Production Planning and Bidding Strategy of Microgrids Participating in Day-Ahead Market Using Game Theory

Nasrin Ayani
Mohamed Shabanpour

Abstract

A microgrid (MG) is part of a power generation system, which independently serves a local area. In recent years, using MGs has become more popular in the electricity industry, for it optimizes the generation, transmission, and distribution of electricity. Nonetheless, discovering MGs' optimal generation scheduling and distribution strategy to capture the competitive market is still under investigation. This study intends to offer MGs a production planning model and a bidding strategy to participate in the next-day market. First, using optimization methods and predicted meteorological data, the authors propose an efficient production planning in which MGs' total thermal commitment and production costs are minimized, and the renewable thermal dispatch is optimized. In this step, MGs participate in the day-ahead competitive market to exchange their realized surplus or needed power. Secondly, using a non-cooperative Stackelberg game between multiple energy providers (MGs with abundance) and energy consumers (MGs in need), the authors match supply with demand at the optimal price. In the end, a numerical experiment was conducted, which indicates that applying the proposed model is more profitable for both MGs with surplus and MGs in need of power.

Keywords: Microgrid, Production Planning, Competitive Market, Game Theory

1. Introduction

The traditional power generation system is centralized with three primary layers: generation, transmission, and distribution. It is mainly based on fossil fuels, which is alarming due to their scarcity, high pollution, and loss rate. In this system, vertical integration, equipment depreciation, machine fatigue, and excessive infrastructure complexity increase the likelihood of blackouts and make the system prone to shutdown. In addition, 8% of production is lost during the transmission and distribution phase in the network. Also, the high risk of investment, large amounts of capital in this sector, and legal barriers related to the monopoly market of electricity have made the construction of new production stations unreasonable (Basua, et al., 2011).

In recent decades, the electricity industry has changed from centralized to decentralized due to the rising electricity price, the growing consumption volume, and the emergence of new technologies. In the decentralized system, production monopoly has been broken and shifted to deregulation and competitiveness, where companies have to compete to sell or buy electricity (Kagiannas, et al., 2004). Moreover, the resources come closer to the target consumers by using modern energy systems such as distributed generation (DG) and microgrid (MG).

The main issue in this study is how MGs participate in the electricity market of the next day. In simple terms, MGs prepare a plan based on the expected load and meteorological data a day before the market opens up. Following determining the surplus or needed amount of each MG per hour, the company decides to sell or buy power. In this research, two models are examined to formulate this process.

In the first model, which is referred to as the conventional model, MGs participate in a two-way auction on the main grid by submitting their bids. Next, the awarded power is determined along with the purchase or sales price at each hour of the next day. Eventually, MGs with surplus reschedule their production to supply the awarded power.

In the second model, the proposed one, MGs first trade power with themselves, then exchange any surplus with the main grid. In the end, MGs with abundance reschedule their production considering the awarded power. In this part, game theory is used to model the competition among MGs.

It should be noted that addressing issues related to MGs result in the following improvements (Chowdhury, et al., 2009):

A) Environmental protection:

Applying MGs in power generation diminishes greenhouse gas emissions and particulate matter. In addition, the possibility of using clean energy sources such as wind and sun in MGs can significantly counteract global warming. Moreover, consumers and resources' proximity allows them to be aware of the dangers of excessive electricity generation (pollution and noise) and encourages them to consume energy properly.

B) Operations and investment:

MGs shorten the gap between electrical resources and load consumption, strengthening the voltage profile, reducing the accumulation and cutting losses of transmission and distribution feeders, and minimizing investment risk in expanding production and transmission systems.

C) Power quality and reliability:

By employing MGs, more reliable matching between supply and demand occurs. Also, it paves the way of overcoming the adverse effects of significant outages on residential customers, decreasing plants downtime, and optimizing the recovery process through cold startup performance of small resources.

D) Advantages regarding the electricity market:

Operating MGs in the electricity market ends the monopoly of large companies and establishes a more innovative and competitive market. Moreover, MGs maintain the economic balance between investing in the grids and DG, which reduces electricity prices by up to 10% in the long run.

Table 1: Notations of MG production planning model

Parameters	**Definition**
$D(t)$	Demand for each MG at time t
C_{min}	Minimum battery charge
C_{max}	Maximum battery charge
$Pchmax$	Maximum charged power capacity in the battery
$Pdchmax$	Maximum discharged power from the battery
a_i, b_i, c_i	Parameters related to the cost of the i^{th} microturbine per MG
$Tcold_i$	The cold start time of i^{th} microturbine per MG
MDT_i	Minimum down time of i^{th} microturbine per MG
MUT_i	Minimum up time of i^{th} microturbine per MG
SH_i	Hot startup cost of i^{th} microturbine per MG (in hot mode)
SC_i	Cold startup cost of i^{th} microturbine per MG (in cold mode)
$PTmax_i$	The maximum generation limit of i^{th} microturbine per MG
$PTmin_i$	The minimum generation limit of i^{th} microturbine per MG
Variables	**Definition**
$PT(t)$	Total output of thermal systems in a MG at time t
$Pdch(t)$	Discharged power from the battery at time t
$Pch(t)$	Charged power in the battery at time t
$C(t)$	Battery charge at time t
$PPV(t)$	The total photovoltaic power at time t
$G(t)$	Insolation at time t
$PW(t)$	Total wind power at time t
$V(t)$	Wind velocity at time t
$u_i(t)$	The on or off state of i^{th} microturbine per MG at time t, boolean value
$PT_i(t)$	Generation of i^{th} microturbine per MG at time t
$S_i(t)$	The setup cost of i^{th} microturbine per MG at time t
$Toff_i(t)$	The continuously off time of i^{th} microturbine per MG at time t
$Ton_i(t)$	The continuously on time of i^{th} microturbine per MG at time t
$K(t)$	The required power rate of each MG at time t
$Smg\_t_i(t)$	The surplus amount of i^{th} microturbine per MG at time t
$Smg(t)$	The surplus amount of each MG at time t
Sets	**Definition**
N	The number of microturbines per MG

Table 2: Notations

Parameters	Definition
u_0	Voltage difference among MGs
u	Voltage difference between each MG and main grid
r	Resistance per kilometer
β	Power dissipation in the grid transformer
C_i	The budget of i^{th} MG
Cpk_i	The budget of i^{th} MG at peak hours
Kmg_i	The shortage of i^{th} MG
Smg_i	The surplus of j^{th} MG per hour
$prload_k$	Bid price for k^{th} load
$prdg_l$	The bid price of l^{th} production source
$load_k$	Power proposed by k^{th} load to the grid
$pmaxdg_l$	Power proposed by dg_i to the grid
$prmg_i$	The bid price of the i^{th} MG to the grid
$prmg_j$	The bid price of the j^{th} MG to the grid
Variables	**Definition**
$Fxmg_i$	Final power obtained by the i^{th} MG from grid after subtracting dissipation
xmg_i	Initial power that the i^{th} MG buys from the grid and has to pay
$Fpmg_j$	Power that j^{th} MG sells to the grid and gain money
pmg_j	Power that i^{th} MG must generate to sell $FPmg_i$ to the grid regarding dissipation
$xmg_{i,j}$	Power that i^{th} MG buy from j^{th} grid
$pmg_{i,j}$	Power that j^{th} MG must generate to sell $FPmg_i$ to i^{th} MG regarding dissipation
$prrmg_j$	The selling price of j^{th} MG in the proposed model
d_i	Distance between i^{th} MG and the main grid
$d_{i,j}$	Distance between i^{th} and j^{th} MGs
R_i	Resistance between i^{th} MG and the main grid
$R_{i,j}$	Resistance between i^{th} and j^{th} MGs
$xload_k$	Awarded power of k^{th} load
pdg_l	Awarded power of l^{th} production source
Sets	**Definition**
N	MGs with surplus power
M	MGs in need of power
P	Number of Loads
Q	Number of main production resources of the grid
Index:	**Definition**
i	Number of MGs in need of power
j	Number of MGs with surplus
k	Number of loads
l	Number of main production resources of the grid

2. Definitions, Theories, and Literature Review

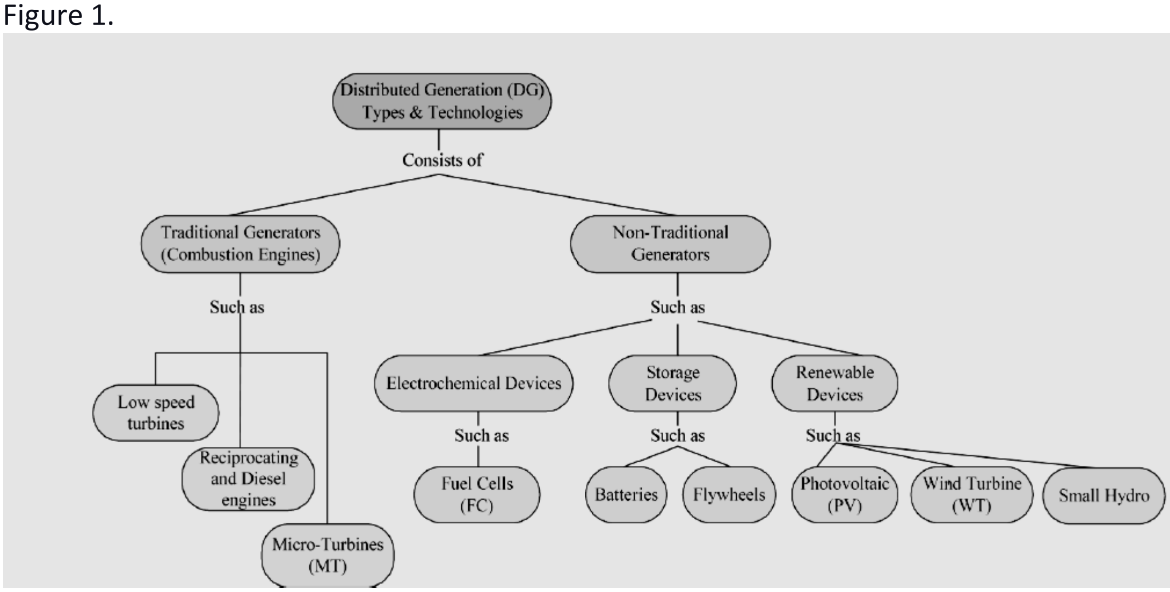
In this section, first, the structure of MG and the electricity market are defined. Secondly, related game theory concepts are briefly presented. In the end, previous publication methodologies and results are discussed.

Definitions and Theories

Distributed Generation

Distributed generation, also called distributed energy sources, is defined as a small-scale power generation utilizing various technologies for use on-site. Distributed energy resources (DER) consist of distributed generation (DG) units, distributed storage (DS) units, combined production units, demand-side management units, and control technologies. The technologies available in DG units include piston engines, combustion turbines, micro-turbines, wind turbines, fuel cells, photovoltaic-thermal systems, photovoltaic cells, low-pressure hydropower plants, and geothermal systems. Figure 1 shows some of the diverse energy sources employed in DG systems (Chowdhury, et al., 2009). The excellent efficiency rate of DG (more than 20%) has a significant impact on developing operations, control, protection and enhances the reliability of available power in the electricity industry.

Figure 1.



