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# Profit-Sharing Rule for Networked Microgrids Based on Myerson Value in Cooperative Game

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**ABSTRACT** Networked microgrids (MGs) have several advantages over individual MGs such as reliability improvement and cost reduction. To promote the mutual connection of individual MGs, a rational and predictable profit-sharing rule is required. This study investigates a rule for the fair distribution of profit in networked MGs according to their contributions that come from connecting between them. Cooperative game theory defines profit-sharing problems such as the Nash bargaining solution (NBS) and Shapley value. However, as the two solution concepts are used assuming that the network is complete, they do not account for the positional contribution of each MG in a given network. We propose a variation of the Shapley value designed for an incomplete network, the Myerson value. We investigate how Myerson value-based profit-sharing rule can account for both the role and positional contributions of each MG. Using Korean data, we compare the profit distribution results for the three sharing rules (the NBS, Shapley value, and Myerson value). The result confirms that the proposed rule fairly distributes the profit according to one’s contribution, even when MGs are incompletely connected.

**INDEX TERMS** Cooperative game theory, Myerson value, Nash bargaining solution (NBS), network structure, networked microgrids, Shapley value.

## I. INTRODUCTION

Renewable energy has been attracting increasing attention in recent years owing to global warming. The cost of renewable energy has decreased considerably because of technological advancements and the economies of scale, so it has become economically feasible nowadays. In some countries such as Germany and China, renewable energy has reached grid parity, that is, the economics of renewable energy have become the same as those of conventional fossil-fuel-based generators. Accordingly, the total installed capacity of renewable energy worldwide is 171 GW in 2019, while that of non-renewable energy is 65 GW in the same year [1]. However, renewable energy has an adverse effect on the power system because of its intermittent and uncertain power output. Therefore, with high penetrations of renewable energy, power networks need to prepare for a reliable operation [2]. One of

the promising solutions for this problem is microgrid (MG) which is a small-scale power system.

To operate MGs in a more economical and reliable way, neighboring MGs need to be connected to exchange electricity; this configuration is called networked MGs, multi-MGs, or community MGs [3]. Thus, an MG that requires a more amount of electricity can use the surplus electricity supplied by a neighboring MG, resulting in improved reliability and economic profit [4]. As each MG is an independent entity, a proper market design [5], [6] and control schemes [7], [8] are required to promote electricity exchange in the networked MGs. Another important aspect of networked MGs is the components in each MG. In contrast to the optimal components in a single MG, the components of each MG in the network are determined based on the demand and supply of the neighboring MG as well as its own. For instance, an MG in the network having high renewable resources and high demand invests more renewable generators than an isolated MG to obtain benefits from electricity exchange. Therefore, the electricity exchange between MGs should be considered

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at the planning stage to maximize the profit<sup>1</sup> from this networking. It is called a cooperative MG planning problem [4]. This is a more complicated and less highlighted problem compared with a single MG planning problem.

The expected profit and investment required help an MG to decide whether to join a network. Therefore, a fair, clear, and predictable profit-sharing rule needs to be designed for networked MGs at the planning stage. Such a profit-sharing problem is well defined by cooperative game theory. Some studies have investigated the creation of a coalition group to obtain mutual profits [9], [10]. Cooperative game theory consists of several solution concepts for a group, that is, coalition, such as the Nash bargaining solution (NBS) [11] and the Shapley value [12].

In power systems, the concept of a cooperative game is widely used, such as for energy storage [13] and demand response [14]. In addition, studies on networked MGs using cooperative game theory have been conducted recently [15]–[19]. In [15], the MGs in the network exchange electricity based on the NBS. Another study based on cooperative game theory [16] ensured a fair cost share among MGs in a coalition using a nucleolus-based cost allocation method. In [17], a pricing mechanism has been proposed to integrate large-scale renewable energy sources into the power system. The proposed method uses a game vector to set the price interactively. A local electricity exchange algorithm based on cooperative game theory has been proposed [18]. It uses the Shapley value to identify incentives for each MG; thus, the MGs in the network trade electricity locally with neighboring MGs. Game theory is used to propose electricity exchange between not only MGs but also prosumers [20]. These studies have focused on electricity exchange or control between MGs or prosumers in daily operation under the assumption of a fully connected network.

Profit-sharing in power system is required both at the planning stage and at daily operation. Previously MG planning [21] and profit-sharing rule based on NBS [4] and Shapley value [22] have been investigated. Most of the MG planning and profit-sharing works assumed a fully connected network. This assumption, however, is not always valid in power system. This work proposes a new profit-sharing rule at the planning stage under incomplete networks. To measure the contribution of each MG, especially under an incomplete network, we use Myerson value. Myerson value is a variation of Shapley value that designed for incomplete network [23]. In this paper, a new profit-sharing rule based on Myerson value is proposed to achieve a fair and rational sharing for grid-connected networked MGs. It can count each MG's contributions to the joint profit from two different aspects: role and positional contributions. We show different profit-sharing results when a network is fully connected or not. Using the three different profit-sharing rules (NBS, Shapley value, and Myerson value), a case study that uses Korean data confirms

the proposed Myerson value-based rule shares the profit in a fair manner, even when MGs are incompletely connected.

The remainder of this paper is organized as follows. Section II describes the theoretical model of MG planning and daily operation. In Section III, the solutions for cooperative MG planning problems are examined. Section IV reviews three cooperative game-theoretic solutions, namely, the NBS, Shapley value, and Myerson value. Section V presents the profit-sharing rules based on the cooperative game-theoretic solutions. In Section VI, the results of the proposed profit-sharing rule using the relevant data from Korea are presented. Finally, this paper is concluded in Section VII.

## II. SYSTEM MODEL

Consider several interconnected MGs connected to the main grid. We consider a fixed and finite set of MGs  $N = \{1, 2, \dots, n\}$ . Each MG  $i \in N$  can invest in renewable generators, and the variables to be optimized are the amounts of investment. The interconnected MGs jointly plan the capacity of their renewable generators to explore the diversity of renewable energy potentials at different locations. The amount of investment determines the availability of renewable energy in the long term, and thus affects the daily operational cost. The accumulative operational cost of an MG is also considered at the planning stage because it is substantial over the lifespan of the MG. The objective function of each MG is the minimization of its total cost, that is, the sum of the investment and operational costs.

Important decisions regarding each MG are made in two stages. In the first stage, decisions on long-term investments are required, such as whether to invest in renewable generators and the amount of generation capacity. The second stage is intended for a short-term operation, that is, the daily operation under the generation capacity given by the first stage. The main control variable for the second stage is the amount of electricity purchased from the main grid in a day.

### A. LONG-TERM INVESTMENT COST

In this paper, we assume that the cost function of long-term investment is a convex function [24]. That is, the marginal cost of investment increases as the generator capacity increases. This assumption reflects the land price, which is a large share of investment costs, as in the case of renewable generators. The physical and economic situation of renewable installation from a place with a low land price to a high land price is considered, with the increase in the size of the installation. Especially, we model the cost as a quadratic function. The long-term investment cost of MG  $i$ ,  $C_i^l$ , in the first stage can be expressed as

$$C_i^l(z_i^s, G_i^s, z_i^w, G_i^w) = z_i^s \cdot (F_i^s + a_i^s(G_i^s)^2 + b_i^s G_i^s) + z_i^w \cdot (F_i^w + a_i^w(G_i^w)^2 + b_i^w G_i^w) \quad (1)$$

where  $z_i^r = \{0, 1\}$ ,  $r \in \{s, w\}$  is the dummy variable for the investment decisions of MG  $i$  for solar and wind generators. When this variable is 1 and 0, the MG invests and does not

<sup>1</sup>In this paper, we define the profit as the amount of reduction between the cost of networked MGs and the sum of costs of isolated MGs.

invest, respectively. The capacity of the renewable generator to be installed is  $G_i^r$ . The coefficients of the cost function are  $F_i^r$ ,  $a_i^r$  and  $b_i^r$ . The constant term  $F_i^r$  is the initial cost of installation, and  $a_i^r$  and  $b_i^r$  are the coefficients of the second- and first-order terms, respectively.<sup>2</sup>

Note that in this work, the investment cost function is not necessarily limited to such a quadratic function. Any types of investment cost function is acceptable only if the optimization problem in Section V is able to be solved. Also, (1) can represent a linear cost function by setting  $a_i^r = 0$ .

