit, energy index of reliability and loss of power supply probability, and give most suitable results for a clustered microgrid.

Chapter 7 Conclusions and Recommendations

This chapter summarises the main findings of the thesis. Some recommendations for future studies in this area are also introduced here.

7.1 Conclusions

The research presented in this thesis focuses on the design of different hybrid power systems based on various game theory techniques, and the key objectives are achieved based on single-object and multi-object optimisation. Different criteria are used for the optimisation, and their outcomes are analysed and compared for validation. To improve the efficiency, reliability and overall profit of the power system, the approaches of microgrid clustering and peer-to-peer energy trading are used. Multiple computation methods are used to make a simulation model in MATLAB software based on the optimisation problems.

7.2 Summary of Contributions

Chapter 2

- Proposed a hybrid power system, which is the combination of renewable energy resources including wind turbines, photovoltaic panels and batteries to meet the electrical load requirement in grid-connected mode.
- Cooperative and non-cooperative game models are designed, and results showed that the payoff values are optimum when all the players are in a single coalition and cooperating with one another.
- The results are validated through sensitivity analysis for electricity price and discount rate.
- In the end, the results of the proposed hybrid power system are compared with one of the existing research models and it confirms the feasibility of the proposed hybrid power system.

Chapter 3

- Achieved a suitable capacity allocation of generation resources and batteries with a game theory technique Nash equilibrium.
- The annual maximum profit of the power system is obtained through Shapely values, and comparative analysis is performed between the game theory techniques and values of maximum profit.
- In this analysis, a cooperative game model is considered where all the players are in the coalition through different combinations. It is clear from the results of the Nash equilibrium that the value of annual profit is higher when all the players of the game model are in coalition with one another, and suitable sizes of generation resources and batteries are proposed.
- The results of Nash equilibrium are further compared with Shapley values, and the results of higher annual profit for each microgrid are shown. It is also illustrated for Shapley values that distribution of the annual profit among the generation resources and batteries is fair for every possible coalition with respect to the players' contribution.
- The annual profit of each microgrid is maximum and feasible when cooperative game theory Shapely values are used. In the end, the sensitivity analysis validated the results of a networked microgrid and checked the influence on decision variables of generation resources and batteries for both game theory techniques.

Chapter 4

- Performed the planning of a clustered microgrid using a cooperative game theory technique called the Nash bargaining solution, and addressed the maximising of profit and determining of the optimum capacity of individual microgrids' components. It is found that the careful selection of the players in a game formation for annual profit is at a maximum when wind turbines and solar panels are considered as players in a coalition to achieve the Nash bargaining solution.
- The values of annual profit are lower for all the other combinations of cooperative game models. In this research, the optimum capacity allocation of generation resources to meet the load requirements, under stochastic weather condition for the planning of the clustered microgrid are guaranteed, which can

be significantly useful for microgrid owners or utility companies to maximise their profit.

- The results are confirmed by the sensitivity analysis of electricity price and discount rate. The trend of profit values guarantees the theoretical basis for the capacity allocation of each generation source and annual profit for the clustered microgrid.

Chapter 5

- Designed a multi-objective optimisation based on the game theory technique for the optimum sizing of the players in order to achieve the optimum payoff values of the multi-microgrids system. The two benchmarks, LCOE and the I_R, are defined, and the optimisation is performed for single-object and multi-objective functions.
- The results illustrated that optimization of the multi-objective function gave the optimum payoff values compared to the single-object function.
- The sizes of the players justified that the total contribution of the players in each microgrid is compatible with its residential load requirement.
- The capacity allocation of the players is further verified with the symmetrical trend $P^*_{WT} > P^*_{PP} > P^*_{SB}$ for both types of optimisation.

Chapter 6

- Developed a multi-objective optimisation for the optimum sizing of renewable energy resources to achieve the maximum payoff values from a clustered microgrid. The architecture is designed based on a game theory technique for both P2P and P2G energy trading schemes. The criteria of APF, EIR and $LPSP$ are considered for the optimisation of multi-objective function.
- The results are compared for both single-objective and multi-objective optimisation. The outcomes showed that the payoff values are best when both criteria are considered simultaneously as multi-objective function.
- The sizes of the players are most suitable after the multi-objective optimisation.
- The sizes of the players are verified because their trend is symmetrical $\mathcal{P}^*_{\mathcal{W}} > \mathcal{P}^*_{\mathcal{SP}} > \mathcal{P}^*_{\mathcal{B}}$ in all the payoff values of P2P and P2G energy trading.
- The sensitivity analysis has verified the feasibility of formulated multi-objective function for the clustered microgrid.