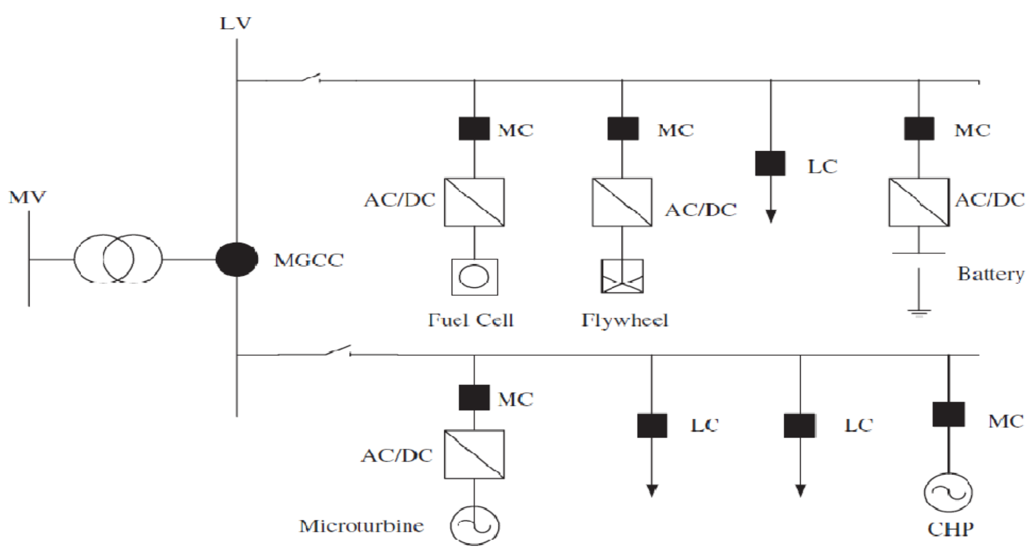
Microgird

Extensive studies that attempt to obtain maximum technical and economic efficiency of distributed generation systems have led to the emergence of MGs. An MG is part of a distribution network and a power system, consisting of DG units and independently serving a local area. Designing MGs aims to create a system that includes several production units and centralized loads and acts as a sufficiently reliable and economically viable electrical system. When an error occurs in the system, an independent MG forms like an electrical island; in this case, the MG supplies all or at least a portion of essential loads. Moreover, when connected to the main grid, the MG is solely accountable for generating power and selling its surplus production (Lasseter.R.H & Paigi.P, 2004).

Microgrid Structure

An MG has a hierarchical structure at the highest level of which is MG control center (MGCC). MGCC is generally responsible for managing MG operations. The two fundamental elements of MGCC are the energy management module (EMM) and the protection coordination module (PCM). EMM must ensure the supply of electrical and thermal loads to the consumers, required actions regarding contract provision with the main grid, minimize causalities, reduce greenhouse gas emissions, and the highest possible efficiency of resources. PCM performs against errors in MG or main grid and provides proper protection coordination.

Figure2. shows the functional structure of a MG.

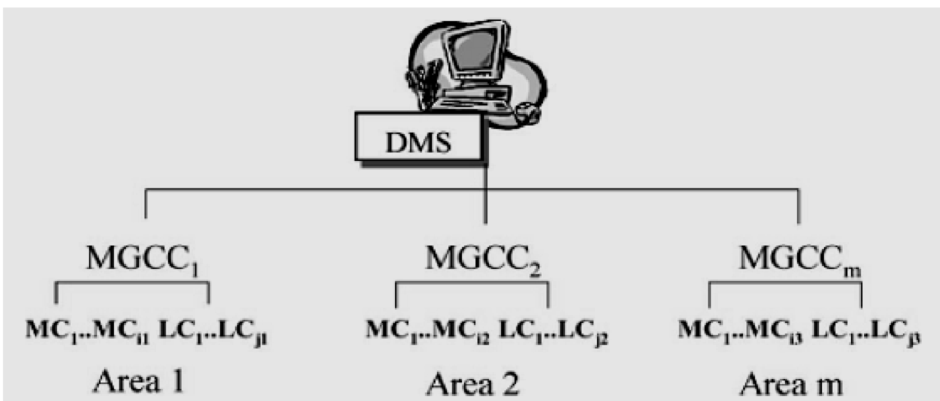


Integrated and regular control of multiple MGs in one system is required to maintain the economical and cost-effective operations of the entire system. Therefore, a hierarchical control structure including three levels of control has been proposed (G & Hatziargyriou.N.D, 2008):

- Micro-Source Controller (MC) and Load Controller (LC)
- MGCC
- Distribution Management system (DMS)

Maximizing MG value and optimizing its performance is the responsibility of MGCC, and DMS coordinates the activity of multiple MGs in a system. This process requires a two-way telecommunication connection between MGCC and MC / LC. This hierarchical control is shown in Figure (3.2).

Figure 3.



Electricity Market (Power Exchange)

Over the past two decades, the power generation industry has shifted from a central monopoly to a deregulated and competitive market. In monopolistic markets, the wholesale or retail market of electricity is within the discretion of a particular company. Under these circumstances, the company generates power at a certain level of reliability and a wholly controlled price for all customers. In comparison to the monopolistic market, deregulation gradually emerged following privatization experience in industries such as transportation and telecommunications. Furthermore, centralized and costly investments in the sector, which leads to surplus energy supply, stimulate deregulation in developed countries. Also, technology development by which production efficiency is enhanced has boosted this process (Ayani, 2014).

Competition in the Electricity Market

Concerning competitiveness, electricity markets are divided into the following four main categories (Ayani, 2014):

1- **Monopoly:**
   In monopolistic markets, the production, transmission, and sale of electricity are within the control of a private company or government organization.

2- **Competition in Production:**
   Power plants and manufacturing companies compete to sell electricity to a large buyer entity based on bilateral contracts in these markets. Therefore, market risk is passed on to consumers, and there is little incentive to improve the operations of power plants.

3- **Wholesale Competition:**
   It is a system whereby a distributor would have the option to buy its energy from a variety of power producers. The power producers would be able to compete to sell their products to various distribution companies.

4- **Retail Competition**
   All small and large customers directly choose the electricity supplier. In these markets, there are usually intermediaries or agencies that allow energy exchange among market participants.

Transaction in the Electricity Market

There are three main types of transaction in the electricity market (Shahidehpour.M, 2002):

1- **Poolco Model:**
   Poolco is a central electricity market that benefits from price transparency by holding auctions. In this model, traders announce their bid prices and volumes to the poolco.

2- **Bilateral Contracts Model:**
   In this model, sellers and buyers agree on the amount and price independently outside the market. However, they must notify the system operator of the technical aspects so that enabling the agency to declare the feasibility of the agreement.

3- **Combined Model:**
   This model is a mixture of two prior models.

Electricity Market Periods

Based on time, the electricity market is divided into two periods (Shahidehpour.M, 2002):

1- **Day-ahead Market:**
   This approach is used to plan for the next day. In this market, companies submit their offers for the next 24-hour, which are evaluated based on the market structure.

2- **Real-time Market:**
   This market is for instant buying and selling, which is usually used to adjust the transactions of the previous day. In this market, agreements are concluded only a few minutes before trading energy.

Receipt and Payment in the Electricity Market

Receipt and payment are based on one of the following two methods (Basu, et al., 2007):

1- **Uniform Pricing:**
   It is the most widely used method in the electricity market. Subsequent to buyers' offers in uniform pricing policy, the market manager utilizes the lowest bid to form the supply curve and the predicted amounts of energy required; their intersection determines the market price. The disadvantage of this method is the possibility of building excessive market power.

2- **Pay as Bid:**
   This method is designed to avoid market power. In the process, following discovering the awarded bid and the final market price, sellers and buyers transact precisely at the amount of their submission.

Pricing in the Electricity Market

There are various methods for modeling the market and determining the optimal bidding strategy, the most famous of which are divided into three main categories: equilibrium, simulation, and optimization (Ventosa.M, et al., 2005).

1- **Equilibrium Models**
   In equilibrium models, game theory is applied to model the behavior of all market participants where the market is incomplete. It is usually challenging to model all the technical limitations and arrive at a closed-form of answers with analytical methods in game theory. To cope with this problem, simulation methods are used based on equilibrium modeling.

2- **Simulation Models**

In simulation models, artificial intelligence and agent-based methods are employed, and data mining and machine learning approaches enable each participant to make market decisions.

3- **Optimization Models**
Optimization models maximize the profit of a shareholder regarding technical and economic constraints. In these models, price is considered a function of supply, which is obtained through forecasting methods such as regression and time series. These models are suitable for markets in perfect competition where the pricing of units is ineffective in the market settlement price.

Game Theory

Game theory is a conceptual framework with a set of mathematical tools to model the interaction of players with diverse and sometimes conflicting goals, which is widely used in the sciences such as economics, business, and psychology. Another application of game theory is the design and analysis of communication systems. In smart grids, game theory manages the demand side and monitors and controls the moment. Moreover, this theory is applied in pricing and modeling the competitive market among MGs (Saad, et al., 2012).

In one viewpoint, games are divided into two categories: cooperative and non-cooperative (Saad, et al., 2012). In a **cooperative game**, participants seek to maximize the group's profit. Here, the vital concern is examining the conditions and deciding whether to join a cooperation group or form a coalition. Conversely, in **non-cooperative** games, the actors have conflicting or relatively conflicting goals and only seek to boost their own profit. In these games, there is no cooperation among players.

In another viewpoint, games are sorted into two models: Bertrand and Cournot competition (Gibbons.R, 1992).

Bertrand Competition:

In the Bertrand model, sellers' competition and supply are a function of price. For example, consider two players, 1 and 2. The supply for each player is as follows:

$$q_1 = a - bp_1 + \alpha\, bp_2 \qquad (2.1)$$

$$q_2 = a - bp_2 + \alpha\, bp_1 \qquad (2.2)$$

The cost per seller (MG) is usually a quadratic function of supply, but we consider it linear for simplicity in this example. The profit function of each seller is expressed as follows:

$$\pi_1(p_1, p_2) = p_1 q_1 - cq_1 = p_1(a - bp_1 + \alpha\, bp_2) - c(a - bp_1 + \alpha\, bp_2) \qquad (2.3)$$

$$\pi_2(p_1, p_2) = p_2 q_2 - c q_2 = p_2(a - b p_2 + \alpha\, b p_1) - c(a - b p_2 + \alpha\, b p_1) \qquad (2.4)$$

Each seller attempts to maximize their profits. Therefore, by deriving the above relations with respect to the price and equating it to zero, we have:

$$\frac{\partial \pi_1(p_1, p_2)}{\partial p_1} = 0 \;\Rightarrow\; p_1 = \frac{a + \alpha\, b p_2 + cb}{2b} \qquad (2.5)$$

$$\frac{\partial \pi_2(p_2, p_1)}{\partial p_2} = 0 \;\Rightarrow\; p_2 = \frac{a + \alpha\, b p_1 + cb}{2b} \qquad (2.6)$$

Equilibrium prices and subsequently optimal supply rate are calculated by simultaneously solving equations (2.5) and (2.6). (Basu, et al., 2007)

Cournot Competition:

In Cournot models, sellers' competition and offering price are a function of supply. In this model, an offered price can be considered as the market price. For example, suppose two players, 1 and 2. The market price is as follows:

$$p = \alpha - Q = \alpha - q_1 - q_2 \qquad (2.7)$$

The profit function of each seller is expressed in this way:

$$\pi_1(q_1, q_2) = p\, q_1 - c q_1 = (\alpha - q_1 - q_2) q_1 - c q_1) \qquad (2.8)$$

$$\pi_2(q_1, q_2) = p\, q_2 - c q_2 = (\alpha - q_1 - q_2) q_2 - c q_2) \qquad (2.9)$$

Each seller seeks to maximize their profits. Therefore, by deriving the above relations with respect to the supply and equating it to zero, we have:

$$\frac{\partial \pi_1(q_1, q_2)}{\partial q_1} = 0 \;\Rightarrow\; q_1 = \frac{a - c - q_2}{2} \qquad (2.10)$$

$$\frac{\partial \pi_2(q_1, q_2)}{\partial q_2} = 0 \;\Rightarrow\; q_2 = \frac{a - c - q_1}{2} \qquad (2.11)$$

Equilibrium supplies and subsequently optimal price are calculated by simultaneously solving equations (2.10) and (2.11) (Basu, et al., 2007).