### B. SHORT-TERM OPERATIONAL COST

This section describes the second-stage cost of MG  $i$ , that is, the short-term operational costs  $C_i^O$ . We use the operation period of one day, which is divided into  $T = \{1, 2, \dots, 24\}$ . First, the daily operational power supply and demand need to be defined. The demand of MG  $i$  at time  $t$ ,  $d_i^t$ , represents the total power demand of an MG. On the supply side, the electricity supply to MG  $i$  at time  $t$  consists of the amount of power purchased from the main grid  $q_i^t$  and the MG's own renewable generation  $g_i^t$ . The amount of electricity self-generated by renewable generators is limited by the installed capacity  $G_i^r$  determined by the first stage. That is,

$$g_i^t \leq \sum_r G_i^r \eta_i^{r,t}, \quad \forall t \in T, \forall i \in N \quad (2)$$

where  $\eta_i^{r,t}$  denotes the generation efficiency of renewable generator  $r$  at time  $t$ . Moreover, the electricity flow between MG  $i$  and the main grid is limited by

$$P_i^{min} \leq q_i^t \leq P_i^{max}, \quad (3)$$

where  $P_i^{min}$  and  $P_i^{max}$  are the minimum and maximum amounts of electricity of  $q_i^t$ , respectively. Note that when  $q_i^t < 0$ , MG  $i$  sells its electricity to the main grid. If a reverse power flow to the main grid is not allowed,  $P_i^{min} = 0$ .

Now, we formulate the cost function of daily operation. As the amount of self-generated electricity is determined by the installed capacity  $G_i^r$  determined in the first stage, the cost of the second stage of the operation is the sum of the purchasing costs from the main grid. This can be expressed as

$$C_i^O(\{q_i^t\}_t) = \sum_t p^t q_i^t, \quad (4)$$

where  $\{p^t\}_t$  denotes the electricity price supplied by the main grid at  $t$ . It is defined as

$$p^t = \begin{cases} p_b^t & \text{if } q_i^t \geq 0 \\ p_s^t & \text{if } q_i^t < 0 \end{cases} \quad (5)$$

where  $p_b^t$  and  $p_s^t$  are electricity purchasing and selling prices, respectively. We assume that  $p_b^t > p_s^t, \forall t \in T$ , as is the case

<sup>2</sup>In [21], the long-term investment cost has two constraints which is related with capacity bound of renewable generators because of geographical, financial, and environmental conditions. However, in this paper, because of the characteristics of the quadratic function of the investment cost (1), this limitation naturally contains in the cost function. Therefore, we do not have constraints on the long-term investment problem as another reference work [4].

in most countries having high penetrations of renewable generators [25].

### III. COOPERATIVE MICROGRIDS PLANNING

Each MG locally balances supply and demand and attempts to minimize the total cost. MGs in different locations may have different profiles and potentials of renewable generation. For example, some locations have adequate renewable sources (e.g., long duration of bright sunshine or strong wind) or economical investment costs (e.g., low land price), whereas others do not. Networked MGs can leverage the diversity of renewable generation profiles through cooperative MG planning. However, when the MGs are not connected and they operate independently, they do not have incentives to overinvest in their local renewable generation and provide electricity to other MGs. Therefore, MGs first decide whether they are cooperative, as the optimal configurations of MGs can be different in non-cooperative and cooperative models. We first present a non-cooperative benchmark problem in this section.

#### A. NON-COOPERATIVE BENCHMARK

In the non-cooperative model, each MG only trades electricity with the main grid and does not exchange it with neighboring MGs. Each MG locally balances supply and demand and attempts to minimize the total cost.

Assuming that the power demand of MG  $i$ ,  $d_i^t$ , can be forecasted with a reasonable accuracy,<sup>3</sup> the local power balance constraint of each MG  $i$  can be expressed as

$$g_i^t + q_i^t = d_i^t, \quad \forall t \in T, \forall i \in N. \quad (6)$$

Now, under the non-cooperative model, we can define the total cost of MG  $i$ ,  $C_i^T$ , which consists of the sum of the long-term investment cost  $C_i^I$  and the short-term operating cost  $C_i^O$ . That is

$$C_i^T(z_i^s, G_i^s, z_i^w, G_i^w, \{q_i^t\}_t) = C_i^I(z_i^s, G_i^s, z_i^w, G_i^w) + \delta C_i^O(\{q_i^t\}_t), \quad (7)$$

where  $\delta$  is a time discount factor that captures the future operating costs at the investment decision stage.<sup>4</sup>

Then, we can formulate the expected total cost minimization problem of MG  $i$  as

$$(NCP) \quad \min_{(z_i^r, G_i^r, q_i)} C_i^T \quad \text{s.t. (2), (3) and (6),} \quad (8)$$

and obtain the optimum denoted as  $C_i^{NC}$ , which is the minimum expected total cost of MG  $i$  that can be achieved without cooperation with the other MGs.

<sup>3</sup>Recent research on a load forecasting for MG [26] shows that its mean absolute percentage error (MAPE) is 3.74 which means that the day-ahead forecasted load is very close to the actual load.

<sup>4</sup>We may consider  $\delta \equiv \sum_{k=1}^K \frac{1}{(1+r_k)^k}$  where  $K$  is lifespan of the MG and  $r_k$  is the interest rate in the period  $k$ .

**B. COOPERATIVE PLANNING**

In the cooperative model, all the MGs in the cooperation group exchange their electricity with the other MGs and with the main grid. Therefore, we first define the amount of electricity supplied from MG  $j$  to MG  $i$  at time  $t$  as  $e_{ij}^t$ . The electricity exchange originates from the power output of the renewable generator. Therefore, the total electricity supply from MG  $i$  is limited by its amount of generation. That is

$$\sum_{j \in N} e_{ji}^t \leq \sum_r G_i^r \eta_i^{r,t}, \quad \forall t \in T, \forall i \in N \quad (9)$$

where  $\sum_j e_{ji}^t$  represents the total electricity supplied from MG  $i$  to the other MGs. Thus,  $e_{ii}$  indicates the amount of electricity consumed by MG  $i$  itself. The right-hand side of (9) represents the total amount of electricity generated by MG  $i$  at time  $t$ . Note that we assume that the transfer capacity of the power line between MGs is sufficiently large.

Thus, we have a new balance equation for MG  $i$  that includes the electricity exchange in the networked MGs. It is expressed as

$$\sum_{j \in N} \eta_{ij} e_{ij}^t + q_i^t = d_i^t, \quad \forall t \in T, \forall i \in N \quad (10)$$

where  $\eta_{ij}$  denotes the distribution efficiency from MG  $i$  to MG  $j$ , which captures the loss during electricity delivery.<sup>5</sup> The first term on the left-hand side represents the total amount of electricity obtained by MG  $i$  from the other MGs which includes self-generated power  $e_{ii}$ . Then, the second term represents the amount of electricity purchased by MG  $i$  from the main grid. The right-hand side represents the load of MG  $i$ .

Now, we define a cooperative planning problem. The objective function under the cooperative model is the minimization of the sum of the total costs of each MG, which is given by

$$(CPP) \quad \min_{(z_i^t, G_i^r, e_i, q_i)} \sum_{i \in N} C_i^T \quad (11)$$

s.t. (3), (9) and (10)

where  $e_i = \{e_{ij}^t, \forall t, \forall j\}$ . Let  $C^T = \sum_i C_i^T$ ,  $C^I = \sum_i C_i^I$ , and  $C^O = \sum_i C_i^O$  denote the total cost, long-term investment cost, and short-term operating cost of the networked MGs, respectively.

Generally, the total cost of the cooperative model is lower than the sum of the costs of each MG in the non-cooperative model. In this paper, we define profit  $\pi$  as the reduced cost, that is, the sum of the costs of each MG in the **non-cooperative planning (NCP) model** minus the total cost of the **cooperative planning problem (CPP) model**. That is,

$$\pi = \sum_i C_i^{NC} - C^{T*}, \quad (12)$$

where superscript  $*$  denotes an optimal solution.

<sup>5</sup>The cost from losses due to electricity delivery is shared by MGs according to sharing rules in Section V.