7.3 Recommendations for Future Work

Based on the contribution from this research, the points below are suggested as potential future areas of study:

1. The proposed power system models consist of single, two and three sets of microgrids that can be improved to include a greater number of microgrids to design a typical power system.
2. The limited technical parameters and uncertainties are taken into account, and the proposed models can be improved with consideration of transmission line parameters and more criteria can be analysed as objective functions.
3. Peer-to-peer energy trading can also be modelled and compared for game theory techniques, such as the bargaining game, Stackelberg game, the evolutionary game and the Bayesian Nash equilibrium models.
4. This thesis focused on one year load and weather forecast data, and accordingly, the models can be improved with input data equal to the life of the components to achieve more realistic results.
5. The game models can be further proposed for P2P energy trading based on an approach of a transactive energy management system where multiple players can control the energy trading.
6. The renewable energy systems can be further modelled and formulated based on i-framework and can be validated using a Monte-Carlo principle.
7. P2P energy trading can further analysed and implemented based of Blockchain technology and can be modelled based on advanced optimization techniques.

Appendix A

Table A.1 Input parameters

Parameters	Values (Units)	Parameters	Values (Units)
Electricity price	\$0.12/kWh	Wind turbine operation and maintenance cost	\$20/(kW.year)
Discount rate	12%	Wind turbine salvage value	\$77/kW
Cut-in wind speed	3 m/s	Solar panel price	\$1890/kW
Cut-out wind speed	20 m/s	Life span of solar panel	20 Years
Rated wind speed	12 m/s	Solar panel operation and maintenance cost	\$20/(kW.year)
Electricity price between peer-to-peer trading [88]	\$0.15/kWh	Solar panel salvage value	\$189/kW
Electricity selling price to the main grid [89]	\$0.10/kWh	Life span of battery	10 Years
Electricity purchasing price from the main grid [90]	\$0.28/kWh	Price of battery	100 \$/kW
Life span of wind turbine	20 Years	Battery operation and maintenance cost	\$1/(kW.year)
Price of wind turbine	770 \$/kW	Battery minimum state of charge	50 W

Table A.2 Attribution statement

Paper numbers and titles	% Total Contributions			
	Co-Author 1 (S.M. Muyeen)	Co-Author 2 (Arindam Ghosh)	Co-Author 3 (Marcelo G. Simoes)	Co-Author 4 (Hamed Bizhani)
Paper 1 Comparative Study on Game-Theoretic Optimum Sizing and Economical Analysis of a Networked Microgrid.	10%	5%	-	5%
Paper 2 Optimal sizing of a networked microgrid using Nash equilibrium for mount magnet.	10%	5%	-	5%
Paper 3 Optimal planning of Clustered Microgrid using a Technique of Cooperative Game Theory.	10%	5%	-	5%
Paper 4 A Peer-to-peer Energy Trading for a Clustered Microgrid – Game Theoretical Approach.	10%	5%	-	5%
Paper 5 A Multi-objective Optimization for Planning of Networked Microgrid using a Game Theory for P2P Energy Trading Scheme.	10%	5%	-	5%
Paper 6 Optimal Sizing and Profit Maximization of Clustered Microgrid using Game Theory Techniques.	10%	-	-	10%
Paper 7 Optimal Sizing of Networked Microgrid using Game Theory considering the Peer-to-Peer Energy Trading.	10%	5%	-	5%
Paper 8 Game Approach for Sizing and Cost Minimization of a Multi-microgrids using a Multi-objective Optimization.	10%	-	5%	5%
Paper 9 Optimization of a Hybrid Power System using a Game Theory approach.	10%	10%	-	-