Best Response Functions

Assume that we have a two-player non-zero-sum game with $f_1(x_1, x_2)$ and $f_2(x_1, x_2)$ as target functions of two non-cooperating players where $x_1 \epsilon X_1$ and $x_2 \epsilon X_2$ indicate the strategies selected by player 1 and player 2 along the receiving area of X_1 and X_2. Suppose

Player 2 chooses the strategy $x_2 = \hat{x}_2$ and announces it to Player 1. The best response of player 1 is obtained as a result of solving the subsequent optimization problem.

$$X_1^R\left(\hat{X}_2\right) = \arg max_{x_1 \in x_2} f_1(x_1, \hat{x}_2)$$

By optimizing all values of $x_2 \epsilon X_2$, the best answer of $X_1^R\left(X_2\right)$ for Player 1 will be a function of x_1. Similarly, the best answer of $X_2^R\left(X_1\right)$ for Player 2 can be perceived as a function of x_1 (Gibbons.R, 1992).

Nash-equilibrium and Stackelberg-equilibrium

Nash equilibrium and Stackelberg equilibrium are among the most used tactics in non-cooperative games. Nash equilibrium is used when players choose a simultaneous strategy in a game. However, in a leader-follower scenario where one player can act ahead of the others, each player's plan can be determined by solving the Stackelberg competition. To find the equilibrium point in both Nash and Stackelberg's strategies, the analysis of the "best response functions" is required (Gibbons.R, 1992).

Nash Equilibrium

Nash Equilibrium, named after John Forbes Nash, is used in a non-cooperative game where players announce their decisions simultaneously and cannot communicate. Each player is assumed to be aware of the other players' equilibrium strategy, and they obtain nothing by changing only their own strategies.

The pair of strategies (X_1^N, X_2^N) form a Nash equilibrium if the following two inequalities are satisfied for all values:

$$f_1(x_1^N, x_2^N) \geq f_1(x_1, x_2^N) \ and \ f_2(x_1^N, x_2^N) \geq f_2(x_1^N, x_2)$$

Where $X_1^N and \ X_2^N$ are the solutions of $max_{x_1 \in X_1} f_1(x_1, x_2^N) \ and \ max_{x_2 \in X_2} f_2(x_1^N, x_2)$, respectively (Saad, et al., 2012).

By assuming continuity, derivability, and convexity of functions f, the above definition implies that if the pair is Nash equilibrium, then the players' decisions must satisfy the following equations:

$$\left.\frac{\partial f_1(x_1, x_2^N)}{\partial x_1}\right|_{x_1 = x_1^N} = 0 \quad , \quad \left.\frac{\partial f_2(x_1^N, x_2)}{\partial x_2}\right|_{x_2 = x_2^N} = 0$$

Moreover, Nash equilibrium is calculated by solving the subsequent system of nonlinear equations:

$$x_1 = x_1^R\,(x_2) \qquad , \qquad x_2 = x_2^R\,(x_1)$$

However, when the response functions are complex and non-convex, it is impossible to find the Nash equilibrium point analytically. In these cases, iterative algorithms based on simulation methods and artificial intelligence are utilized to find the best answer.

Stackelberg Equilibrium

In Stackelberg equilibrium, one player who is considered the leader can act ahead of the other players who are called followers. In a leader-follower environment, the follower chooses the best response based upon the leader's decision, and the leader optimizes his objective function regarding the follower response.

In a two-player game where player 1 is the leader and player 2 is the follower, the strategy $x_1^S \epsilon X_1$ is a Stackelberg equilibrium for the leader if the next equation holds for all values of x_1:

$$(x_1^S, x_2 | x_2 = x_2^R(x_1^S)) \geq f_1(x_1, x_2 | x_2 = x_2^R(x_1)) \; \forall x_1 \neq x_1^S$$

Where $x_2^R(x_1)$ is the best response function of the followers.

Literature Review

In this section, previous publication on the topic are reviewed, some of which have adopted simulation methods to facilitate equilibrium points based on game theory, while others employed data mining techniques.

Sinha et al. have modeled the traditional way of auctioning in the poolco market using two approaches: one-way and two-way auctions. Also, the aggregate supply and demand curve is drawn based on the given relationships, and the intersection is declared as MCP (Sinha, et al., 2008).

In his paper, Saad et al. have used a non-cooperative game to model competition among units of an intelligent network. A two-way auction is used to find the awarded power amount and the market-clearing price. Each vendor has different strategies to offer power, and a minimum price is set for selling that power. They examine varied strategies for the proposed power and obtain the optimal strategy. Buyers also have a maximum price to pay. Any time a two-way auction takes place, the sellers' bids are ascending based on price, while the buyers' bids are descending. The intersection point of the two curves equals the profit of each seller. (Saad, et al., 2011).

Giabardo et al. have used the Cournot competition to model the day-ahead market. In this method, a price-sensitive demand function with known elasticity is used. It is concluded that by raising the demand sensitivity, creating market power possibility decreases. This paper first writes the demand function based on price and then equates it to the total output of the generators. In this way, a relationship is obtained between the generators' supply and the market settlement price. The objective function maximizes the generator's profit by multiplying the settlement price difference by the supply amount from the production cost (Giabardo, et al., 2010).

Rosen and Madlener considered the local market, including several traders of electricity. A two-level model has been presented to obtain the participants' optimal offer in the market. At the top level are sellers looking to increase their profits, and at the bottom are buyers to minimize costs and limit the total supply with respect to demand. The main competition of manufacturers is based on supply, and the game model is Cournot. Finding an analytical solution for this game is complex; therefore, factor-based methods have been used to simulate this game (Rosen & Madlener, 2012).

In their paper, Huang and Sarkar have proposed a dynamic pricing mechanism for generating units within an MG. First, a non-cooperative game occurs among the generators of an MG, and its load is considered inelastic. The competition among the generators is based on the supply, and the price is a function of supply equal to the sum of the final cost and demand minus the total supply of generators. The other part of the article examines the coalition-type cooperative game between MGs with surplus and in need of power. The objective function of the cooperative game is the sum of the generator function in the former section (Huang & Sarkar, 2013).

Maharjan et al. have used a Stackelberg game to model the competition among traders' units in an intelligent network. Sellers at a high level seek to maximize the profits from their sales according to the maximum power at hand. In the second level, buyers seek to maximize their eligibility to buy electricity due to budget constraints. The competition is based on price. The sellers announce their prices as the leader, and the buyers report their budget. In the end, using analytical methods, an iterative algorithm to find the equilibrium point is presented (Maharjan, et al., 2013).

Wang et al. have presented an evolutionary game with incomplete information to analyze pricing strategy in a price-sensitive electricity market. In this paper, factor-based methods are used to model competitors' pricing behavior. At the top level of the game are power generators seeking to increase their profits, and at the bottom level is ISO, which aims to lessen costs and impose grid constraints. Cost functions for producers are quadratic functions of production, the derivative of which is the proposed price (Wang, et al., 2011).

Kasbekar and Sarkar have considered a market that includes several MGs in the neighborhood. In this article, the possibility of exchanging power among MGs is studied. Due to the randomness of production and demand of each MG, the probability of concluding with surplus or needed power has been calculated, and thus a random game has occurred. By solving the game model, the selling price of each MG is obtained. In this model, the technical limitations of MGs are not considered (Kasbekar & Sarkar, 2012).

In their paper, Saad et al. have presented a cooperative coalition-type game for the MGs of an intelligent network. In this game, the coalition reduces the total cost of power dissipation transmitted among MGs. The MGs of this smart system can also exchange power to the main grid. Networks decide whether or not to participate in the coalition by reviewing the power dissipation amount (Saad, et al., 2011).

Ruibal and Mazumdar have used the top three game models, Bertrand, Cournot, and SFE to estimate the optimized price and disperse it at various times. The results reveal that increasing competitors decreases the expected price yet increases its dispersion (Ruibal & Mazumdar, 2008).

Son et al., using game theory, have modeled the two methods of one-price and offer-based payment. The result shows a reduction in costs through payment based on the offer (Son, et al., 2004).

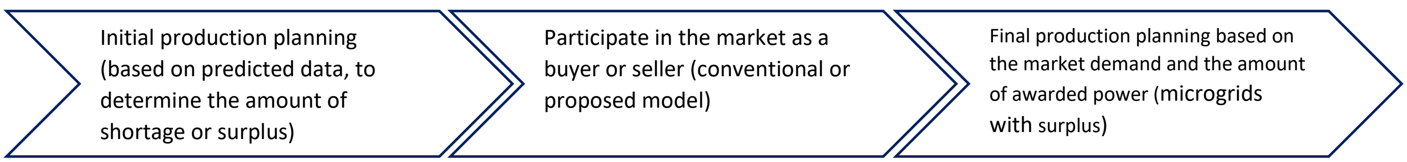
Philpott and Pettersen have also modeled the day-ahead and the moment markets and calculated the offered price and the purchase amount in each of the two markets through game theory (Philpott & Pettersen, 2006).

Azadeh et al. have tried to find the optimal bid strategy in the day-ahead market. The first section's objective function maximizes the supplier's profit without considering the competitors. In the next part, other competitors' suggestions and gains are also examined. This paper uses the genetic algorithm to find the optimal price based on past data (Azadeh, et al., 2012).

3. Mathematical Modeling

As discussed in the previous section, the possibility of trading among MGs and exchanging the ultimate power with the network is considered in the proposed model. The cost of power loss in the transmission process is also taken into account in this research. In a three-step program, MGs first plan their production established on the predicted meteorological data and identify their need or surplus at any hour of the next day. In the next step, they exchange power in the conventional or proposed model. In the last stage, concerning the awarded power in the market, the production for the next day is rescheduled. The following figure shows the three-step process of MGs to plan the day-ahead operations:

Figure 4.

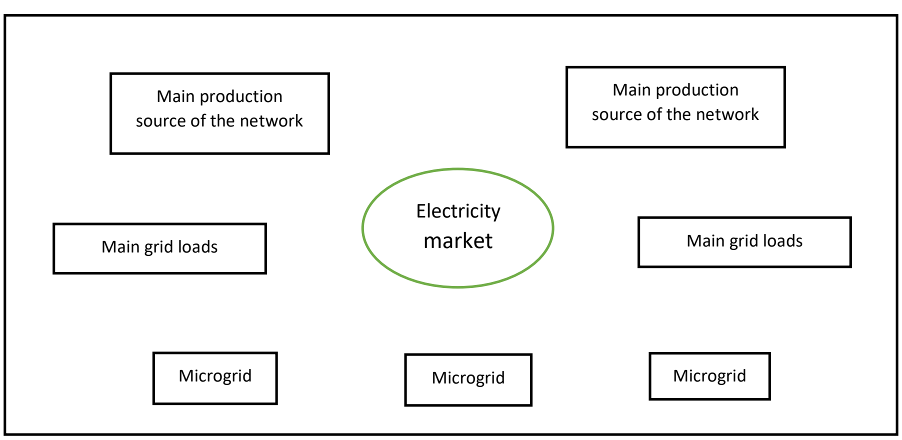


The main grid and each MG's production planning are first introduced in the following sections. Next, the employed loss function is proposed, and the conventional and proposed models are presented for the participation of MGs in the market. In the next chapter, the numerical experiment is implemented to assess the two models using a given network.

Electricity Grid

An electricity grid comprises independent loads with requested power, a specified bid price per hour, the principal production sources of the network, and MGs, as shown below. Each MG includes microturbines, photovoltaic cells, wind turbines, batteries, and controllable loads.

Figure 5. The main grid and its components



In each MG, a model is designed to determine a production planning and electricity generation from wind and sunlight (Logenthiran & Srinivasan, 2009) (Morais, et al., 2010).

Microgrid Production Planning

First, an optimal value is calculated for the total thermal energy necessary for the MGs regarding consumption load using mixed-integer linear programming. Secondly, the cost of production is minimized, and in the end, the renewable thermal dispatch is optimized both by developing mixed-integer nonlinear programming models. It should be highlighted that the on-off status of the microturbine is known in this step. Moreover, in this study, renewable units are free of cost, so wind and photovoltaic power generation are used as much as possible.