Now, the question of a fair sharing of profit under cooperation arises. The following two sections tackle this question using cooperative game-theoretic solution concepts.

**IV. COOPERATIVE GAME THEORETIC SOLUTIONS FOR COST SHARING**

Several cooperative MG planning and profit-sharing rules based on various concepts (e.g., NBS [4], Shapley value [22]) have been investigated to encourage cooperative MG planning among networked MGs.

A cooperative game solution indicates how to share the gains obtained from cooperation among players. In the context of MGs, it indicates how to share the profits of energy cost reduction when MGs are connected to each other. In this section, we introduce the cooperative game-theoretic solutions used in the following analysis. First, we briefly review the two most common cooperative game solutions, NBS and Shapley value, and then, we introduce the Myerson value, a variant of the Shapley value designed for an incomplete network.

**A. NASH BARGAINING SOLUTION (NBS)**

As described in [11], the NBS consists of two parts. The first is the share of an individual player built upon the *feasible set* of achievable payoffs when players cooperate. The second is the *disagreement point*, which generally refers to the payoff of each player in a non-cooperative case. Formally, for  $n$  players, a bargaining problem is described as a pair  $(U, d)$  where a feasible set  $U \subset \mathbb{R}^n$  and disagreement point  $d \in U$ . Usually, it is assumed that  $U$  is convex and compact and that there exists some  $u \in U$  such that  $u > d$ , where  $u$  and  $d$  are the payoff and disagreement vectors of an individual player  $i \in N = \{1, \dots, n\}$ , respectively;  $u = \{u_i\}_{i=1}^n$  and  $d = \{d_i\}_{i=1}^n$ . Denoting the set of all possible bargaining problems by  $B$ , we can define a bargaining solution as a function  $f : B \rightarrow \mathbb{R}^n$  with  $f(U; d) \in U$ . Then, the NBS  $f$  is defined as

$$f(U; d) = \arg \max_{u \in U} \prod_{i \in N} (u_i - d_i). \quad (13)$$

We can interpret  $u_i$  as the share of the total profit received by player  $i$  under cooperation. If players have a symmetric bargaining power, the payoff distribution  $\{u_i\}_i$  through the NBS will be determined such that  $u_i - d_i$  is equalized across players. This indicates that the NBS is designed to assign a greater share to a player with a greater disagreement point.

**B. SHAPLEY VALUE: CONCERNING FAIRNESS**

Another frequently discussed cooperative solution for the MG situation is the Shapley value [27]. This solution is considered to compensate for energy exchange through fair payments for power transactions between power systems according to a mutually agreeable division of the joint operation costs.

Suppose that a coalition  $S$  is a subset of  $N$  and the set of possible coalitions among  $N$  is denoted as  $2^N = \{S | S \subseteq N\}$ .



Let  $s$  and  $n$  denote the numbers of players in  $S$  and  $N$ , respectively. A cooperative game where the Shapley value is defined is given by a pair  $(N, v)$ , where  $v$  is a characteristic function representing the total jointly earned payoff or profit of a coalition  $S, v : 2^N \rightarrow \mathbb{R}$  such that  $v(\emptyset) = 0$ . An allocation is a vector that specifies the payoff received by each player when he/she cooperates with the other players. An allocation rule on a class of games is a function  $\phi$  that assigns to every game  $(N, v)$  in that class an allocation  $\phi(N, v) \in \mathbb{R}^N$ . A value function  $\phi$  assigns to each possible characteristic function  $v$  of an  $n$ -person game  $\phi^{SV}(v) = (\phi_1^{SV}(v), \phi_2^{SV}(v), \dots, \phi_n^{SV}(v))$  of real numbers. Here,  $\phi_i^{SV}(v)$  represents the worth or value of player  $i$  in the game having the characteristic function  $v$ . The idea of the Shapley value is that, given a cost-sharing game, players join the game one at a time in a predetermined order. As each player joins, the cost contribution of each player is his/her net addition to the cost. The Shapley value of a player is the average cost contribution over all possible orderings of the players, and it supports a mutually agreeable division of costs with certain fairness properties. The Shapley value  $\phi_i^{SV}$  of player  $i$  is expressed as

$$\phi_i^{SV}(v) = \sum_S \frac{(s-1)!(n-s)!}{n!} [v(S) - v(S \setminus \{i\})] \quad (14)$$

where the summation subscript  $S$  indicates all the possible subsets of  $N$ , which include  $\{i\}$ . The term  $v(S) - v(S \setminus \{i\})$  refers to the marginal contribution of player  $i$  to the value of the entire coalition  $v(S)$ . Further, the expression  $\frac{(s-1)!(n-s)!}{n!}$  indicates the weighting factor that allocates a proportional share of the marginal contribution of each player in the coalition. Consequently, the Shapley value  $\phi_i^{SV}$  is assigned to player  $i$  according to a given function  $v$  that determines the gain  $v(S)$  for a coalition game  $(N, v)$  with transferable utility for the player set  $N$  measured by a function  $v$  for any non-empty subset  $S \subseteq N$ . Shapley [12] showed that this intuitive and fair solution is uniquely characterized by a set of reasonable axioms.<sup>6</sup>

### C. MYERSON VALUE: FAIRNESS IN A NETWORK

In this section, we consider a cooperative game theoretical solution concept, the Myerson value. Myerson [23] introduced *communication games* where a network representing the communication possibilities between players is associated with a cooperative game and defined a network-restricted game where only coalitions of connected players receive their initial value. In this setting, the role of the network is limited to determining which coalitions are connected. In [29], Jackson and Wolinsky considered a setting in which basic units that generate a value are the networks themselves rather than the coalitions of players. They called this setting *network games*. In their setting, the cooperation possibilities depend on the network structures connecting the players [30].

<sup>6</sup>Those axioms are the efficiency, symmetry, dummy, and additivity. For a detailed discussion on the Shapley value, see [28].

Formally, a communication network is a graph  $(N, g)$  describing the communication (e.g., electricity exchange in our context) possibilities between players. A network is defined as a list of unordered pairs of players  $\{i, j\}$ , where  $\{i, j\} \in g$  indicates that  $i$  and  $j$  are linked under network  $g$ . Here,  $ij \in g$  denotes the link  $\{i, j\}$  under network  $g$ . A link  $ij$  exists in  $g$  if and only if players  $i$  and  $j$  can communicate directly. The set of all possible networks is denoted by  $G$ . The network obtained by adding a link  $ij$  to an existing network  $g$  is denoted by  $g + ij$ , and the network obtained by deleting a link  $ij$  from an existing network  $g$  is denoted by  $g - ij$  (i.e.,  $g + ij = g \cup \{ij\}$  and  $g - ij = g \setminus \{ij\}$ ).

A characteristic function  $v : G \rightarrow \mathbb{R}$  generates the value of cooperation through the formation of links among players, where  $v(\emptyset) = 0$  and  $\emptyset$  is a network with no link. The set of all possible characteristic functions on  $G$  is denoted by  $V$  and  $v(g)$  represents the value generated by the MGs in  $N$  organized through network  $g$ . Then, a cooperative game enriched by a communication network  $(N, g)$  constitutes a network game denoted by the triplet  $(N, v, g)$  or more simply by  $(v, g)$  when  $N$  is fixed. An allocation rule  $\phi : G \times V \rightarrow \mathbb{R}$  describes how the value associated with each network is distributed to the individual players.  $\phi_i(g, v)$  is the payoff to player  $i$  from graph  $g$  under the characteristic function  $v$ . Denote  $N(g) = \{i | \exists j \text{ s.t. } ij \in g\}$  by the set of players involved in at least one link in  $g$  and  $n(g)$  by the cardinality of  $N(g)$ . A path in  $g$  connecting  $i_1$  and  $i_m$  is a set of distinct nodes  $\{i_1, i_2, \dots, i_m\} \subset N(g)$  such that  $\{i_1 i_2, i_2 i_3, \dots, i_{m-1} i_m\} \subset g$ . The network  $g' \subset g$  is a component of  $g$ , denoted by  $C(g)$ . If for all  $i \in N(g')$  and  $j \in N(g'), i \neq j$ , there exists a path in  $g'$  connecting  $i$  and  $j$ , and for any  $i \in N(g')$  and  $j \in N(g), ij \in g$  implies that  $ij \in g'$ . As the communication game is a richer object than a cooperative game as a basis for the vector space spanned by  $V$ , we focus on a class of value functions having a nice property of *component additivity*.