<table>
<tr><td>Paper 10 Peer-to-Peer Energy Trading and Planning of Multi-microgrid System using a Multi-Objective Optimization.</td><td>10%</td><td>-</td><td>5%</td><td>5%</td></tr>
<tr><td></td><td colspan="4">Attribution Statement</td></tr>
<tr><td>Co-Authors’ Names</td><td>Contributions</td><td colspan="3">Co-Authors Acknowledgment.
I acknowledge that these represent my contribution to the above research output.</td></tr>
<tr><td>Co-Author 1
(S.M. Muyeen)</td><td>Conceptualization, review and critical revision of the papers.</td><td colspan="3">Signed: 1st April 2021</td></tr>
<tr><td>Co-Author 2
(Arindam Ghosh)</td><td>Review and critical revision of the papers.</td><td colspan="3">Signed: 1st April 2021</td></tr>
<tr><td>Co-Author 3
(Marcelo G. Simoes)</td><td>Critical revision of the paper.</td><td colspan="3">Signed: 19th April 2021</td></tr>
<tr><td>Co-Author 4
(Hamed Bizhani)</td><td>Simulation, review and editing of the papers.</td><td colspan="3">Signed: 27th March 2021</td></tr>
</table>

References

[1] P. Barbosa, L. Rolim, E. Watanabe, and R. Hanitsch, "Control strategy for grid-connected DC-AC converters with load power factor correction," *IEE Proceedings-Generation, Transmission and Distribution,* vol. 145, no. 5, pp. 487-492, 1998.

[2] L. Xu, X. Ruan, C. Mao, B. Zhang, and Y. Luo, "An improved optimal sizing method for wind-solar-battery hybrid power system," *IEEE transactions on Sustainable Energy,* vol. 4, no. 3, pp. 774-785, 2013.

[3] J. Baxter, M. Gray, and A. Hayes, "Families in regional, rural and remote Australia," *Statistics [ABS],* vol. 3, 2010.

[4] L. Che, M. Khodayar, and M. Shahidehpour, "Only connect: Microgrids for distribution system restoration," *IEEE power and energy magazine,* vol. 12, no. 1, pp. 70-81, 2013.

[5] K. Wee, S. S. Choi, and D. Vilathgamuwa, "Design of a least-cost battery-supercapacitor energy storage system for realizing dispatchable wind power," *IEEE Transactions on sustainable energy,* vol. 4, no. 3, pp. 786-796, 2013.

[6] M. Sedghi, A. Ahmadian, and M. Aliakbar-Golkar, "Optimal storage planning in active distribution network considering uncertainty of wind power distributed generation," *IEEE Transactions on Power Systems,* vol. 31, no. 1, pp. 304-316, 2015.

[7] M. S. Saleh, A. Althaibani, Y. Esa, Y. Mhandi, and A. A. Mohamed, "Impact of clustering microgrids on their stability and resilience during blackouts," in *2015 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE)*, 2015, pp. 195-200: IEEE.

[8] Z. Wang and J. Wang, "Self-healing resilient distribution systems based on sectionalization into microgrids," *IEEE Transactions on Power Systems,* vol. 30, no. 6, pp. 3139-3149, 2015.

[9] N. Li, L. Chen, and M. A. Dahleh, "Demand response using linear supply function bidding," *IEEE Transactions on Smart Grid,* vol. 6, no. 4, pp. 1827-1838, 2015.

[10] E. Bullich-Massagué, F. Díaz-González, M. Aragüés-Peñalba, F. Girbau-Llistuella, P. Olivella-Rosell, and A. Sumper, "Microgrid clustering architectures," *Applied energy,* vol. 212, pp. 340-361, 2018.

[11] A. Khodaei, "Provisional microgrid planning," *IEEE Transactions on Smart Grid,* vol. 8, no. 3, pp. 1096-1104, 2015.

[12] W. W. Tso, C. D. Demirhan, C. F. Heuberger, J. B. Powell, and E. N. Pistikopoulos, "A hierarchical clustering decomposition algorithm for optimizing renewable power systems with storage," *Applied Energy,* vol. 270, p. 115190, 2020.

[13] S. Parhizi, H. Lotfi, A. Khodaei, and S. Bahramirad, "State of the art in research on microgrids: A review," *Ieee Access,* vol. 3, pp. 890-925, 2015.