First Stage

The objective function of this step tries to minimize the total thermal unit commitment, which is modeled as follows:

$$\sum_{t=1}^{24} PT(t) = \sum_{t=1}^{24} D(t) - Pu(t) \qquad (3.1)$$

The constraints of this model are as follows:

$$C(t) = C(t-1) + Pch(t) - Pdch(t) \quad \forall t \qquad (3.2)$$

$$0 \leq Pch(t) \leq Pchmax(t) \times z_1(t) \quad \forall t \qquad (3.3)$$

$$0 \leq Pdch(t) \leq Pdchmax(t) \times z_2(t) \quad \forall t \qquad (3.4)$$

$$C_{min} \leq C(t) \leq C_{max} \quad \forall t \qquad (3.5)$$

$$z_1(t) + z_2(t) \leq 1 \quad \forall t \qquad (3.6)$$

$$z_1(t), z_2(t) = 0 \; or \; 1 \quad \forall t \qquad (3.7)$$

Constraints (3.2) to (3.7) apply to batteries. Constrain (3.2) shows the battery charge per hour based on the battery's initial, stored, and used charge. Constraints (3.3) and (3.4) specify the maximum storage capacity and battery power per hour. Constraint (3.5) indicates the minimum and maximum battery charge per hour. Constrain (3.6) and (3.7) suggest that power is not stored and received from the battery simultaneously.

$$PW(t) = \begin{cases} 0 & v(t) < v_{ci} \\ a'v(t)^4 + b'v(t)^3 + c'v(t)^2 - d'v(t) + e' & v_{ci} < v(t) < v_r \\ 0 & v_{co} < v(t) \end{cases} \quad \forall t$$

(3.8)

Constraint (3.8) is related to wind power at time t. In the above equation a', b', c', d', and e' are the model's parameters, v_{ci} is cut-in velocity, v_{co} is cut-out velocity, and v_r is admissible maximum velocity, the values of which are given in the appendix.

$$PPV(t) = \frac{G(t)}{G_{a,0}}\left[PPVmax - \mu \times \left(T(t) + G(t)\frac{NOCT-20}{800} - T_{M,0}\right)\right] \qquad \forall t \qquad (3.9)$$

Constraint (3.9) relates to the energy generated by the photovoltaic cell at time t. $G_{a,0}$ is the insolation, $T_{M,0}$ is the module temperature, and NOCT is the operating cell temperature at the standard condition. The values of these parameters are given in the appendix.

$$Pu(t) = PPV(t) + PW(t) - Pch(t) + Pdch(t) \qquad \forall t \qquad (3.10)$$

Constraint (3.10) represents the total power output of the wind turbine, photovoltaic cell, and battery per hour. $Pu(t)$ is the amount of renewable energy penetration.

The model of this stage is a mixed-integer linear programming model that is solved by GAMS software and calculates the optimal amount of $PT(t)$.

Second Stage

At this stage, microturbines must generate the $PT(t)$ value, which is obtained in the previous step for every hour. Also, the objective function minimizes production costs and shortages, and it is defined as follows, where M is a very large positive number:

$$\min \sum_{i=1}^{N}\sum_{t=1}^{24} u_i(t) \times (a_i + b_i PT_i(t) + C_i PT_i(t)^2) + S_i(t) \times (1 - u_i(t-1)) \times u_i(t) + M \times K(t)$$

(3.11)

Its constraints are as follows:

$$S_i(t) = \begin{cases} SH_i(t) & Toff_i(t) \le MDT_i + Tcold_i \qquad \forall\, i,t \\ SC_i(t) & Toff_i(t) > MDT_i + Tcold_i \qquad \forall\, i,t \end{cases}$$

(3.12)

Constraint (3.12) indicates that if the continuously off time of the turbine ($Toff$) is longer than the sum of the cold start time ($Tcold$) and the minimum downtime of the turbine (MDT), the cold startup costs (SC) is considered, otherwise, of hot mode is taken into account (SH).

$$(Ton_i(t) - MUT_i) \times \big(u_i(t-1) - u_i(t)\big) \ge 0 \qquad \forall\, i,t \qquad (3.13)$$

$$(Toff_i(t) - MDT_i) \times \big(u_i(t-1) - u_i(t)\big) \le 0 \qquad \forall\, i,t \qquad (3.14)$$

Constraints (3.13) and (3.14) imply that if the microturbine is switched on (off), the MUT (MDT) turbine clock must be switched on (off).

$PTmin_i \leq PT_i(t) \leq PTmax_i \quad \forall\, i, t$ (3.15)

Constraint (3.15) shows the minimum and maximum generation limit of i^{th} microturbine.

$\sum_{i=1}^{N} u_i(t) \times PT_i(t) + K(t) = PT(t) \quad \forall\, t$ (3.16)

In constraint (3.16), it is shown that the generation of microturbines per hour plus the required power must equal the total thermal unit commitment. Also, the model seeks to minimize the need since coefficient K is high in the objective function.

The model is a mixed-integer nonlinear programming model that is solved by GAMS software. The output explains what time each turbine is on or off the day ahead.

Third Stage

In this step, the objective function is in accordance with the second step except that the $u_i(t)$ are known. More precisely, the following function optimizes the renewable thermal dispatch of the system.

$$\min \sum_{i=1}^{N} \sum_{t=1}^{24} u_i^*(t) \times (a_i + b_i PT_i(t) + C_i PT_i(t)^2) + S_i(t) \times (1 - u_i^*(t-1)) \times u_i^*(t) + M \times K(t)$$

(3.17)

The constraints of this step are as follows:

$\sum_{i=1}^{N} u_i^*(t) \times PT_i + Pu(t) + K(h) = D(t) \quad \forall\, i, t$ (3.18)

$PTmin_i \times u_i^*(t) \leq PT_i(t) \leq PTmax_i \times u_i^*(t) \quad \forall\, i, t$ (3.19)

And the other constraints are the same as the constraints of (3.2) to (3.10) of the first stage.

Subsequently, MGs' need and surplus are measured via the following equation.

$Smg(t) = PTmax_i(t) - PT_i(t)$ (3.20)

Loss Function

The resistance between two MGs and the main grid are calculated as follows:

$R_{i,j} = d_{i,j} \times r$ (3.21)

$R_i = d_i \times r$ (3.22)

Based on the different assumptions, the loss functions are defined as follows:

1- If power is transferred from the main grid to the i^{th} MG:

$$Fxmg_i = xmg_i - R_i \left(\frac{xmg_i}{u_0}\right)^2 - \beta \times xmg_i \quad (3.23)$$

2- If power is transferred from the j^{th} MG to the main grid:

$$Fpmg_j = pmg_j - R_j \left(\frac{pmg_j}{u_0}\right)^2 - \beta \times pmg_j \quad (3.24)$$

3- If power is transferred from the i^{th} MG to the j^{th} MG:

$$xmg_{i,j} = pmg_{i,j} - R_{i,j} \left(\frac{pmg_{i,j}}{u_0}\right)^2 - \beta \times pmg_{i,j} \quad (3.25)$$

Conventional Microgrid Models

In the conventional model, subsequent to production planning and determining the surplus or need of each MG per hour, MGs enter the market to trade power with the main grid. In the market, independent loads offer their required power and bid prices to the network.

MG with need in production also announces its demand and bid price based on yesterday's MCP prices. Moreover, the primary production sources of the main grid and MGs with surplus generation declare their marketable power and bid price based on the final cost of production, which is the derivative of the cost function and is shown in the following equation:

$$C(x) = a + bx + cx^2 \quad \overset{d}{\rightarrow} \quad \Pr(x) = \frac{dC(x)}{dx} = b + 2cx \qquad (3.26)$$

Where x is the production volume, $C(x)$ is the cost function, and $\Pr(x)$ is the bid price.

Subsequent to receiving the offers, the network coordinator arranges the purchase offers in descending order and the selling offers in ascending order and announces the day-ahead settlement price per hour. Following stating the price and awarded power by each MG, they reschedule units' production based on their consumption load and the market results.

In this model, the cost of loss due to the transfer of exchanged power is borne by MGs. The mathematical model of the mentioned process is as follows.

$$max \sum_{k=1}^{P} xload_k \times prload_k + \sum_{i=1}^{M} xmg_i \times prmg_i - \sum_{l=1}^{Q} pdg_i \times prdg_i - \sum_{j=1}^{N} Fpmg_j \times prmg_j \quad (3.27)$$

$$xload_k \leq load_k \qquad \forall\, k \qquad (3.28)$$

$$pdg_l \leq pmaxdg_l \qquad \forall\, l \qquad (3.29)$$

$$Fxmg_i = xmg_i - R_i\left(\frac{xmg_i}{u_0}\right)^2 - \beta \times xmg_i \qquad \forall i \qquad (3.30)$$

$$Fxmg_i \leq Kmg_i \qquad \forall i \qquad (3.31)$$

$$Fpmg_j = pmg_j - R_j\left(\frac{pmg_j}{u_0}\right)^2 - \beta \times pmg_j \qquad \forall j \qquad (3.32)$$

$$Fpmg_j \leq Smg_j \qquad \forall j \qquad (3.33)$$

$$\sum_{i=1}^{M} xmg_i + \sum_{k=1}^{p} xload_k = \sum_{j=1}^{N} Fpmg_j + \sum_{l=1}^{Q} Pdg_i \qquad (3.34)$$

$$pmg_j, pdg_l \geq 0 \qquad \forall\, j, l \qquad (3.35)$$

In this model, the trading prices are the same as the bid prices, and the output shows the gained power of networks' members. Moreover, by drawing the supply and demand curve, the market price is obtained. Also, it is assumed that the payment is a single static price. Figure 6 shows the market process of this model.

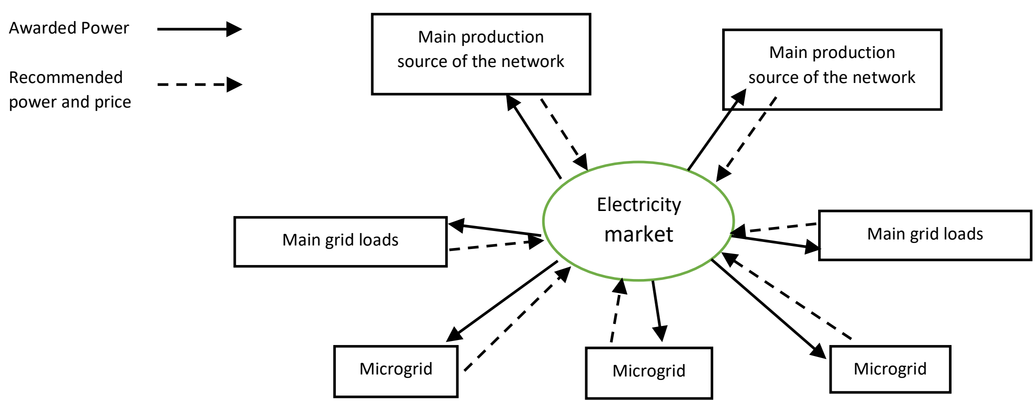


Figure 6. MGs in the main market (conventional model).

Proposed Model

In this model, each MG first plans its production for the next 24 hours based on the predicted meteorological data. MGs then relay the information to the Coordinator, including a generation shortage report and a bid price in hours with excess. The Coordinator sends the bid prices per hour to the short-supply MGs at that time. Subsequently, MGs in need of power determine their desired purchase amount by solving the model and notifying the Coordinator. The Coordinator proclaims these values to MGs with surplus generation so that MGs update their prices. This process iterates until the equilibrium price is discovered.

A Coordinator is required in this model, for it is not clear which MGs have a shortage. Moreover, as mentioned in Chapter 2, when the number of MGs is large, a DMS is needed to organize the operations of MGs; here, DMS is undertaken by the Coordinator. Unlike the previous model, MGs with surplus generation cover power transmission loss. It should be noted that information exchange is considered for one hour, and it is assumed that the first MG requires power.