*Definition 1:* A value function  $v \in V$  is *component additive* if  $\forall g \in G$

$$v(g) = \sum_{g' \in C(g)} v(g') \quad \text{for any } g \in G \text{ and } g' \in C(g). \quad (15)$$

When a characteristic function is component additive, the value of a given component does not depend on the structure of the other components. That is, externalities across the components are precluded. Given any  $S \subset N$ , we may have a complete network among the MGs in  $S$ . Let  $g|_S = \{ij \in g \text{ and } i \in S, j \in S\}$  denote the subnetwork induced by  $g$  among the MGs in  $S \subset N$  obtained by deleting all the links except those that are between the MGs in  $S$ . The allocation rule of the Myerson value is expressed as

$$\phi_i^{MV}(v, g) = \sum_S \frac{(s-1)!(n-s)!}{n!} [v(g|_S) - v(g|_{S \setminus \{i\}})]. \quad (16)$$

where the summation subscript  $S$  represents all the possible subsets of  $N$  that include  $\{i\}$ .<sup>7</sup> Notice that the Myerson value

<sup>7</sup>For the detailed algorithms of the Shapley value and the Myerson value, see [31].

is an allocation rule that considers the position of player  $i$  in the network because it depends on  $g$  and  $v$ . It considers not only the network configuration but also how the generated value depends on the overall network structure. The Myerson value has several good properties similar to the Shapley value.

*Definition 2:* An allocation rule  $\phi$  on a network game is *component efficient* if, for every network game  $(v, g)$  in this class, and for every component

$$\sum_i \phi_i(v, g) = v(g), \quad \text{for all } v \text{ and } g. \quad (17)$$

This property is closely related to the efficiency property of the Shapley value. If the underlying network  $g$  is connected, then the component efficiency corresponds exactly to the efficiency. Fairness requires that removing a link between two players from the graph  $(N, g)$  changes the payoffs of both players by the same amount.

*Definition 3:* An allocation rule  $\phi$  on a class of network games satisfies *fairness* if, for every network game  $(v, g)$  in this class, and for any link  $ij \in g$ ,

$$\phi_i(v, g) - \phi_i(v, g - ij) = \phi_j(v, g) - \phi_j(v, g - ij). \quad (18)$$

Fairness requires that any two linked players benefit equally from their bilateral relationship. This corresponds to an equal treatment principle (or symmetry axiom for the Shapley value) as the two players obtain exactly the same gain (or loss) from the deletion of their link in the network. Myerson not only established that the Myerson value necessarily satisfies the above two conditions, but also that it is the only allocation rule verifying them.

*Theorem 1 (Myerson [1977]):* The Myerson value is the unique allocation rule on the class of communication games satisfying component efficiency and fairness.

## V. PROFIT-SHARING USING COOPERATIVE GAME THEORETIC SOLUTIONS

In this section, we explain how the joint profit is shared among MGs connected in a network according to the three cooperative game solutions presented in Section IV. Although the cost is shared, we use the term ‘‘profit-sharing’’ in that the MGs share the profit from cost reduction due to cooperation. Applying cooperative game-theoretic solutions, we classify the network conditions into two categories: complete and incomplete networks. A complete network indicates that all the nodes in it are connected, that is, it is a fully connected network; incomplete networks indicate the opposite. We first investigate cooperative planning and profit-sharing rules for a complete network and subsequently for an incomplete network.

### A. PROFIT-SHARING VIA NASH BARGAINING SOLUTION FOR COMPLETE NETWORKS

For the NBS, it is convenient to consider the choices of MGs in two steps, as described in [4]. During the planning period, the networked MGs cooperatively decide their grid configuration and share the investment costs through a sharing rule.

During the operation period, each MG operates and bears its operating cost, but such individual operation costs are already considered in the predetermined sharing rule. In other words, the profit share in the planning period covers not only investment cost but also operation cost, that is, the total cost. Let  $u^I = \{u_i^I\}_i$  be the joint investment cost-sharing vector for all the MGs. The summation of all the individual investment cost shares should be equal to the total investment expense. That is,

$$\sum_i u_i^I = \sum_i C_i^I \quad (19)$$

Such a profit-sharing scheme should cover the total cost. In addition, the total cost of each MG should be less than that in the non-cooperative benchmark to guarantee that each MG is willing to participate in cooperative planning. This yields the following incentive constraint:

$$u_i^I + \delta C_i^O(q_i) \leq C_i^{NC}, \quad \forall i \in N. \quad (20)$$

Note that the total cost of MG  $i$  in the cooperative model consists of its shared investment cost  $u_i^I$  and the total expected operational cost  $\delta C_i^O(q_i)$ .

An NBS can be expressed as

$$(NBS) \quad \max_{(z_i^I, G_i^I, e_i, q_i, u_i)_i} \prod_{i \in N} [C_i^{NC} - (u_i^I + \delta C_i^O(q_i))] \\ \text{s.t. (3), (9), (10), (19), and (20)}$$

To solve this, we conduct two steps, as described in [15]. First, we solve the joint investment and operation problem of the system, which is the same as the cooperative planning problem (CPP). Second, given the optimal planning and operation decisions in the first step, the cost-sharing problem (CSP) is formulated as

$$(CSP) \quad \max_{u_i^I} \prod_{i \in N} [C_i^{NC} - (u_i^I + \delta C_i^{O*})] \\ \text{s.t. (19) and (20).} \quad (21)$$

Given the optimal planning of renewable generation by solving the (CPP) we solve the (CSP) to derive the optimal cost sharing to incentivize cooperative planning. The (CPP) can be solved using a mixed-integer programming solver, and the (CSP) is a standard convex optimization problem. As a solution to (21), we can obtain the investment cost share for MG  $i$  ( $u_i^{I*}$ ) as follows:

$$u_i^{I*} = C_i^{NC} - \delta C_i^{O*} + \frac{\sum_j (C_j^{I*} + \delta C_j^{O*}) - \sum_j C_j^{NC}}{n}. \quad (22)$$

In terms of the total cost-sharing, the profit share received by an individual MG  $i$  according to NBS ( $\phi_i^{NBS}$ ) is given by

$$\phi_i^{NBS} = u_i^{I*} + \delta C_i^{O*}. \quad (23)$$

Notice that the summation of (23) over  $i$  with (22) yields  $\sum_i \phi_i^{NBS} = \sum_i C_i^I$  again. From the result of (23), we observe that the profit share of MG  $i$  is increasing in its outside option,

that is, its cost in a non-cooperative case,  $C_i^{NC}$ . However, the profit share of MG  $i$  under the NBS  $\pi_i^{NBS} = C_i^{NC} - \phi_i^{NBS}$  is equally distributed over the MGs in the network. That is,  $\pi_i^{NBS}$  does not vary according to  $i$ , that is,

$$\pi_i^{NBS} = \frac{1}{n} \left\{ \sum_j C_j^{NC} - \sum_j (C_j^{I*} + \delta C_j^{O*}) \right\}. \quad (24)$$

**B. PROFIT-SHARING VIA SHAPLEY VALUE FOR COMPLETE NETWORKS**

Consider a case in which the joint profit is allocated through the Shapley value. In this case, the cost of MG  $i$  will be  $\phi_i^{SV}$  in (14). The characteristic function  $v(S)$  in our context is the sum of the total costs of each MG in coalition  $S$ , and it is obtained by solving the modified (CPP). That is, by replacing  $N$  with  $S$  for both the objective function and related constraints, we can have the (CPP<sub>S</sub>) for a given coalition  $S$  as follows:

$$(CPP_S)v(S) = \min_{(z_i^r, G_i^r, e_i, q_i)} \sum_{i \in S} C_i^T$$

s.t. (3), (9) and (10)

According to the definition of the Shapley value, we need to calculate  $v(S)$  for each  $S \in 2^N$ . Substituting each value in (14), we can obtain the profit share of MG  $i$  via the Shapley value,  $\phi_i^{SV}$ .