[14] F. A. Alturki, A. A. Al-Shamma'a, H. M. Farh, and K. AlSharabi, "Optimal sizing of autonomous hybrid energy system using supply-demand-based optimization algorithm," *International Journal of Energy Research,* vol. 45, no. 1, pp. 605-625, 2021.

[15] H. Yang, L. Lu, and W. Zhou, "A novel optimization sizing model for hybrid solar-wind power generation system," *Solar energy,* vol. 81, no. 1, pp. 76-84, 2007.

[16] I. Firtina-Ertis, C. Acar, and E. Erturk, "Optimal sizing design of an isolated stand-alone hybrid wind-hydrogen system for a zero-energy house," *Applied Energy,* vol. 274, p. 115244, 2020.

[17] L. Wang and C. Singh, "PSO-based multi-criteria optimum design of a grid-connected hybrid power system with multiple renewable sources of energy," in *2007 IEEE Swarm Intelligence Symposium*, 2007, pp. 250-257: IEEE.

[18] I. Abouzahr and R. Ramakumar, "Loss of power supply probability of stand-alone wind electric conversion systems: A closed form solution approach," *IEEE Transactions on Energy Conversion,* vol. 5, no. 3, pp. 445-452, 1990.

[19] E. Gavanidous and A. Bakirtzis, "Design of a stand alone system with renewable energy sources using trade off methods," *IEEE Transactions on Energy Conversion,* vol. 7, no. 1, pp. 42-48, 1992.

[20] H. Yang and J. Burnett, "Design of a building-integrated photovoltaic system in Hong Kong," *Proceedings of Renewable and Advanced Energy Systems for the 21st Century, Maui, Hawaii*, pp. 1284-1290, 1999.

[21] R. Li, H. Ma, F. Wang, Y. Wang, Y. Liu, and Z. Li, "Game optimization theory and application in distribution system expansion planning, including distributed generation," *Energies,* vol. 6, no. 2, pp. 1101-1124, 2013.

[22] X. Liu, S. Wang, and J. Sun, "Energy management for community energy network with CHP based on cooperative game," *Energies,* vol. 11, no. 5, p. 1066, 2018.

[23] S. Yang *et al.*, "An income distributing optimization model for cooperative operation among different types of power sellers considering different scenarios," *Energies,* vol. 11, no. 11, p. 2895, 2018.

[24] N. Liu, M. Cheng, and L. Ma, "Multi-Party Energy Management for Networks of PV-Assisted Charging Stations: A Game Theoretical Approach," *Energies,* vol. 10, no. 7, p. 905, 2017.

[25] M. J. Sanjari and G. B. Gharehpetian, "Game-theoretic approach to cooperative control of distributed energy resources in islanded microgrid considering voltage and frequency stability," *Neural Computing and Applications,* vol. 25, no. 2, pp. 343-351, 2014.

[26] Z. Sherinov and A. Ünveren, "Multi-objective imperialistic competitive algorithm with multiple non-dominated sets for the solution of global optimization problems," *Soft Computing,* vol. 22, no. 24, pp. 8273-8288, 2018.

[27] C. M. Subramanian, A. Krishna, and A. Kaur, "Game theory-based requirements analysis in the i* framework," *The Computer Journal,* vol. 61, no. 3, pp. 427-446, 2018.

[28] R. Myerson, "Game Theory: Analysis of Conflict, Harvard University Press, Cambridge, MA," *London England,* 1991.

[29] S. R. Dabbagh and M. K. Sheikh-El-Eslami, "Risk-based profit allocation to DERs integrated with a virtual power plant using cooperative Game theory," *Electric Power Systems Research,* vol. 121, pp. 368-378, 2015.

[30] Q. Lu, Y. Sun, and S. Mei, *Nonlinear control systems and power system dynamics*. Springer Science & Business Media, 2013.

[31] K. N. Hasan, R. Preece, and J. V. Milanović, "Application of game theoretic approaches for identification of critical parameters affecting power system

small-disturbance stability," *International Journal of Electrical Power & Energy Systems*, vol. 97, pp. 344-352, 2018.