To examine the game among MGs, one must observe their behavior. Unlike the proposed model in this study, previous research has modeled the game between energy producers and end-user consumers, not MGs, and they have not considered the loss cost of MGs (Maharjan, et al., 2013). Furthermore, their utility function is of the logarithmic type (Maharjan, et al., 2013), while in our model, the isoelastic utility function, which establishes a more logical relationship between purchase and price, was utilized.

MGs with surplus generation seek to maximize their profits, so no cooperation occurs. Moreover, they are unaware of the competitors' cost function, which determines the bid price and competitors' strategy; therefore, the competition is non-complete. Also, MGs competition is the Bertrand model since it is based on price rather than supply. In addition, MGs with surplus first enter the game and announce their initial bid price per hour. Subsequently, other participants determine the volume of their purchases; thus, the game between MGs with surplus and in need of power is of the Stackelberg type (leader-follower).

MGs in need of power

The objective function of these MGs maximizes the utility of purchased energy per hour. Also, the utility function used in this research is of the isoelastic type, the general form of which is as follows:

$$u(x) = \frac{x^{1-p}}{1-p} \qquad (3.35)$$

Where u is the utility function, x is the used power, and p equals to 0.5. The objective function of non-periodic deficient networks is as follows:

$$max \sum_{j=1}^{N} \sum_{i=1}^{M} 2\sqrt{xmg_{i,j}} \qquad (3.37)$$

Also, its constraint is:

$\sum_{j=1}^{N} xmg_{i,j} \times prrmg_j \leq C_i \quad \forall i$ (3.38)

MGs in need of power hold many consumers, including industrial, domestic, or commercial. Depending on the type of consumer, the allocated budget to cover the shortage varies. The above constraint expresses the budget constraint for each MG in need.

$\sum_{j=1}^{N} xmg_{i,j} \times prrmg_j \leq Cpk_i \quad \forall\, i$ (3.39)

Constraint (3.38) is replaced by (3.39) during peak hours, for consumers have to spend more money.

$\sum_{j=1}^{N} xmg_{i,j} \leq Kmg_i \quad \forall\, i$ (3.40)

Constraint (3.40) states that the purchase amount of i^{th} MG per hour should not exceed the shortage at that hour.

$\sum_{i=1}^{M} xmg_{i,j} \leq Smg_j \quad \forall\, j$ (3.41)

The above Constraint indicates that the purchase amount of j^{th} MG should not be more than the surplus of that MG.

$xmg_{i,j} \geq 0 \quad \forall\, i, j$ (3.42)

$prrmg_j \geq 0 \quad \forall\, j$ (3.43)

These two constraints show that the purchase amount and the bid price must be non-negative.

Investigation of MGs with Surplus

The profit function of each MG with surplus per hour is as follows:

$z_j = prrmg_j \times \sum_{i=1}^{M} xmg_{i,j} - Cost(pmg_{i,j}) \quad \forall\, j$ (3.44)

At this stage, the transformer causes no loss; therefore, in the above function, $xmg_{i,j}$ should be replaced with the following value:

$xmg_{i,j} = pmg_{i,j} - R_{i,j}\left(\frac{Pmg_{i,j}}{u}\right)$ (3.45)

Solving the Proposed Stackelberg Model

As mentioned before, in the Stackelberg game, an MG with surplus generation is the leader. Following announcing the price, the MG in need of power states its purchase amount. In the next round, prices are updated until the purchase volume decreases, and the previous round price is considered the equilibrium price. The main procedure is to state the model of MG in need with the KKT (Karush-Kuhn-Tucker) terms and obtain a closed-form. Due to the complexity of the model, MAPLE software was used to obtain the form. The model is solved by the following iterative algorithm, which is written in GAMS software.

Suppose we have three MGs with surplus: 2, 3, and 4; and a MG in need of power: 1. The algorithm is written as follows:

Step 1: Set an initial value for each $prrmg_j$

Step 2: Solve the model for MGs in need of power and return the value of z_j to each MG with surplus.

Step 3: If the new z_j for each MG is greater than its previous value, change the value of $prrmg_j$ to $prrmg_j + a$ and go to step two. Otherwise, declare $prrmg_j$ as the equilibrium price. (a is a small positive number)

Conclusion

This chapter presents two models for MGs' participation in the electricity industry. Following production planning based on predicted meteorological data, each MG realizes its surplus or required power and participates in a day-ahead competitive market. The conventional market is a single-price auction, and non-equilibrium methods are employed to model participants' behavior. In contrast, the proposed market is an equilibrium model, and the auction takes place based on the leader bid in a non-cooperative Stackelberg game. In the next chapter, we will solve the models numerically and review the results.

4. Chapter Four

Computational Experiment

In this chapter, the authors numerically solve the models presented in the previous chapter in the form of an example.

Introducing the Examined Network

The network consists of five independent networks, two main sources of production, and four MGs. The data corresponding to the resistance and distances are as follows:

$r = 0.2\ \Omega$

$d_1, d_2, d_3, d_4 = 40km$

$d_{12} = 5km, d_{13} = 7km, d_{14} = 6km$

$d_{42} = 8km, d_{43} = 7km$

First, we solve the production planning models of each MG.

Production Planning Results of each MG

The parameters related to photovoltaic cells, wind turbines, and batteries are given in Tables (a. 9) to (a. 11) in the appendix. In each MG, four photovoltaic cells and four wind turbines with the mentioned parameters have been used. Data related to each MG, including the amount of sunlight, air temperature, wind speed, and MG load per hour for one day, is presented in Tables (a.5) to (a. 8). Moreover, consumption turbines data of each MG are included in tables (a.1) to (a.4).

Due to the low cost of production from photovoltaic cells and wind turbines, all the electricity generated by renewable energy is penetrated. The remaining amount is supplied from the turbines. By implementing the production planning model for MGs in GAMS software, the electricity generation volume and the need or surplus of each MG per hour are computed and presented in Tables (4.3) to (4.6).

Table (4.3). Power produced by sun and wind and needed power in MG1

Time	1	2	3	4	5	6	7	8
ppv1(kW)	0	0	0	0	133.56	304.9	366.08	671.27
pw1(kW)	124.1	174	244.4	201.3	327.1	457.8	560	452
pw+ppv	124.1	174	244.4	201.3	460.6	762.7	926.1	1123.3
kmg1	75.9	126	255.6	498.7	339.4	237.3	173.9	76.7
Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
ppv1(kW)	916.67	977.84	1173.5	1222.4	1198	1222.4	977.81	855.48
pw1(kW)	364.3	378.9	259.3	208.3	135.9	81.8	29.1	26.4
pw+ppv	1281	1356.7	1432.8	1430.8	1333.9	1304.3	1006.9	881.9
kmg1	119	243.3	267.2	369.2	416.1	395.7	593.1	518.1
Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
ppv1(kW)	366.06	304.88	219.22	96.83	60.12	0	0	0
pw1(kW)	13.4	19.3	6.3	15.2	29.1	38	38	72.6
pw+ppv	379.4	324.1	225.5	112	89.2	38	38	72.6
kmg1	720.6	125.9	574.5	88	510.8	212	362	227.4

Table (4.5). Power generated by wind, sun, and surplus in MG2

Time	1	2	3	4	5	6	7	8
ppv2(kW)	0	0	0	0	134.64	305.98	367.16	672.35
pw2(kW)	44.7	77.1	129.9	96.7	201.3	342.1	516.1	334.6
pw+ppv	44.7	77.1	129.9	96.7	335.9	648	883.3	1006.9
Smg2	200	200	200	196.7	196.5	196.6	196.5	196.6
Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
ppv2(kW)	917.75	978.91	1174.63	1223.55	1199.09	1223.54	978.89	856.56
pw2(kW)	237.1	251.8	142	101.9	51.9	21.5	2.5	2.1
pw+ppv	1154.9	1230.7	1316.6	1325.5	1251	1245	981.4	858.6
Smg2	196.7	196.9	196.5	125.5	81.9	81.7	82	82
Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
ppv2(kW)	367.14	305.96	220.3	97.91	61.2	0	0	0
pw2(kW)	0	1.5	0	0	2.5	4.4	4.4	17.2
pw+ppv	367.1	307.5	220.3	97.9	63.7	4.4	4.4	17.2
Smg2	82	81.9	82	82	82	81.9	82	117.2

Table (4.6). Power generated by wind, sun, and surplus in MG3

Time	1	2	3	4	5	6	7	8
ppv3(kW)	0	0	0	0	136.8	308.14	369.3	674.51
pw3(kW)	91.6	135.9	201.3	160.9	281.7	420.5	518.3	413.9
pw+ppv	91.6	135.9	201.3	160.9	418.5	728.7	887.6	1088.4
Smg3	300	300	300	300	300	300	300	300
Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
ppv3(kW)	919.92	981.08	1176.8	1225.72	1201.25	1225.7	981.06	858.72
pw3(kW)	319.5	334.6	215.4	167.4	101.9	55.8	15.2	13.4
pw+ppv	1239.4	1315.6	1392.2	1393.1	1303.2	1281.5	996.3	872.1
Smg3	300	300	292.2	193.1	172.549	172.887	172.357	171.336
Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
ppv3(kW)	369.3	308.12	222.46	100.07	63.36	0	0	0
pw3(kW)	5.3	8.7	2.1	6.3	15.2	21.5	21.5	48.2
pw+ppv	374.6	316.9	224.5	106.4	78.6	21.5	21.5	48.2
Smg3	173.16	167.5	174.999	173.35	174.822	172.64	221.5	300

Table (4.7). Power generated by wind and sun; surplus and shortage in MG4

Time	1	2	3	4	5	6	7	8
ppv4(kW)	0	0	0	0	139.24	310.58	371.77	676.9
pw4(kW)	96.7	142	208.3	167.4	289.3	427.1	516	420.5
pw+ppv	96.7	142	208.3	167.4	428.5	737.7	887.8	1097.5
Smg4_t2	167.2	150	152.6	0	0	0	0	0
Smg4_t3	0	0	0	250	254.534	250	246.689	267.038
Kmg4	0	0	0	0	0	0	0	0
Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
ppv4(kW)	922.36	983.52	1179.2	1228.2	1203.7	1228.1	983.5	861.2
pw4(kW)	327.1	342.1	222.6	174	107.3	59.7	17.2	15.2
pw+ppv	1249.4	1325.6	1401.8	1402.1	1310.9	1287.9	1000.7	876.4
Smg4_t2	0	0	0	0	0	0	0	0
Smg4_t3	246.721	254.296	182.28	102.14	10.95	0	0	0
Kmg4	0	0	0	0	0	112.11	78.62	323.64
Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
ppv4(kW)	371.75	310.57	224.9	102.52	65.81	0	0	0
pw4(kW)	6.3	10.2	2.5	7.5	17.2	23.9	23.9	51.9
pw+ppv	378.1	320.7	227.4	110	83	23.9	23.9	51.9
Smg4_t2	0	0	0	0	0	0	23.9	51.9
Smg4_t3	0	0	0	0	82.97	123.9	0	0
Kmg4	99.85	0	246.7	169.08	0	0	0	0

As can be seen, the first MG requires power in all 24 hours, yet the second and third MGs are in surplus. Also, the fourth MG is forced to turn on the third turbine from 4 a.m. to 10 p.m owing to increased consumption load; however, it is still in need from 1 to 8 p.m. Therefore, from 1 to 3 a.m. and 11 to 12 p.m., the MG sells the surplus of its second turbine; moreover, the bid price is based on the cost of this turbine. Also, from 4 to 12 a.m. and 9 to 10 p.m., the MG sells the surplus of its third turbine, by which the bid price is determined. It suffers from shortages from 1 to 8 p.m., so it enters the market as a buyer. It should be noted that 10 a.m. to 8 p.m. is considered as peak load hours.

Results in the Market according to the Conventional Model

As mentioned, there are five independent loads in this market, the data for which (bid) is given in Table (a. 13). The bid price of these loads is based on the prediction of the day-ahead market settlement price. Data for two scattered sources are given in Table (a. 12), for which the bid price is equal to the final cost.