**C. PROFIT-SHARING VIA MYERSON VALUE FOR INCOMPLETE NETWORKS**

Both the NBS and Shapley values are obtained under the assumption of a complete network. However, this assumption is not always valid in power networks. Some MGs in a power network are directly connected to each other, whereas others are not. This incomplete connectedness results in each MG having a different position on the network. For instance, the positions of the MGs are not homogeneous in a star-shaped topology. An MG in an edge position can be connected to the MGs in other edge positions only through the central MG, whereas the central MG can be directly connected to any MG in the network. Thus, we introduce a Myerson-value-based profit-sharing rule to capture the position heterogeneity of MGs. As the Myerson value is a variation of the Shapley value, a similar mapping is used. As the characteristic function  $\phi(v, g)$  of the Myerson value varies under a network condition  $g$ , the (CPP) needs to be modified accordingly as follows:

$$(CPP_g)v(g|S) = \min_{(z_i^r, G_i^r, e_i, q_i)} \sum_{S' \in S|g} \sum_{i \in S'} C_i^T$$

s.t. (3), (9) and (10)

where  $S|g$  denotes the partition of  $S$  consisting of the maximal connected coalitions induced by  $g$ . According to the definition of the Myerson value, we need to calculate  $v(g|S)$  for each  $S \in N|g$  and for given  $g \in G$ . Substituting each value in (16), we can obtain the profit share of MG  $i$  via the Myerson value,  $\phi_i^{MV}$ .

**TABLE 1. Total cost  $C^T$  for all combinations according to topologies.**

$S$	{L}	{H <sub>1</sub> }	{H <sub>2</sub> }	{L, H <sub>1</sub> }	{L, H <sub>2</sub> }	{H <sub>1</sub> , H <sub>2</sub> }	{L, H <sub>1</sub> , H <sub>2</sub> }
$C^T$	50	100	100	120	200	200	220

**D. COMPARISON OF SOLUTIONS**

This section compares the different profit-sharing rules using a simple numerical example, particularly illustrating how the Myerson value can capture the position aspect of each MG, whereas the other solutions cannot. Suppose that there are three MGs, and each MG is one of two regional types,  $L$  and  $H$ . The  $L$ -type region indicates a region with a low load and abundant renewable potential, whereas the  $H$ -type region has a high load and scarce potential. Suppose that there is one  $L$ -type region and two  $H$ -type regions, denoted by  $L$ , and  $H_1$  and  $H_2$ , respectively.

The cost structure for each case is summarized in Table 1. When all the three MGs cooperate with each other, the total cost becomes 220. If they do not cooperate at all,  $L$  bears a cost of 50, whereas each of  $H_1$  and  $H_2$  bears a cost of 100. That is, the total profit  $\pi$  from cooperation is 30. When  $L$  and only one  $H_1$  cooperate, the joint cost is 120. Finally, when both  $H_1$  and  $H_2$  cooperate, their joint cost is 200.

Now, consider how MGs share the gains from cooperation according to the different profit-sharing rules.

1) NASH BARGAINING SOLUTION

For simplicity, it is assumed that there is no operation cost,  $C_i^O = 0$  for all  $i$ . Then, the NBS in (22) and (23) is simplified as  $\phi_i^{NBS} = u_i^{I*} = C_i^{NC} + \frac{1}{n}(\sum_i C_i^{I*} - \sum_j C_j^{NC})$ . From the above cost structure,  $C_L^{NC} = 50$ ,  $C_{H_i}^{NC} = 100$ ,  $\sum_i C_i^{I*} = 220$ , and  $n = 3$ . Thus, from (23), the profit sharing of each MG  $i$  under the NBS is  $\phi_L^{NBS} = 40$  and  $\phi_{H_i}^{NBS} = 90$  for  $i \in \{1, 2\}$ , so  $\pi_i^{NBS} = 10$  for each MG  $i$ .

That is, under the NBS, an MG that faces a higher cost in a non-cooperative situation tends to attain a larger share. Whether a sharing rule fairly accounts for the individual cost and generation contributions to the joint operation can be considered to calculate the payments for the power exchanged. However, the NBS does not account for such a concern.

2) SHAPLEY VALUE

To obtain the Shapley value, we first need to calculate the value for each coalition from the cost structure. That is, the value function  $v$  for each coalition is the same as  $C^T$  in Table 1, and we assume a grand coalition, that is,  $s = n = 3$ . Thus, from (14), the Shapley values for each MG are  $\phi_L^{SV} = 30$  and  $\phi_{H_i}^{SV} = 95$ . Therefore, the profits under the Shapley value are  $\pi_L^{SV} = 20$  and  $\pi_{H_i}^{SV} = 5$ . In this example, as there is only one abundant resource region, it is rewarded twice as much and the other high-load regions are rewarded half as much compared with the profits under the NBS. It is confirmed that the Shapley value counts the contribution of each MG, whereas the NBS does not. Note that when there are two  $L$ -type MGs ( $L_1$  and  $L_2$ ) and one

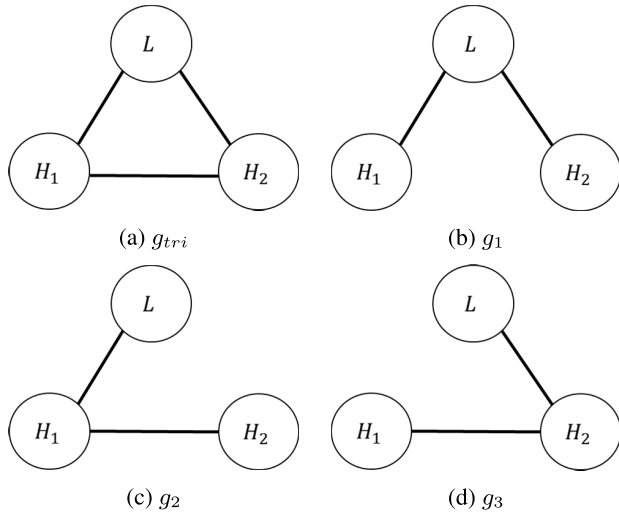


FIGURE 1. Network structures.

$H$ -type MG ( $H$ ), the result is the opposite. That is,  $\pi_{L_i}^{SV} = 5$  and  $\pi_H^{SV} = 20$ .

Although the Shapley value is a cooperative solution considering fairness, there is a limitation in that the relationship among the MGs in the network structure is overlooked.

### 3) MYERSON VALUE

For the Myerson value, we need to consider the topology of the network explicitly. There are two possible topologies with three MGs: triangle and line topologies. The triangle topology represents a complete network and the result shows no difference between the Shapley and Myerson values in this example. In contrast, the line topology is an incomplete network in that there is an unconnected pair of MGs. Three different network structures  $g_1, g_2, g_3$  are possible, which are expressed as follows:

$$\begin{aligned} g_{tri} &= (\{LH_1\}, \{LH_2\}, \{H_1H_2\}), \\ g_1 &= (\{LH_1\}, \{LH_2\}), \\ g_2 &= (\{LH_1\}, \{H_1H_2\}), \\ g_3 &= (\{LH_2\}, \{H_1H_2\}). \end{aligned}$$

The graphical representations of  $g_{tri}, g_1, g_2,$  and  $g_3$  are shown in Fig. 1.

The elements required to calculate the Myerson value can be described as follows. As an example, consider a case under  $g_2$ . Here,  $v(g_2|_S)$  needs to be obtained for all  $S \subseteq N$  to obtain the Myerson value. First, notice that  $v(g_2|_N) = 220$  because  $N|_{g_2} = N = \{L, H_1, H_2\}$ .<sup>8</sup> We define  $S_{LH_1} \equiv \{L, H_1\}$ ,  $S_{LH_2} \equiv \{L, H_2\}$ , and  $S_{H_1H_2} \equiv \{H_1, H_2\}$ . Then, we can observe that  $S_{LH_1} = S_{LH_1}|_{g_2}$  and  $S_{H_1H_2} = S_{H_1H_2}|_{g_2}$  because these pairs are connected. However, the case of  $S_{LH_2}$  is different in that there is no  $LH_2$  link. That

<sup>8</sup>We slightly abuse a notation here. Because  $N|_{g_2}$  is a partition, it should be denoted by  $\{\{L, H_1, H_2\}\}$ .

TABLE 2. Myerson value  $\phi_i^{MV}$  according to different topologies. When the topology is complete,  $\phi_i^{MV}$  is the same as the Shapley value  $\phi_i^{SV}$ .