[32] E. Mojica-Nava, C. A. Macana, and N. Quijano, "Dynamic population games for optimal dispatch on hierarchical microgrid control," *IEEE Transactions on Systems, Man, and Cybernetics: Systems,* vol. 44, no. 3, pp. 306-317, 2013.

[33] F. A. Mohamed and H. N. Koivo, "Multiobjective optimization using modified game theory for online management of microgrid," *European Transactions on Electrical Power,* vol. 21, no. 1, pp. 839-854, 2011.

[34] C. Gamarra and J. M. Guerrero, "Computational optimization techniques applied to microgrids planning: A review," *Renewable and Sustainable Energy Reviews,* vol. 48, pp. 413-424, 2015.

[35] S. Pal, S. Thakur, R. Kumar, and B. Panigrahi, "A strategical game theoretic based demand response model for residential consumers in a fair environment," *International Journal of Electrical Power & Energy Systems,* vol. 97, pp. 201-210, 2018.

[36] M. Latifi, A. Rastegarnia, A. Khalili, V. Vahidpour, and S. Sanei, "A distributed game-theoretic demand response with multi-class appliance control in smart grid," *Electric Power Systems Research,* vol. 176, p. 105946, 2019.

[37] P. Wang, J. Ma, and L. Song, "Balanced interest distribution in smart grid: a Nash bargaining demand side management scheme," in *2016 IEEE Global Communications Conference (GLOBECOM)*, 2016, pp. 1-6: IEEE.

[38] N. Yu, L. Tesfatsion, and C.-C. Liu, "Financial bilateral contract negotiation in wholesale electricity markets using Nash bargaining theory," *IEEE Transactions on Power Systems,* vol. 27, no. 1, pp. 251-267, 2011.

[39] Y. Luo, S. Itaya, S. Nakamura, and P. Davis, "Autonomous cooperative energy trading between prosumers for microgrid systems," in *39th annual IEEE conference on local computer networks workshops*, 2014, pp. 693-696: IEEE.

[40] S. Kuruseelan and C. Vaithilingam, "Peer-to-peer energy trading of a community connected with an AC and DC microgrid," *Energies,* vol. 12, no. 19, p. 3709, 2019.

[41] Y. Hong, S. Goel, and W. M. Liu, "An efficient and privacy-preserving scheme for P2P energy exchange among smart microgrids," *International Journal of Energy Research,* vol. 40, no. 3, pp. 313-331, 2016.

[42] C. Long, J. Wu, C. Zhang, M. Cheng, and A. Al-Wakeel, "Feasibility of peer-to-peer energy trading in low voltage electrical distribution networks," *Energy Procedia*, vol. 105, pp. 2227-2232, 2017.

[43] M. E. Peck and D. Wagman, "Energy trading for fun and profit buy your neighbor's rooftop solar power or sell your own-it'll all be on a blockchain," *IEEE Spectrum*, vol. 54, no. 10, pp. 56-61, 2017.

[44] Y. Zhang, T. Ma, P. E. Campana, Y. Yamaguchi, and Y. Dai, "A techno-economic sizing method for grid-connected household photovoltaic battery systems," *Applied Energy*, vol. 269, p. 115106, 2020.

[45] A. Paudel, K. Chaudhari, C. Long, and H. B. Gooi, "Peer-to-peer energy trading in a prosumer-based community microgrid: A game-theoretic model," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 8, pp. 6087-6097, 2018.

[46] N. Mendis, K. M. Muttaqi, S. Perera, and M. N. Uddin, "Remote area power supply system: an integrated control approach based on active power balance," *IEEE Industry Applications Magazine*, vol. 21, no. 2, pp. 63-76, 2014.

[47] J. Romankiewicz, C. Marnay, N. Zhou, and M. Qu, "Lessons from international experience for China's microgrid demonstration program," *Energy Policy*, vol. 67, pp. 198-208, 2014.

[48] (20 January 2021). *Wind Energy in NSW*. Available: https://energy.nsw.gov.au/renewables/renewable-generation/wind-energy-nsw

[49] (24 January 2021). *Solar Power in Wahroonga, NSW*. Available: https://www.energymatters.com.au/solar-location/wahroonga-2076/

[50] (24 January 2021). *Wikipedia, Laverton, Western Australia*. Available: https://en.wikipedia.org/wiki/Laverton,_Western_Australia.