MG 1 participated in the market as a buyer at all hours, where the amount of power to buy equals its shortage. The bid price of this MG is based on the prediction of the day-ahead market settlement price. MGs 2 and 3 participate in the market at all hours as sellers, where the amount of power offered equals the excess power they have per hour. The bid price for this MG equals its final cost. MG 4 participates in this market as a seller from 1 to 12 a.m. and 9 to 12 p.m. From 1 to 3 a.m. and 11 to 12 p.m., the bid amount is the surplus of the second turbine, and the bid price is based on the final cost of this turbine. The proposed amount is the surplus of the third turbine from 4 to 12 a.m. and 9 to 10 p.m., and the bid price is based on the final cost of this turbine. Due to its surplus or need, it does not participate in the market from 1 and 6 p.m. It participated in the market as a buyer from 2 to 5 p.m. and 7 to 8 p.m., where the power bid amount equals its shortage, and the bid price is based on the prediction of the day-ahead market settlement price. After presenting the proposals, according to what has been said, the conventional market model is implemented, and the following results are obtained. The settlement price for each hour of the day ahead is given in Table (4.7).

Table (4.7). MCP at any hour of the day ahead

Time	1	2	3	4	5	6	7	8	9	10	11	12
MCP	21.6	21.7	21.7	21.8	21.8	22.6	22.6	22.0	24.0	22.8	25.0	23.0
Time	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
MCP	25.5	25.5	25.3	25.3	25.3	25.3	25.0	25.0	23.0	22.5	22.4	22.4

Awarded power by each load is given in Tables (4.8) to (4.12).

Table (4.8). Power won by load 1

Time	1	2	3	4	5	6	7	8	9	10	11	12
xload1	400	450	420	520	400	600	310	370	160	250	370	360
Time	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
xload1	400	460	220	360	150	180	460	400	240	320	400	320

Table (4.9). Power won by load 2

Time	1	2	3	4	5	6	7	8	9	10	11	12
xload2	400	400	420	350	420	430	470	400	450	440	220	290
Time	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
xload2	290	430	470	400	460	450	430	440	460	430	470	420

Table (4.10). Power won by load 3

Time	1	2	3	4	5	6	7	8	9	10	11	12
xload3	650	670	680	600	620	650	630	600	670	600	690	640
Time	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
xload3	610	610	600	600	670	660	650	650	660	630	640	670

Table (4.11). Power won by load 4

Time	1	2	3	4	5	6	7	8	9	10	11	12
xload4	240	260	270	310	330	340	330	350	360	350	350	350
Time	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
xload4	340	340	340	330	350	350	300	350	360	360	370	370

Table (4.12). Power won by load 5

Time	1	2	3	4	5	6	7	8	9	10	11	12
xload5	400	410	410	420	430	180	460	480	560	560	570	560
Time	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
xload5	560	360	570	510	570	560	360	360	480	460	320	420

The two primary sources of production sell all their power in this market. As mentioned above, MGs also offer their suggestions. For each MG during off-peak hours, in tables (4.13) to (4.16), kmg is the amount of power requested, $prmg$ is the bid price, and xmg is the awarded power per hour. During surplus generation, Smg is the amount of power offered, $prmg$ is the price offered according to the final cost, and $Fpmg$ is the awarded power amount. Power transmission loss and the cost of each MG in need or the profit of each surplus MG are also calculated in the other columns. Also, MCP is the final purchase or sale price.

In the following tables, the cost of MGs in need is calculated as follows:

$$Cost_i = xmg_i \times MCP$$

In MGs with surplus, the profit is computed as follows:

$$profit_j = Fpmg_j \times MCP - a_j - b_j \times pmg_j - c_j \times (pmg_j)^2$$

Table (4.13). Results from the presence of MG 1 in the main market

Time	1	2	3	4	5	6	7	8
prmg1	22.4	22.4	22.5	22.5	22.6	22.6	22.6	23
xmg1	89.5	89.3	89.1	88.9	45	0	0	87
Fxmg1	62.1	62	61.9	61.8	37.6	0	0	61
Cost	1936.54	1937.06	1935.42	1933.34	978.85	0.00	0.00	1913.05
Loss	27.4	27.3	27.2	27.1	7.4	0	0	25.9
Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
prmg1	24	24.5	25	25	25.5	25.5	25.3	25.3
xmg1	0	65	0	54.3	0	0	0	0
Fxmg1	0	50.2	0	43.8	0	0	0	0
Cost	0.00	1478.66	0.00	1249.48	0.00	0.00	0.00	0.00
Loss	0	14.8	0	10.5	0	0	0	0
Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
prmg1	25.3	25.3	25	25	25	24	23.8	23.8
xmg1	0	0	0	0	51.1	83.3	34	84.2

Fxmg1	0	0	0	0	41.7	59.4	29.6	59.8
Cost	0.00	0.00	0.00	0.00	1176.01	1874.99	761.13	1884.22
Loss	0	0	0	0	9.4	23.9	4.4	24.4

Table (4.14). Results from the presence of MG 2 in the main market

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
prmg2(bid)	12.59	12.59	12.59	12.59	12.59	12.6	12.6	12.59
p mg2	148.08	148.13	148.26	148.27	148.42	149.07	149.07	148.31
Fp mg2	74.95	74.95	74.96	74.96	74.96	74.98	74.98	74.96
Profit	-229	-225	-225	-223	-223	-169	-169	-205
Loss	73.13	73.17	73.3	73.31	73.46	74.1	74.09	73.36
Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
prmg2(bid)	12.6	12.6	12.6	12.5	12.35	12.38	12.33	12.36
p mg2	149.88	149.19	150.27	125.5	87.2	95.8	81.4	91
Fp mg2	75	74.98	75.01	72.59	61.12	64.52	58.57	62.68
Profit	-74	-159	-3	102	467	447	459	444
Loss	74.88	74.2	75.26	52.91	26.08	31.28	22.83	28.32
Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
prmg2(bid)	12.35	12.35	12.35	12.35	12.31	12.31	12.32	12.47
p mg2	87.8	88.2	86.3	86.4	77.7	76.9	78.9	117.2
Fp mg2	61.38	61.54	60.74	60.78	56.83	56.44	57.4	70.9
Profit	451	450	438	438	333	305	295	123
Loss	26.42	26.66	25.56	25.62	20.87	20.46	21.5	46.3

Table (4.15). Results from the presence of MG 3 in the main market

Time	1	2	3	4	5	6	7	8
pr mg3(bid)	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8
p mg3	154.9	154.9	154.9	154.9	154.9	154.8	154.8	154.9
Fp mg3	75	75	75	75	75	75	75	75
Profit	-6	-2	1	3	5	68	68	21
Loss	79.9	79.9	79.9	79.9	79.9	79.8	79.8	79.9
Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
pr mg3(bid)	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.7
p mg3	154.7	154.8	154.6	154.8	153.2	154.6	154.6	146.4
Fp mg3	75	75	75	75	75	75	75	74.9
Profit	174	79	250	98	303	288	269	353
Loss	79.7	79.8	79.6	79.8	78.1	79.6	79.6	71.5
Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
pr mg3(bid)	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.6
p mg3	154.6	154.6	154.6	154.6	154.8	154.9	154.8	117.2
Fp mg3	75	75	75	75	75	75	75	70.9
Profit	269	269	250	250	98	59	50	360
Loss	79.6	79.5	79.6	79.6	79.8	79.9	79.8	46.3

Table (4.16). Results from the presence of MG 4 in the main market

Time	1	2	3	4	5	6	7	8
pr mg4(bid)	10.7	10.7	10.7	14.4	14.4	14.4	14.4	14.4
p mg4	147.9	147.9	148.0	148.6	148.8	149.5	149.5	148.7
Fp mg4	74.9	74.9	74.9	75.0	75.0	75.0	75.0	75.0
Profit	68.6	72.1	73.2	-523.2	-523.8	-471.9	-472.2	-505.0
Loss	72.9	73.0	73.1	73.6	73.8	74.5	74.5	73.7
xmg4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
pr mg4(bid)	14.5	14.4	14.5	14.3	0.0	0.0	0.0	0.0
p mg4	150.3	149.6	150.7	102.1	0.0	0.0	0.0	0.0
Fp mg4	75	75	75	66.7	0	0	0	0
Profit	-378.3	-462.1	-308.7	48.8	0.0	0.0	0.0	0.0
Loss	75.3	74.6	75.7	35.4	0.0	0.0	0.0	0.0
xmg4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**

pr mg4(bid)	0.0	0.0	0.0	0.0	14.2	14.4	10.1	10.3
p mg4	0.0	0.0	0.0	0.0	83.0	123.9	23.9	51.9
Fp mg4	0.0	0.0	0.0	0.0	59.0	72.0	21.6	42.2
Profit	0.0	0.0	0.0	0.0	145.1	-177.6	222.7	399.4
Loss	0.0	0.0	0.0	0.0	24.0	51.9	2.3	9.7
xmg4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Results in the Market according to the Proposed Model

The following tables show the amount of power exchange and its price per hour. As can be seen during peak hours, prices rise as MGs in need allocate more budget. MG 4 also has to turn on its third turbine at this time, which is more costly; therefore, prices are rising. The price distinction of MGs with abundance is based on the difference between the production cost and their distance from the MGs in need. If these values were the same, the prices would be the same. The following tables show the results of MG in the local market.

Table (4.17). Results from the presence of MG 1 in the local market

Time	1	2	3	4	5	6	7	8
xmg1	63.1	62.7	63.1	57.8	57.8	57.8	57.8	57.8
Fxmg1	63.1	62.7	63.1	57.8	57.8	57.8	57.8	57.8
Cost	2000.0	2000.0	2000.0	2000.0	2000.0	2000.0	2000.0	2000.0
Loss	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
xmg1	57.8	78.0	78.0	76.9	54.0	46.1	52.6	53.1
Fxmg1	57.8	78.0	78.0	76.9	54.0	46.1	52.6	53.1
Cost	2000.0	3000.0	3000.0	3000.0	2920.0	3000.0	3000.0	3000.0
Loss	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
xmg1	54.7	54.0	54.7	52.9	56.2	56.2	52.7	60.5
Fxmg1	54.7	54.0	54.7	52.9	56.2	56.2	52.7	60.5
Cost	3000.0	2920.0	3000.0	3000.0	2000.0	2000.0	2000.0	2000.0
Loss	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table (4.18). Results from the presence of MG 2 in the local market

Time	1	2	3	4	5	6	7	8
prr mg2	36.9	38.0	36.9	36.9	36.9	36.9	36.9	36.9
p mg2	16.2	15.4	16.2	17.9	17.9	17.9	17.9	17.9
Fp mg2	15.7	14.9	15.7	17.2	17.2	17.2	17.2	17.2
Profit	353.1	351.1	353.1	389.6	389.6	389.6	389.6	389.6
Loss	0.5	0.5	0.5	0.7	0.7	0.7	0.7	0.7
Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
prr mg2	36.9	39.5	39.5	41.6	60.0	61.3	71.3	68.8
p mg2	17.9	26.1	26.1	23.8	23.9	59.9	38.5	40.9
Fp mg2	17.2	24.7	24.7	22.7	22.0	54.9	36.5	38.6
Profit	389.6	630.4	630.4	624.6	1002.1	2604.5	2102.7	2128.4
Loss	0.7	1.4	1.4	1.2	1.9	5.0	2.1	2.3
Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
prr mg2	62.5	60.0	62.5	70.0	38.0	38.0	42.2	39.1
p mg2	48.0	23.9	48.0	39.7	17.3	17.3	14.8	15.1
Fp mg2	44.8	22.0	44.8	37.5	16.7	16.7	14.4	14.6
Profit	2189.3	1002.1	2189.3	2115.6	394.3	394.3	397.2	359.3
Loss	3.2	1.9	3.2	2.2	0.6	0.6	0.5	0.5