Topology	$L$	$H_1$	$H_2$
$g_{tri}$	30	95	95
$g_1$	30	95	95
$g_2$	35	85	100
$g_3$	35	100	85

is,  $S_{LH_2}|_{g_2} = \{\{L\}, \{H_2\}\} \neq S_{LH_2}$ . Thus, from Table 1, we can compute the value for each sub-network.  $v(g_2|_{S_{H_1H_2}}) = 200$ ,  $v(g_2|_{S_{LH_2}}) = 150$ , and  $v(g_2|_{S_{LH_1}}) = 120$ . We omit singleton cases because they are straightforward. Therefore, from (16), the Myerson values for each MG  $i$ ,  $\phi_i^{MV}$ , are listed in Table 2.

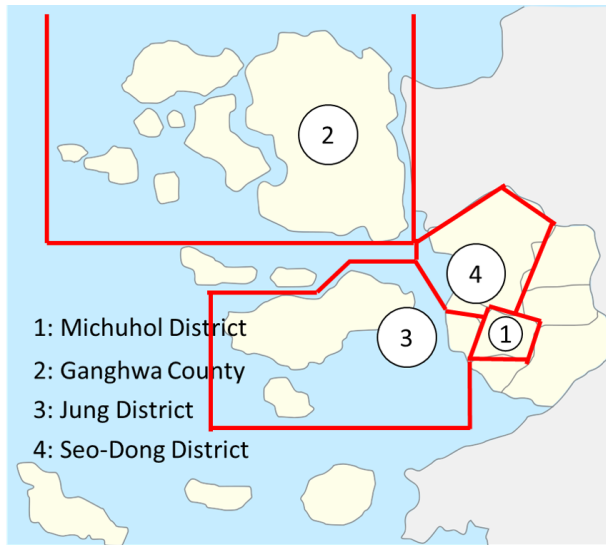
As expected, the profit share of an MG varies depending on its position. Whenever an MG takes a central position, it obtains a greater profit share compared with the case where it takes a peripheral position. This is because a central MG contributes to the coalition by playing a bridging role between the peripheral MGs. In this example,  $L$  obtains a profit of  $\pi_L^{MV} = 20$  when it is located at the center, that is, Fig. 1b, whereas it obtains a profit of  $\pi_L^{MV} = 15$  when it is in the periphery, that is, Figs. 1c and 1d. In addition, under  $g_2$ ,  $H_1$  is located at an important position, that is, connecting the edges. Without  $H_1$ ,  $L$  cannot connect to the other MGs. Therefore,  $L$  and  $H_1$  equally share the profits from cooperation, that is,  $\pi_L^{MV} = \pi_{H_1}^{MV} = 15$ . However, as  $H_2$  is at the edge and connecting  $H_1$  and  $H_2$  yields a profit of 0, it obtains no profit, that is,  $\pi_{H_2}^{MV} = 0$ . The same result is observed under  $g_3$ . In this graph,  $H_2$  obtains a greater profit because of its positional contribution.

For the NBS, we may calculate the profit even for incomplete networks. However, notably, the NBS is obtained in two parts: the joint cost under the cooperative part and the individual cost under the non-cooperative part  $d$ . As electricity exchange between MGs is possible as long as they are linked either directly or indirectly, the connected MGs incur the same joint costs under cooperation and individual costs under non-cooperation, regardless of their position in the network structure. Thus, the network position does not affect the NBS for each MG. Note that it is evident why the Shapley value does not capture the network aspect, based on its definition (14).

## VI. EVALUATIONS

In this section, we first evaluate the amount of profit, which is defined as the sum of costs of non-cooperative MG planning minus the cost of cooperative MG planning, as presented in Section III. Then, the proposed profit-sharing rule based on the Myerson value is evaluated in comparison with those based on the NBS and Shapley value. A case study is performed using real data from Incheon, a first-tier administrative division in Korea. We use CVX, i.e., a package for specifying and solving convex programs, to get an optimization solution [32].





**FIGURE 2.** Map of Incheon. It is assumed that grid-connected MGs supply electricity for the four regions: Michuhol District, Ganghwa County, Jung District, and Seo-Dong District.

**A. PARAMETER SETTINGS**

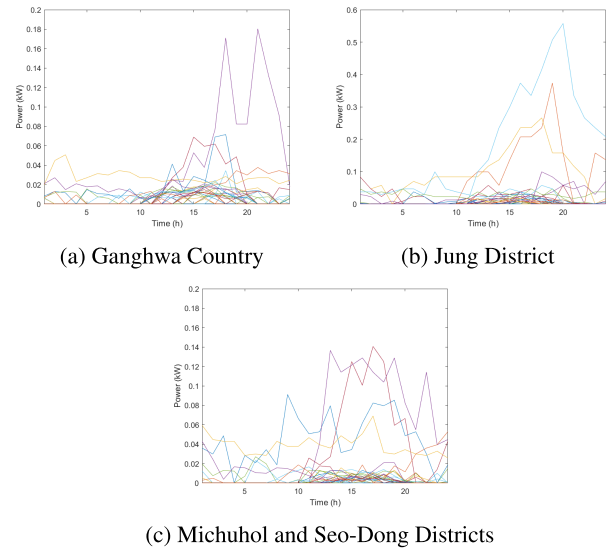
Incheon, located on the west coast of Korea, consists of 10 second-tier administrative divisions: eight districts (mostly industrial and commercial areas) and two counties (mostly agricultural areas). To simplify our case study, we chose five of the above regions and combined two homogeneous districts (Seo District and Dong District) into a single district (Seo-Dong District). Therefore, we consider four regions: Michuhol District, Ganghwa County, Jung District, and Seo-Dong District. It is assumed that they built grid-connected MGs. Their geographical representation is shown in Fig. 2. The four regions show different characteristics in terms of renewable resources, load curves, and land prices.

Incheon has three meteorological stations, which are located in Ganghwa County, Jung District, and the inland area (Michuhol District and Seo-Dong District). From these stations, we can obtain wind speed data from Korea Meteorological Administration,<sup>9</sup> and the wind power outputs are derived using the corresponding equation [33, eq. (4), p. 9].<sup>10</sup> Fig. 3 shows the wind power outputs in the Incheon region using meteorological data in April 2018. Among the three regions, Jung District has the best wind resources. We assume that the solar irradiation of the four regions is almost the same because they are geographically close to each other.

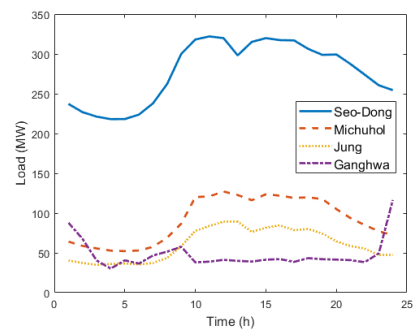
In Michuhol District, the electricity consumption for residential and commercial loads is more than 70%. Ganghwa County is an agricultural area in which there is a considerable

<sup>9</sup>Korean Meteorological Data Portal, Standard Bulletin (Korean), <https://data.kma.go.kr/data/grnd/selectAsosRltmList.do?pgmNo=36>

<sup>10</sup>That is  $P_w = \frac{1}{2} \rho A \bar{u}^3$ , where  $\rho$ ,  $A$ , and  $\bar{u}$  denote the density of the air, blade swept area, and wind speed, respectively. In this equation, wind power output is proportional to the cube of the wind speed. We use cut-in speed and rated speed as 3.45 m/s and 20 m/s, respectively.



**FIGURE 3.** Wind power output of Incheon districts on 10 days of April, 2018.



**FIGURE 4.** Daily load curves for the four regions on a day in April 2018.

consumption of midnight electricity.<sup>11</sup> Midnight electricity accounts for approximately 25% of the total electricity consumption in this region. In Jung District, commercial and industrial loads account for a major proportion of electricity consumption (more than 85%). Seo-Dong District is an industrial area that consumes a high amount of electricity. Industrial load accounts for more than 80% of the total load in the region. Fig. 4 shows the daily load curves for the four regions on a day in April 2018.<sup>12</sup> As Seo-Dong District is a distinct industrial area, its load is the highest, and it consumes a considerable amount of electricity even during the night. Ganghwa County consumes more electricity during the night than during the day owing to its high consumption of midnight electricity and its lowest population. Michuhol and Jung Districts show normal commercial and residential load curves.