[51] (24 January 2021). *Willy Weather, Laverton Wind Forecast*. Available: http://wind.willyweather.com.au/wa/goldfields/laverton.html.

[52] (24 January 2021). *Weather Zone, Mount Magnet Climate*. Available: http://www.weatherzone.com.au/climate/station.jsp?lt=site&lc=7600

[53] (24 January 2021). *Willy Weather, Mount Magnet Wind Forecast*. Available: http://wind.willyweather.com.au/wa/midwest/mount-magnet.html

[54] (24 January 2021). *Wahroonga Monthly Climate Averages*. Available: https://www.worldweatheronline.com/lang/en-au/wahroonga-weather-averages/new-south-wales/au.aspx

[55] (24 January 2021). *Weather Laverton* Available: https://www.meteoblue.com/en/weather/archive/export/mount-magnet_australia_2065578.

[56] (24 January 2021). *Weather Mount Magnet*. Available: https://www.meteoblue.com/en/weather/archive/export/mount-magnet_australia_2065578.

[57] (24 January 2021). *Ausgrid Solar home electricity data*. Available: https://www.ausgrid.com.au/Industry/Our-Research/Data-to-share/Solar-home-electricity-data.

[58] S. Mei, Y. Wang, F. Liu, X. Zhang, and Z. Sun, "Games Approaches for hybrid microgrid planning," *IEEE Transactions on Sustainable Energy*, vol. 3, 2012.

[59] R. B. Myerson, *Game theory*. Harvard university press, 2013.

[60] Q. Lu, S. Mei, W. Hu, F. F. Wu, Y. Ni, and T. Shen, "Nonlinear decentralized disturbance attenuation excitation control via new recursive design for multi-machine power systems," *IEEE Transactions on Power Systems*, vol. 16, no. 4, pp. 729-736, 2001.

[61] A. Démuth, "Game Theory and the Problem of Decision Making," *Edition Cognitive Studies*, 2013.

[62] *International encylopedia of the social sciences*.

[63] L. Zeng *et al.*, "Modeling interprovincial cooperative energy saving in China: An electricity utilization perspective," *Energies*, vol. 11, no. 1, p. 241, 2018.

[64] N. Jia and R. Yokoyama, "Profit allocation of independent power producers based on cooperative Game theory," *International journal of electrical power & energy systems*, vol. 25, no. 8, pp. 633-641, 2003.

[65] X. Tan and T. Lie, "Application of the Shapley value on transmission cost allocation in the competitive power market environment," *IEE Proceedings-Generation, Transmission and Distribution*, vol. 149, no. 1, pp. 15-20, 2002.

[66] L. Petrosjan and G. Zaccour, "Time-consistent Shapley value allocation of pollution cost reduction," *Journal of economic dynamics and control*, vol. 27, no. 3, pp. 381-398, 2003.

[67] E. Atashpaz-Gargari and C. Lucas, "Imperialist competitive algorithm: an algorithm for optimization inspired by imperialistic competition," in *2007 IEEE congress on evolutionary computation*, 2007, pp. 4661-4667: Ieee.

[68] F. Sarayloo and R. Tavakkoli-Moghaddam, "Imperialistic competitive algorithm for solving a dynamic cell formation problem with production planning," in *International Conference on Intelligent Computing*, 2010, pp. 266-276: Springer.

[69] (30 September 2019). *Mount Magnet location information*. Available: http://www.mtmagnet.wa.gov.au/pages/12-location-information

[70] (30 September 2019). *Renewable Energy Used for Electricity Generation in Australia* Available: https://www.aph.gov.au/About_Parliament/Parliamentary_Departments/Parliamentary_Library/pubs/rp/rp0001/01RP08

[71] Q. Lu, Y. Sun, and S. Mei, *Nonlinear control systems and power system dynamics*. Springer Science & Business Media, 2001.

[72] K. Ma, Q. Han, C. Chen, and X. Guan, "Bandwidth allocation for cooperative relay networks based on Nash bargaining solution," *International Journal of Communication Systems*, vol. 25, no. 8, pp. 1044-1058, 2012.