Table (4.19). Results from the presence of MG 3 in the local market

Time	1	2	3	4	5	6	7	8
prr mg3	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
p mg3	25.6	25.8	25.6	28.3	28.3	28.3	28.3	28.3
Fp mg3	23.7	23.9	23.7	26.0	26.0	26.0	26.0	26.0
Profit	433.3	436.9	433.3	474.9	475.0	474.9	474.9	474.9
Loss	1.9	1.9	1.9	2.3	2.3	2.3	2.3	2.3
Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
prr mg3	30.0	36.3	36.3	36.3	50.0	70.0	50.0	50.0
p mg3	28.3	32.3	32.3	32.9	36.6	44.7	83.3	81.9
Fp mg3	26.0	29.3	29.3	29.8	32.0	20.0	35.3	34.7
Profit	474.9	716.7	716.7	727.8	1210.7	928.4	892.3	880.9
Loss	2.3	3.0	3.0	3.1	4.6	24.7	48.1	47.2
Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
prr mg3	50.0	50.0	50.0	50.0	31.3	31.3	33.8	32.5
p mg3	78.2	36.6	78.2	82.6	26.6	26.6	24.1	22.6
Fp mg3	33.3	32.0	33.3	35.0	24.6	24.6	22.4	21.1

profit	849.7	1210.7	849.7	886.7	480.0	480.0	494.1	438.9
Loss	44.8	4.6	44.8	47.6	2.1	2.1	1.7	1.5

Table (4.20). Results from the presence of MG 4 in the local market

Time	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
prr mg4	30.0	30.0	30.0	40.0	40.0	40.0	40.0	40.0
p mg4	25.3	25.5	25.3	15.2	15.2	15.2	15.2	15.2
Fp mg4	23.7	23.9	23.7	14.6	14.6	14.6	14.6	14.6
profit	436.4	440.1	436.4	331.9	331.9	331.9	331.9	331.9
Loss	1.6	1.6	1.6	0.6	0.6	0.6	0.6	0.6
xmg4	0	0	0	0	0	0	0	0
Cost	0	0	0	0	0	0	0	0
Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
prr mg4	40.0	40.0	40.0	40.0	0	0	0	0
p mg4	15.2	25.7	25.7	26.2	0	0	0	0
Fp mg4	14.6	24.1	24.1	24.5	0	0	0	0
profit	331.9	562.0	562.0	571.3	0	0	0	0
Loss	0.6	1.6	1.6	1.7	0	0	0	0
xmg4	0	0	0	0	0	50.7	57.9	58.4
Cost	0	0	0	0	0	3300.0	3300.0	3300.1
Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
prr mg4	0	0	0	0	40	40	40	30
p mg4	0	0	0	0	15.6	15.6	16.6	26.5
Fp mg4	0	0	0	0	15.0	15.0	16.0	24.8
profit	0	0	0	0	341.1	341.1	451.1	456.3
Loss	0	0	0	0	0.6	0.6	0.7	1.7
xmg4	60.1	0	60.1	58.1	0	0	0	0
Cost	3300.0	0	3300.0	3300.0	0	0	0	0

Once MGs have entered their local market, they can exchange the rest of their surplus in the main network. The MGs in need will no longer buy from the network, for they have used all their budget in the local market.

To compare the two models, we need to look at the need of MGs, the ultimate power it gets, and the cost it pays, namely, $Fxmg$ and cost per model. Also, the final profit and the amount it can sell for the MG with surplus, i.e., $Fpmg$ and profit in both models, must be compared. The following tables compare these variables in each model, and the awarded values are specified. As can be seen, in off-peak hours, MGs in need prefer to participate in the local MG market. This advantage is more evident during peak hours. MGs with surplus choose to join the local MG market and sell the remaining power in the primary market during peak and off-peak hours.

Table (4.21). Comparison of two markets in MG1

	Time	1	2	3	4	5	6	7	8
Conventional Model	Fxmg1	62.1	62	61.9	61.8	37.6	0	0	61
	Cost	1936	1937	1935.4	1933.3	978.9	0	0	1913.1
Proposed Model	Fxmg1	63.1	62.7	63.1	57.8	57.8	57.8	57.8	57.8
	Cost	2000	2000	2000	2000	2000	2000	2000	2000
	Time	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Conventional Model	Fxmg1	0	50.2	0	43.8	0	0	0	0
	Cost	0	1478.7	0	1249.5	0	0	0	0
Proposed Model	Fxmg1	57.8	78	78	76.9	54	46.1	52.6	53.1
	Cost	2000	3000	3000	3000	2920	3000	3000	3000
	Time	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Conventional Model	Fxmg1	0	0	0	0	41.7	59.4	29.6	59.8
	Cost	0	0	0	0	1176	1875	761.1	1884.2
Proposed Model	Fxmg1	54.7	54	54.7	52.9	56.2	56.2	52.7	60.5
	Cost	3000	2920	3000	3000	2000	2000	2000	2000

Table (4.22). Comparison of two markets in MG2

Model	Market	Time	1	2	3	4	5	6	7	8
Conventional Model	Main Market	pmg2	148	148	148	148	148	149	149	148
		Fp mg2	75	75	75	75	75	75	75	75
		Profit	-229	-225	-225	-223	-223	-169	-169	-205
Proposed Model	Local Market	Fp mg2	16	15	16	17	17	17	17	17
		Profit	353	351	353	390	390	390	390	390
	Main Market	pmg2	148	148	148	148	148	149	149	148
		Fp mg2	75	75	75	75	75	75	75	75
		Profit	-229	-225	-225	-223	-223	-169	-169	-205

Model	Market	Time	9	10	11	12	13	14	15	16
Conventional Model	Main Market	pmg2	150	149	150	126	87	96	81	91
		Fp mg2	75	75	75	73	61	65	59	63
		Profit	-74	-159	-3	102	467	447	459	444
Proposed Model	Local Market	Fp mg2	17	25	25	23	22	55	36	39
		Profit	390	630	630	625	1002	2604	2103	2128
	Main Market	pmg2	150	148	150	102	58	22	43	41
		Fp mg2	75	75	75	67	46	20	37	35
		Profit	-74	-148	-3	260	442	214	368	354

Model	Market	Time	17	18	19	20	21	22	23	24
Conventional Model	Main Market	pmg2	88	88	86	86	78	77	79	117
		Fp mg2	61	62	61	61	57	56	57	71
		Profit	451	450	438	438	333	305	295	123
Proposed Model	Local Market	Fp mg2	45	22	45	38	17	17	14	15
		Profit	2189	1002	2189	2116	394	394	397	359
	Main Market	pmg2	34	58	34	42	65	65	67	102
		Fp mg2	30	46	30	36	50	50	51	67
		Profit	307	431	300	352	336	310	305	216

Table (4.23). Comparison of two markets in MG3

Model	Market	Time	1	2	3	4	5	6	7	8
Conventional Model	Main Market	pmg3	154.9	154.9	154.9	154.9	154.9	154.8	154.8	154.9
		Fp mg3	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0
		profit	-6	-2	1	3	5	68	68	21
Proposed Model	Local Market	Fp mg3	23.7	23.9	23.7	26.0	26.0	26.0	26.0	26.0
		profit	433.3	436.9	433.3	474.9	475.0	474.9	474.9	474.9
	Main Market	pmg3	154.9	154.9	154.9	154.9	154.9	154.8	154.8	154.9
		Fp mg3	75.0	75.0	75.0	75.0	75.0	75.0	75.0	75.0
		profit	-6	-2	1	3	5	68	68	21

Model	Market	Time	9	10	11	12	13	14	15	16
Conventional Model	Main Market	pmg3	154.7	154.8	154.6	154.8	153.2	154.6	154.6	146.4
		Fp mg3	75.0	75.0	75.0	75.0	75.0	75.0	75.0	74.9
		profit	174	79	250	98	303	288	269	353
Proposed Model	Local Market	Fp mg3	26.0	29.3	29.3	29.8	32.0	20.0	35.3	34.7
		profit	474.9	716.7	716.7	727.8	1210.7	928.4	892.3	880.9
	Main Market	pmg3	154.7	154.9	154.6	154.9	136.0	128.2	89.0	89.4
		Fp mg3	75.0	75.0	75.0	75.0	74.1	73.0	61.9	62.0
		profit	174	79	250	98	463.5	519.4	632.5	632.4

Model	Market	Time	17	18	19	20	21	22	23	24
Conventional Model	Main Market	pmg3	154.6	154.6	154.6	154.6	154.8	154.9	154.8	117.2
		Fp mg3	75.0	75.0	75.0	75.0	75.0	75.0	75.0	70.9
		Profit	269	269	250	250	98	59	50	360
Proposed Model	Local Market	Fp mg3	33.3	32.0	33.3	35.0	24.6	24.6	22.4	21.1
		Profit	849.7	1210.7	849.7	886.7	480.0	480.0	494.1	438.9
	Main Market	pmg3	95.0	130.9	96.8	90.7	148.2	146.0	154.9	154.9
		Fp mg3	64.2	73.5	64.9	62.6	75.0	74.9	75.0	75.0
		profit	629.0	482.8	610.5	616.4	167.0	151.2	49.7	49.5

Table (4.24). Comparison of two markets in MG4

Model	Market	Time	1	2	3	4	5	6	7	8
Conventional Model	Main Market	pmg4	148	148	148	149	149	150	150	149
		Fp mg4	75	75	75	75	75	75	75	75
		profit	68.6	72.1	73.2	-523.2	-523.8	-471.9	-472.2	-505
		xmg4	0	0	0	0	0	0	0	0
		cost	0	0	0	0	0	0	0	0
Proposed Model	Local Market	Fp mg4	24	24	24	15	15	15	15	15
		profit	436	440	436	332	332	332	332	332
		xmg4	0	0	0	0	0	0	0	0
		cost	0	0	0	0	0	0	0	0
	Main Market	pmg4	142	124	127	148	149	150	150	149
		Fp mg4	75	72	73	75	75	75	75	75
		profit	125	267	250	-521	-521	-472	-472	-503

Model	Market	Time	9	10	11	12	13	14	15	16
Conventional Model	Main Market	pmg4	150	150	151	102	0	0	0	0
		Fp mg4	75	75	75	67	0	0	0	0
		profit	-378.3	-462.1	-308.7	48.8	0	0	0	0
		xmg4	0	0	0	0	0	0	0	0
		cost	0	0	0	0	0	0	0	0
Proposed Model	Local Market	Fp mg4	15	24	24	24	0	0	0	0
		profit	332	562	562	571	0	0	0	0
		xmg4	0	0	0	0	0	51	58	58
		cost	0	0	0	0	0	3300	3300	3300
	Main Market	pmg4	150	149	151	76	0	0	0	0
		Fp mg4	75	75	75	56	0	0	0	0
		profit	-378	-448	-309	175	0	0	0	0

Model	Market	Time	17	18	19	20	21	22	23	24
Conventional Model	Main Market	pmg4	0	0	0	0	83	124	24	52
		Fp mg4	0	0	0	0	59	72	22	42
		profit	0	0	0	0	145.1	-177.6	222.7	399.4
		xmg4	0	0	0	0	0	0	0	0
		cost	0	0	0	0	0	0	0	0
Proposed Model	Local Market	Fp mg4	0	0	0	0	15	15	16	25
		profit	0	0	0	0	341	341	451	456
		xmg4	60	0	60	58	0	0	0	0
		cost	3300	0	3300	3300	0	0	0	0
	Main Market	pmg4	0	0	0	0	67	108	7	24
		Fp mg4	0	0	0	0	51	69	7	22
		profit	0	0	0	0	194	-30	63	235

5- Chapter Five

Conclusion and Suggestions

Considering widespread changes in environmental conditions such as increasing pollution, rising fuel prices, increasing electricity demand, and introducing new concepts such as MGs and distributed generation, a new framework for managing the interactions between power generation and distribution systems is required. Modern distribution systems, which have brought production locations closer to consumption places, and renewable energy have played a significant role in reducing the problems of traditional systems. At the same time, changing the electricity industry structure, i.e., moving from a monopoly to a competitive environment, requires recognizing and creating new trends for units to participate in the market and increase their profits and desirability.