<sup>11</sup>Midnight electricity provided by KEPCO is designed for heat storage appliances and cool storage system during off-peak time. Further detailed information is available at <http://cyber.kepcoco.kr/ckepco/front/jsp/CY/E/E/CYEEHP00207.jsp>.

<sup>12</sup>We use this actual load data as the power demand of MG  $i$ ,  $d_i^t$  to solve (NCP), (CPP), and the cooperative game problem.

**TABLE 3. Land price and parameter settings of Michuhol District, Ganghwa County, Jung District, and Seo-Dong District (unit of land price: KRW/m<sup>2</sup>, where 1 USD = 1,200 KRW).**

Region	Land price	$a_n^s$	$b_n^s$	$F_n^s$	$a_n^w$	$b_n^w$	$F_n^w$ (KRW)
Michuhol	8,634	100	1000	0	-	-	-
Ganghwa	291	5	1000	0	1.25	350	600,000,000
Jung	5,827	30	1000	0	1.25	350	600,000,000
Seo-Dong	6,573	65	1000	0	-	-	-

Table 3 lists the land price and parameter settings for the four regions. Solar PV installation costs can be classified into linear and curvature costs with the capacity of PV generators. Linear costs represents a fixed costs per unit capacity of solar PV. Examples of linear costs include the costs of solar panels, inverters, and junction boxes. The linear cost is modeled as the first-order coefficient  $b_n^s$  in (1). Curvature costs are assumed to be described by the second-order coefficient  $a_n^s$  in (1). The second-order coefficient captures the land price to build the renewable generator which increases as the amount of the renewable generator increases. It is because the renewable generator will be installed from low land price area to high. The second-order coefficient varies with the region. We use the official land price announced by the Ministry of Land, Infrastructure and Transport in Korea to estimate the variable costs in each region.<sup>13</sup> Accordingly, the coefficient values of investment cost for solar PV ( $a_n^s$  and  $b_n^s$ ) are obtained. Moreover, it is assumed that solar PV does not require a fixed cost, i.e.,  $F_n^s = 0, \forall n \in N$  because solar PV will be installed inland areas. However, as Korea does not have sufficient wind resources in inland areas, we assume that there is no plan to install wind farms in these areas. We only consider offshore wind farms, such as those in Ganghwa County and Jung District. To build offshore wind farms, it is assumed that a considerable fixed cost  $F_n^w$  is required and that the wind turbine has relatively low coefficient values.

In this case study, we use the time-of-use (TOU) price offered by the Korea Electric Power Corporation (KEPCO) for the purchasing price of electricity from the main grid  $p_b^t$ . The electricity price is set as KRW 61.6/kWh, KRW 84.1/kWh, and KRW 114.8/kWh during off-peak, mid-peak, and peak periods, respectively.<sup>14</sup> We assume that the selling price to the main grid is half the purchasing price, that is,  $p_s^t = \frac{1}{2}p_b^t$  [34]. In addition, the amount of electricity transferred from/to the main grid is not limited, that is,  $P_i^{min}$  and  $P_i^{max}$  are sufficiently large. We set the time discount factor  $\delta$  to 5.5% per year, the lifespan of each MG to 20 years, and the distribution efficiency between any two MGs  $\eta_{ij}$  to 98%. Note that Choosing  $\eta_{ij}$  is an important factor in the case of international connections such as the Asian super grid. However, in this work, because Incheon is a small land size, we set a constant value for all power flows.

<sup>13</sup>Public Data Portal, Standard Bulletin (Korean), <https://www.data.go.kr/dataset/15004246/fileData.do>

<sup>14</sup>Further detailed information on electricity price is available at <https://home.kepco.co.kr/kepco/EN/F/htmlView/ENFBHP00102.do?menuCd=EN060201>. And the currency is 1 USD = 1,200 KRW

## B. SIMULATION RESULTS

### 1) MICROGRID PLANNING

We first investigate the MG planning result for three scenarios: i) without MG, that is, without installing renewable generators ii) non-cooperative MG planning, and iii) cooperative MG planning. In non-cooperative planning, MGs do not exchange electricity with each other, they either purchase electricity from the main grid or use the electricity generated by their own renewable generators.

Table 4 presents the MG planning results for each scenario. Even under a non-cooperative case, all the four regions have an incentive to install renewable generators because the difference in overall costs between the cases with and without renewable generators is large. Electricity supply with renewable options allows the regions to achieve a cost reduction of 12.5%. The saving varies with the region. Because of high land prices and poor wind resources, Michuhol District and Seo-Dong District have little incentive to invest in renewable resources, so they attain a small profit. Ganghwa County has a strong incentive to invest in solar PV owing to its low land price, but it does not have sufficient incentive to invest in wind turbines because of its low wind speed. Finally, Jung District invests in both wind farms and solar PV due to its good wind resources.

The installed capacity of solar PV for Michuhol District is 15,796 kW, and its investment cost is 25 billion KRW. That is, the average cost of solar PV generators per Watt is about 1,581 KRW/W (1.32 USD/W). Note that according to the NREL technical report [35], the PV system cost per Watt is 1.83 USD/W and 1.06 USD/W in 2018 for commercial (200 kW) and utility-scale (100 MW), respectively, which confirms that the parameter settings in this work reflect the reality.

In a cooperative case where electricity exchange between MGs is possible, MGs are expected to achieve cost reduction jointly. This is because MGs with rich renewable resources may invest in more renewable generators, and consequently, MGs in high-load regions may import electricity from their neighbor MGs at a lower price than that from the main grid. Table 4 lists the costs and renewable capacities of the cooperative case. The overall cost of the four MGs in the cooperative case is 3,560 billion KRW, which is 6.95% (266 billion KRW) lower than that of the non-cooperative case with renewable resources.

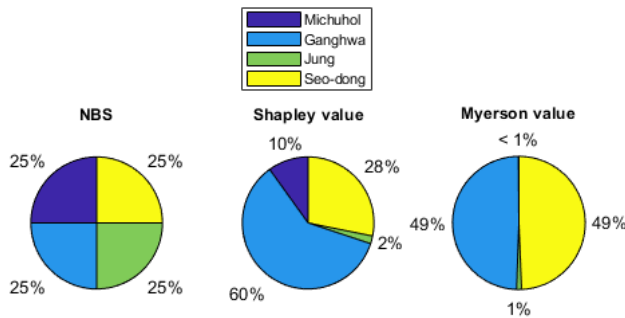
In the last two rows of Table 4, the capacities of the installed renewable generators in the case of non-cooperative and cooperative MGs are derived, allowing comparison between the two cases. In the scarce resource regions (Michuhol and Seo-Dong), there is almost no difference in the amounts of installed renewable generators between the two cases. In addition, Jung District shows little difference because the potential capacity of its renewable resources is similar to the supply of electricity in the region. However, Ganghwa County which has abundant renewable resources invests more in renewable generators. In the case

**TABLE 4. Microgrid planning result: cost and installed renewable capacity (unit of cost: billion KRW).**

		Michuhol	Ganghwa	Jung	Seo-Dong	total
without renew.	$C_i^T$	864	409	573	2,528	4,374
non-cooperative MG	$C_i^T = C_i^I + \delta C_i^O$	839	193	305	2,490	3,826
	$C_i^I$	25	134	183	38	381
	$\delta C_i^O$	814	58	121	2,452	3,445
	$G_i^s$ (kW)	15,796	163,835	43,653	24,301	247,585
cooperative MG	$G_i^w$ (kW)	0	0	316,602	0	316,602
	$C^T = C^I + \delta C^O$					3,560
	$C^I$					816
	$\delta C^O$					2,744
	$G_i^s$ (kW)	15,480	309,597	51,600	23,816	400,493
	$G_i^w$ (kW)	0	0	394,673	0	394,673

**TABLE 5. Profit-sharing results for the NBS, Shapley value, and Myerson value. The bold font means the highest profit. (unit: billion KRW).**

	Michuhol	Ganghwa	Jung	Seo-Dong
$C_i^{NC}$	839	193	305	2,490
$\phi_i^{NBS}$	772	126	238	2,423
$\pi_i^{NBS}$	<b>66.5</b>	<b>66.5</b>	<b>66.5</b>	<b>66.5</b>
$\phi_i^{SV}$	812	33	300	2,415
$\pi_i^{SV}$	26.5	<b>159.6</b>	5.0	75.0
$\phi_i^{MV}$	838	61	301	2,359
$\pi_i^{MV}$	0.3	131.2	3.2	<b>131.4</b>



**FIGURE 5. Percentage profit shares according to the different profit-sharing rules.**

of non-cooperative MGs, although Ganghwa County has sufficient scope to install more renewable generators, its own loads do not consume the self-supplied electricity completely. After cooperation, the high-resource regions can find the demand for its excess potential supply. Then, the question of distributing such joint profit among these regions arises.