[73] J. E. Suris, L. A. DaSilva, Z. Han, A. B. MacKenzie, and R. S. Komali, "Asymptotic optimality for distributed spectrum sharing using bargaining solutions," *IEEE Transactions on Wireless Communications*, vol. 8, no. 10, pp. 5225-5237, 2009.

[74] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proceedings of ICNN'95-international conference on neural networks*, 1995, vol. 4, pp. 1942-1948: IEEE.

[75] Z.-L. Gaing, "Particle swarm optimization to solving the economic dispatch considering the generator constraints," *IEEE transactions on power systems*, vol. 18, no. 3, pp. 1187-1195, 2003.

[76] A. M. Entekhabi-Nooshabadi, H. Hashemi-Dezaki, and S. A. Taher, "Optimal microgrid’s protection coordination considering N-1 contingency and optimum relay characteristics," *Applied Soft Computing*, vol. 98, p. 106741, 2021.

[77] L. Ali, S. Muyeen, H. Bizhani, and A. Ghosh, "Optimal planning of clustered microgrid using a technique of cooperative game theory," *Electric Power Systems Research*, vol. 183, p. 106262, 2020.

[78] A. Korkmaz, E. Kılıç, M. Türkay, Ö. F. Çakmak, T. Y. Arslan, and U. Erdoğan, "A Blockchain Based P2P Energy Trading Solution for Smart Grids."

[79] (2021, 10 July). *Power Ledger*. Available: https://www.powerledger.io/platform

[80] L. Ali, S. Muyeen, H. Bizhani, and A. Ghosh, "Comparative study on game-theoretic optimum sizing and economical analysis of a networked microgrid," *Energies,* vol. 12, no. 20, p. 4004, 2019.

[81] F. S. Gorostiza, F. Gonzalez-Longatt, and J. L. Rueda, "Multi-objective optimal provision of fast frequency response from EV clusters," *IET Generation, Transmission & Distribution,* vol. 14, no. 23, pp. 5580-5587, 2020.

[82] S. Ali, H. Bizhani, and A. Ghosh, "'Optimal sizing of a networked microgrid using Nash equilibrium for mount magnet," in *Proc. Int. Conf. Smart Power Internet Energy Syst.(SPIES)*, 2019, pp. 1-6.

[83] M. Kiehbadroudinezhad, A. Rajabipour, M. Cada, and M. Khanali, "Modeling, design, and optimization of a cost-effective and reliable hybrid renewable energy system integrated with desalination using the division algorithm," *International Journal of Energy Research,* vol. 45, no. 1, pp. 429-452, 2021.

[84] M. J. Mayer, A. Szilágyi, and G. Gróf, "Environmental and economic multi-objective optimization of a household level hybrid renewable energy system by genetic algorithm," *Applied Energy,* vol. 269, p. 115058, 2020.

[85] L. Wang, W. Gu, Z. Wu, H. Qiu, and G. Pan, "Non-cooperative game-based multilateral contract transactions in power-heating integrated systems," *Applied Energy*, vol. 268, p. 114930, 2020.

[86] E. Sarker *et al.*, "Progress on the demand side management in smart grid and optimization approaches," *International Journal of Energy Research*, vol. 45, no. 1, pp. 36-64, 2021.

[87] A. Heydari, M. M. Nezhad, E. Pirshayan, D. A. Garcia, F. Keynia, and L. De Santoli, "Short-term electricity price and load forecasting in isolated power grids based on composite neural network and gravitational search optimization algorithm," *Applied Energy,* vol. 277, p. 115503, 2020.

[88] (13 January 2021). *Synergy – ReNeW Nexus (P2P) Plan - Pricing*. Available: https://www.synergy.net.au/Our-energy/For-tomorrow/RENeW-Nexus-Trial

[89] (13 January 2021). *Current Solar Feed-in Teriffs in Australia – State by State*. Available: https://www.solarmarket.com.au/residential-solar/current-feed-in-tariffs/

[90] (13 January 2021). *Household electricity pricing*. Available: https://www.wa.gov.au/organisation/energy-policy-wa/household-electricity-pricing