This research offers MGs efficient production planning based on predicted meteorological data in three steps. First, by developing a mixed-integer linear programming model, MGs minimize their total thermal commitment. In the next step, MGs employ mixed-integer nonlinear programming to minimize production costs. MGs optimize renewable thermal dispatch in the last step by applying mixed-integer nonlinear programming. Following this process, MGs realize their required or surplus power per hour of the day ahead and enter the competitive market to exchange energy. Here, the authors propose a game-theoretic model to discover the optimal bidding strategy and compare it with the conventional model.

In the conventional model, independent MGs offer their required power and bid prices to the Coordinator. MG in need also announces its demand and bid price based on yesterday's MCP prices. Scattered resources and MGs with abundance also declare their marketable capacity and bid price based on the final production cost. After receiving the offers, the Coordinator arranges the purchase offers in descending order and the selling offers in ascending order and announces the day-ahead equilibrium price per hour. Following announcing this price and MGs' awarded power, they reschedule their units' production. In this case, the MGs themselves bear the cost of transferring traded power.

In the proposed model, the authors develop a game-theoretic model to model the market participants' behavior. To this end, a non-cooperative Stackelberg game is built to settle the optimal price between MGs with surplus and MGs in need of power. First, MGs compete and exchange energy through the Stackelberg game. Subsequently, if required, they can sell the surplus or buy the remaining need in the main network according to the conventional model. Eventually, MGs with surplus reschedule their production and cover the loss cost.

Numerical experiments results reveal that MGs in need are more inclined to participate in the local market. The loss in the local market among MGs is much less than the primary network market. Although the payment value in the main network market seems lower, abundant money will be spent on power dissipation. Moreover, increased load consumption reduces the possibility of winning sufficient power to supply the demand of MG in need during peak hours.

MGs with a surplus also prefer to sell their power in the local market due to the possibility of selling at a higher price. If they offered the same price in the primary market, they could not compete with the other competitors, who profit by selling more at a lower price. However, if MGs with surplus take such an approach, the primary network is still not very profitable, for their loss rate escalates sharply as supply increases. Therefore, they choose the local market to exchange power. Moreover, after participating in the local market, they can also enter the primary network market to sell their surplus.

Future Suggestions

This research used the predicted meteorological data to solve the production planning model definitively. Although random data is not expected to affect the conclusion, it will significantly improve modeling the situation. We also assumed that MGs in need were price-sensitive and were looking to buy power, given the budget and the degree of utility. Nevertheless, depending on consumers, the function of utility, budget, and the degree of sensitivity to prices vary. The model can be brought closer to the actual situation by considering various types of consumers.

In this study, there are no restrictions related to distribution in the system, i.e., the Optimal Power Flow Problem, so prices do not depend on loading location and production in the feeders. Considering these issues, point prices can be calculated in further research. The employed game in this research is non-cooperative; a cooperative game can occur among MGs. In this case, trading among MGs will not happen, and power is just transferred, which aims to reduce loss. Also, cooperative games with various objective functions can be considered. In this study, only the competition in the energy market is considered, while MGs can also participate in the reservation market.

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Appendix

Table a1. MG1 turbine information

	Micro Turbine 1	Micro Turbine 2	Micro Turbine 3
Pmax (kW)	400	300	200
Pmin(kW)	100	100	100
a (ct/hr)	20	30	40
b (ct/kWhr)	10	12	14
c (ct/kW² hr)×0.0001	25	20	15
MUT(hr)	3	2	2
MDT(hr)	3	2	2
Hot start cost(ct)	460	750	720
Cold start cost(ct)	920	1500	1440
Cold start time(hr)	2	1	1
Initial status(hr)	1	1	-2

Table a2. MG2 turbine information

	MicroTurbin 1	MicroTurbin 2	MicroTurbin 3
Pmax (kW)	600	400	300
Pmin(kW)	100	100	100
a (ct/hr)	5	20	30
b (ct/kWhr)	4	8	12
c (ct/kW² hr)×0.0001	10	25	20
MUT(hr)	5	3	2
MDT(hr)	5	3	2
Hot start cost(ct)	550	450	750
Cold start cost(ct)	1100	900	1500
Cold start time(hr)	3	2	1
Initial status(hr)	-1	-1	-1

Table a3. MG3 turbine information

	MicroTurbin 1	MicroTurbin 2	MicroTurbin 3
Pmax (kW)	600	400	400
Pmin(kW)	100	100	100
a (ct/hr)	5	20	20
b (ct/kWhr)	6	8	10
c (ct/kW² hr)×0.0001	20	25	25
MUT(hr)	5	3	3
MDT(hr)	5	3	3
Hot start cost(ct)	500	450	460
Cold start cost(ct)	1000	900	920
Cold start time(hr)	3	2	2
Initial status(hr)	1	1	-1

Table a4. MG4 turbine information

	MicroTurbin 1	MicroTurbin 2	MicroTurbin 3
Pmax (kW)	600	400	200
Pmin(kW)	100	100	100
a (ct/hr)	5	20	40
b (ct/kWhr)	4	10	14
c (ct/kW² hr)×0.0001	10	25	15
MUT(hr)	5	3	2
MDT(hr)	5	3	2
Hot start cost(ct)	550	460	720
Cold start cost(ct)	1100	920	1440
Cold start time(hr)	3	2	1
Initial status(hr)	1	-1	-1

Table a.5 Solar radiation, temperature, wind velocity, and demand in MG1

Time	G(kW/m^2)	T(c)	V(m/s)	D(kW)
1	0	24.7	7.4	1100
2	0	24.6	8.2	1200
3	0	24.4	9.2	1400
4	0	24.2	8.6	1600
5	92.75	24.3	10.3	1700
6	211.75	24.4	12.2	1900
7	254.25	25.4	15.3	2000
8	466.25	26.4	12.1	2100
9	636.75	27.4	10.8	2300
10	679.25	27.9	11	2500
11	815.25	28.4	9.4	2600
12	849.25	28.7	8.7	2700
13	832.25	28.9	7.6	2650
14	849.25	29.6	6.6	2600
15	679.25	29.7	5.2	2500
16	594.25	29.9	5.1	2300.0
17	254.25	29.7	4.5	2000.0
18	211.75	29.4	4.8	1850.0
19	152.25	28.9	4	1700.0
20	67.25	27.6	4.6	1600.0
21	41.75	26.4	5.2	1500.0
22	0	25.9	5.5	1400
23	0	25.4	5.5	1300
24	0	24.9	6.4	1200

Table a.6 Solar radiation, temperature, wind velocity, and demand in MG2

Time	G(kW/m^2)	T(c)	V(m/s)	D(kW)
1	0	24.8	5.7	1000
2	0	24.7	6.5	1100
3	0	24.5	7.5	1200
4	0	24.3	6.9	1400
5	93.5	24.4	8.6	1600
6	212.5	24.5	10.5	1800
7	255	25.5	13.6	1900
8	467	26.5	10.4	2000
9	637.5	27.5	9.1	2100
10	680	28	9.3	2300
11	816	28.5	7.7	2400
12	850	28.8	7	2500
13	833	29	5.9	2550
14	850	29.7	4.9	2400
15	680	29.8	3.5	2200
16	595	30	3.4	2100
17	255	29.8	2.8	1800
18	212.5	29.5	3.1	1700
19	153	29	2.3	1600
20	68	27.7	2.9	1500
21	42.5	26.5	3.5	1500
22	0	26	3.8	1400
23	0	25.5	3.8	1300
24	0	25	4.7	1200

Table a.7 Solar radiation, temperature, wind velocity, and demand in MG3

Time	G(kW/m²)	T(c)	V(m/s)	D(kW)
1	0	24.3	6.8	1000
2	0	24.2	7.6	1100
3	0	24	8.6	1300
4	0	23.8	8	1500
5	95	23.9	9.7	1600
6	214	24	11.6	1800
7	256.5	25	14.7	1900
8	468.5	26	11.5	2000
9	639	27	10.2	2200
10	681.5	27.5	10.4	2400
11	817.5	28	8.8	2500
12	851.5	28.3	8.1	2600
13	834.5	28.5	7	2550
14	851.5	29.2	6	2500
15	681.5	29.3	4.6	2400
16	596.5	29.5	4.5	2200
17	256.5	29.3	3.9	1900
18	214	29	4.2	1750
19	154.5	28.5	3.4	1600
20	69.5	27.2	4	1500
21	44	26	4.6	1400
22	0	25.5	4.9	1300
23	0	25	4.9	1200
24	0	24.5	5.8	1100

Table a.8 Solar radiation, temperature, wind velocity, and demand in MG4

Time	G(kW/m²)	T(c)	V(m/s)	D(kW)
1	0	24.9	6.9	1000
2	0	24.8	7.7	1150
3	0	24.6	8.7	1200
4	0	24.4	8.1	1400
5	96.7	24.5	9.8	1500
6	215.7	24.6	11.7	1600
7	258.2	25.6	14.8	1700
8	470.2	26.6	11.6	1800
9	640.7	27.6	10.3	2000
10	683.2	28.1	10.5	2200
11	819.2	28.6	8.9	2300
12	853.2	28.9	8.2	2500
13	836.2	29.1	7.1	2500
14	853.2	29.8	6.1	2600
15	683.2	29.9	4.7	2650
16	598.2	30.1	4.6	2400
17	258.2	29.9	4	2200
18	215.7	29.6	4.3	1900
19	156.2	29.1	3.5	1700
20	71.2	27.8	4.1	1500
21	45.7	26.6	4.7	1200
22	0	26.1	5	1100
23	0	25.6	5	1000
24	0	25.1	5.9	1000

Table a.9 Photovoltaic cell data

$G_{a,0}$	$T_{M,0}$	μ	NOCT	PPVmax
1000	25	−0.0045	44	360

Table a.10 Wind turbine data

V_{ci}	V_r	V_{co}	a'	b'	c'	d'	e'	PWmax
3	15.01	17	-0.015	0.33	-0.9	-2.1	7.1	140

Table a.11 Battery data

Cmin	Cmax	Pchmax	Pdchmax
1250	2500	500	500

Table a.12 The main production resources of the network data

	DG1	**DG2**
PDGmax	1200	1000
a (ct/hr)	27	11
b (ct/kWhr)	19	20
c (ct/kW^2 hr)×0.0001	7	5

Table a.13 loads' recommendation

Time	load1	prload1	load2	prload2	load3	prload3	load4	prload4	load5	prload5
1	400	23.7	400	24	650	24.2	240	24.5	400	24.7
2	450	23.8	400	23.9	670	24.1	260	24.4	410	24.6
3	510	23.9	420	23.9	680	24	270	24.3	410	24.5
4	520	24	440	24	600	24.1	310	24.2	420	24.4
5	580	24.1	420	24.1	620	24.1	330	24.1	430	24.3
6	600	24.2	430	24.2	650	24.2	340	24.2	430	24.2
7	560	24.2	470	24.3	630	24.3	330	24.3	460	24.3
8	500	25	400	28	600	26	350	27.5	480	28.5
9	460	27	450	29	670	28	360	29	560	28.5
10	410	28	440	28.5	600	28.5	350	30	560	29
11	370	29.5	480	29	690	29.5	350	29	570	30
12	360	29.5	450	29	640	29.5	350	29	560	30
13	400	30	450	30	610	30	340	31	560	30
14	460	30	430	30	610	30	340	31	560	30
15	470	29.5	470	30	600	30	340	30.5	570	30
16	500	29.5	400	30	600	30	330	30.5	510	30
17	470	29.5	460	30	670	30	350	29.5	570	30
18	460	29.5	450	30	660	30	350	30	560	30
19	460	29.5	430	30	650	29.5	300	30	560	29
20	400	29.5	440	30	650	29.8	350	30	500	29
21	380	29	460	29.5	660	29.5	360	29	480	29.5
22	360	27	430	29.5	630	29.5	360	27.5	460	29.5
23	400	26.5	470	27	640	27	370	27	440	26.5
24	390	26.5	420	27	670	27	370	27	420	26.5