2) PROFIT-SHARING

This section compares the results of the profit-sharing rules: the NBS, Shapley value, and Myerson value. Table 5 lists the total cost and profit  $\pi_i$  of MG  $i$ , and Fig. 5 shows the distribution of the joint profit among the MGs under each sharing rule. Note that the joint profit from cooperation is 266 billion KRW, that is,  $\pi = 3,826 - 3,560 = 266$ , for all profit-sharing rules.

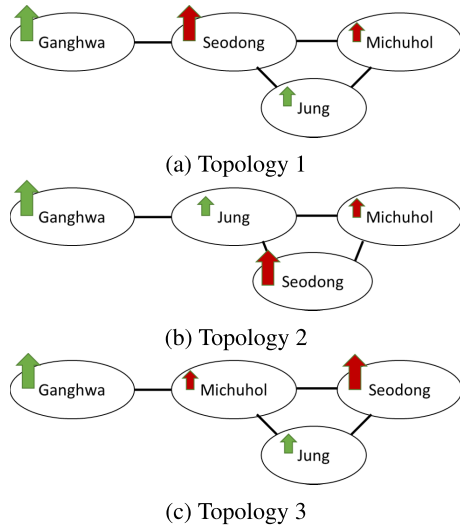
• Profit-Sharing Results for the NBS, Shapley Value, and Myerson Value

We consider the NBS case first. In terms of cost reduction “rate,” Michuhol, Ganghwa, Jung, and Seo-Dong could

reduce their overall cost by 7.9%, 34.5%, 21.8%, and 2.7%, respectively. However, in terms of the absolute amount of cost reduction, each MG receives the equal profit, as shown in Fig. 5, regardless of its contribution. This result is derived from the definition of the NBS, which maximizes the sum of cost differences between cooperation and non-cooperation for every participant. Each MG should obtain an equal difference, that is, individual profit, to maximize the product of the differences for each MG. Because it is not evident whether this sharing rule is fair, we investigate alternatives.

Another well-known candidate is the Shapley value. It is designed to reflect the contribution of each player, which is the amount of additional joint profit that can be attained by a region if it joins the network. The Shapley value  $\phi_i^{SV}$  of each MG  $i$  is listed in Table 5. As the participation of Ganghwa County is critical to creating joint profit, its supplier role is highly appreciated. Compared with the NBS, we can observe that the share of profits of Ganghwa County increased to 60% from 25%, as shown in Fig. 5. This is possible because the other regions incurred greater burdens (or received a smaller share of the joint profit) than under the NBS. Because of its role as the main consumer, Seo-Dong District received the second-largest share of profit, and thus, it incurred an almost similar profit to that under the NBS. Thus, the Shapley value successfully accounts for the “role” contribution of each player. However, both the Shapley value and NBS ignore how the MGs are connected in a network structure, so they achieve the same sharing outcomes regardless of the network structure. Consequently, they overlook the “positional” contribution of each MG in a network.

We construct a logical topology of Incheon, as shown in Fig. 6a to investigate the “positional” contribution of each region. From the figure, we can observe that Seo-Dong District is an important position that connects the main supplier, Ganghwa, and the other regions. Consequently, Seo-Dong District receives the same amount of profit as Ganghwa County under the Myerson-value-based sharing rule, as shown in Fig. 5. However, Michuhol and Jung Districts receive a very small amount of profit because they offer neither positional nor role contributions. Therefore,



**FIGURE 6.** Three reference topologies. Topology 1 is the original topology of Incheon, whereas the other topologies are modified to investigate the effect of the Myerson value. The green and red arrows at each MG represent the amount of natural resources and load, respectively. For example, Ganghwa and Seo-Dong have the largest amount of resources and highest load, respectively.

**TABLE 6.** Profit-sharing results for Myerson value under three different topologies. The bold font indicates the highest profit. (unit: billion KRW).

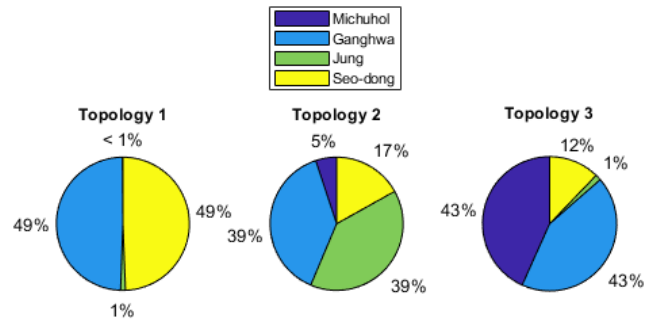
	Michuhol	Ganghwa	Jung	Seo-Dong
$C_i^{NC}$	839	193	305	2,490
$\phi_i^{MV1}$	838	61	301	2,359
$\pi_i^{MV1}$	0.3	131.2	3.2	<b>131.4</b>
$\phi_i^{MV2}$	825	90	200	2,445
$\pi_i^{MV2}$	13.5	102.6	<b>105.0</b>	45.0
$\phi_i^{MV3}$	723	78	301	2,458
$\pi_i^{MV3}$	<b>115.2</b>	114.7	3.8	32.4

it is confirmed that the Myerson value successfully accounts for not only the role contribution, but also the positional contribution.

**• Positional Contributions Captured by Myerson Value**

We conduct a hypothetical test by switching the positions of regions to investigate how the Myerson value considers the positional contribution of each MG. In addition to the original topology of Incheon, as shown in Fig. 6a, we consider two hypothetical topologies in Figs. 6b and 6c.

Table 6 lists the Myerson values for different topologies, where  $\phi_i^{MV1}$ ,  $\phi_i^{MV2}$ , and  $\phi_i^{MV3}$  denote the Myerson values for topologies 1, 2, and 3, respectively. Fig. 7 shows the profit of each MG for the three topologies. Topology 2 is formed by switching the position of Seo-Dong District with that of Jung District. In this topology, Jung District takes the link position between the supply and demand regions. Consequently, it can receive a major share of the profit. However, as Jung District does not have a sufficient load to consume the electricity from Ganghwa County, the high-demand regions (Michuhol and Seo-Dong Districts) also somewhat contribute under this topology.



**FIGURE 7.** Percentage profit shares based on the Myerson value according to three topologies.

Topology 3 is formed by switching the position of Seo-Dong District with that of Michuhol District. Similar to topology 2, Michuhol receives a major share of the profit, but not as much as that of Seo-Dong District in topology 1 because its load is not sufficient to consume the entire supply of Ganghwa County.

Notably, neither the NBS nor the Shapley value can yield such different outcomes corresponding to different topologies because neither solution considers the underlying network structure in its definition. In summary, we observe that the NBS does not account for either the role or positional contributions, and that the Shapley value accounts for the role contribution but not the positional contribution. However, the Myerson value accounts for both the role and positional contributions.

**VII. CONCLUSION**

Networked, or community, microgrids (MGs) are a promising trend to adopt intermittent and uncertain renewable energy resources. When heterogeneous MGs are connected to each other, the total cost of the MGs is reduced compared with the sum of the costs of isolated MGs. Thus, a rational and predictable profit-sharing rule is required to promote connections among MGs. In this paper, we proposed a profit-sharing rule in networked MGs based on the Myerson value. A profit-sharing rule based on the Nash bargaining solution (NBS) always shares the profit equally among the MGs. Another rule using the Shapley value only considers the role contribution of each MG. The proposed Myerson-value-based profit-sharing rule accounts for both the positional and role contributions of each MG. Through a case study using Korean data, we show the results of the different profit-sharing rules, thus confirming the validity of the proposed rule.

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