Abstract—In recent years, interest in smart grids has increased globally along with the trend to reduce greenhouse gas emissions. One of the smart grid research areas actively being done is energy trading in a microgrid. In particular, an energy trading system in the microgrid within an island should consider the own energy independence of the microgrid very seriously. In this paper, we propose a new metric to evaluate the energy independence of an energy trading system in a microgrid. The energy independence is discussed through energy trading simulation, which is first performed in this paper. Furthermore, we numerically present the proper energy trading cycle under various conditions with an existing energy trading mechanism.

I. INTRODUCTION

Recently, there has been a growing interest in smart grids in order to reduce greenhouse gas emissions worldwide. The global smart grid market, with a one-billion-dollar investment made in 2010, has been steadily growing despite the low oil price level since 2014. Also, the EU has set the 20-20-20 goals, which is to reduce greenhouse gas emissions by 20% from the emission level in 1990, to increase energy share ratio of renewable energy by 20%, and to improve energy efficiency by 20%; they are actively pursuing the construction of a smart grid to achieve these goals.

Energy trading among prosumers is emerging as a major research topic in smart grids. Prosumer, a synthesized word of producer and consumer, produces electricity by using a new and renewable energy generation facilities such as solar cells and wind turbines. He also sells the produced energy to the market or other prosumers. As the cost of installing renewable energy generators declined, and as the demand for reducing the electricity bills increased, a new market for these prosumers has been created. Originally, the advent of this new market is based on the growing environmental awareness, a demand for a new energy source, and the need in energy independence. These demands have been fulfilled via new technological advances such as distributed power generation, renewable energy, energy storage system (ESS), electric vehicles, etc. As a result, a new class called energy prosumers have emerged [1].

Many studies related to energy trading among prosumers in microgrid are under way. Because of the characteristics of prosumers that have a competitive relationship with each other in energy trading, there are many studies using game theory. In [2], Nash equilibrium is derived by modeling an energy trading mechanism as a Stackelberg game in a situation where energy trading among prosumers takes place periodically. This Nash equilibrium tells the price at which the prosumer will trade and how much energy the prosumer will sell. In [3], [4], when the necessary information is not given in [2], a methodology for deriving the same result using the learning technique is presented.

However, most energy trading researches including the above studies suggest an energy trading mechanism only for a single moment. In other words, there is no consideration on how the trading situation changes over time. In addition, there has not been evaluation and comparison of each energy trading mechanism. The goal of many energy trading papers is to maximize the energy independence of islands where each prosumer or prosumer is dense. Here, the concept of energy independence is mentioned in the smart grid industry in recent years, and it has been mentioned directly in a few studies [5]. However, there is no research where the definition is properly made. In this paper, we will clearly define the concept of energy independence that can compare the algorithms presented in various energy trading studies, and compare the trading algorithms using this metric. The contribution of this paper is as follows.

- We first proposed the definition of an ‘energy independence’ to evaluate the energy trading mechanism in a microgrid. This metric can be used as a benchmark to evaluate existing energy trading mechanisms.
- We simulated the existing energy trading mechanism for the first time, reflecting the practical situation over time. Through the simulation, we were able to remind of the important factors to be considered in the energy trading mechanism.
• In the energy trading system, the energy trading cycle between the microgrid is a very important factor. Through this, we have presented the proper energy trading cycle through simulation.

The remainder of this paper is organized as follows. The proposed model and metric are explained in Section 2 and 3, respectively. In Section 4, the energy trading simulation is discussed. Some numerical results are also discussed in Section 4, and finally, the conclusion of this paper is provided in Section 5.

II. System Model

In this section, we propose a system model to apply the energy trading mechanism. Consider an island with L prosumers, who can generate energy by heterogenous renewable sources. Denote the set of L prosumers by $J = \{\omega_1, \omega_2, \ldots, \omega_L\}$, where $\omega_k$ is the kth prosumer in the island. $\omega_k$ has an ESS with maximum capacity $E_{k,\text{max}}$. When prosumers trade energy among themselves, trading price $p_t$ is determined by energy trading mechanism. If a prosumer does not receive enough energy through the trade among prosumers, he should buy energy at a slightly higher price $p_b$ from the main grid. If a prosumer is unable to sell enough energy through the trade among prosumers or produces energy that exceeds its storage capacity, he should sell energy to the main grid at a slightly cheaper price $p_s$. Obviously, these prices satisfy $p_s < p_t < p_b$.

For the kth prosumer on the ith date, let $g_{k,i}(t)$ be the rate of energy generated at time $t$, and let $c_{k,i}(t)$ be the rate of energy consumed at time $t$ ($0 \leq t \leq 24$). To consider a time slotted system, let $T$ be the unit time interval such that $NT = 24$ with $N \in \mathbb{N}$. Let $G_{k,i}[n]$ be the amount of energy generated in time interval $[(n-1)T, nT]$ and $C_{k,i}[n]$ be the amount of energy consumed in the same time interval; that is, $G_{k,i}[n] = \int_{(n-1)T}^{nT} g_{k,i}(t)dt$ and $C_{k,i}[n] = \int_{(n-1)T}^{nT} c_{k,i}(t)dt$. Clearly, the domain of $n$ is $n\in\{1, 2, \ldots, N\}$. To make well-defined time slotted system, assume that $g_{k,i}(t)$ and $c_{k,i}(t)$ is monotone in the unit interval $[(n-1)T, nT]$. Let $E_{k,i}[m]$ be the amount of energy stored in the kth prosumer’s ESS at time $mT$ on the ith date. Here, the domain of $n$ is $m \in \{0, 1, \ldots, N\}$ and $E_{k,i}[N] = E_{k,i}[1] + 0$.

Now, looking at a unit time interval, the prosumer may produce less energy than it consumes, or produce more energy than the ESS capacity, during this time unit. Note that at the beginning of a unit time interval $n$, the energy possessed by the prosumer is $E_{k,i}[n-1]$, the energy produced in this period is $G_{k,i}[n]$, and the energy consumed is $C_{k,i}[n]$. Here we can consider the following two cases, and Fig. 1 illustrated these cases.

1) Case 1: When energy is not enough, the prosumer should buy energy from the main grid in this time unit interval, that is, $E_{k,i}[n-1] + G_{k,i}[n] - C_{k,i}[n] < 0$. In this case, the amount of energy to be purchased from the main grid is $G_{k,i}[n] - (E_{k,i}[n-1] + G_{k,i}[n] - C_{k,i}[n])$, and will be denoted by $B_{k,i}[n]$.

2) Case 2: When energy needs to be sold to the main grid beyond the capacity of the ESS, that is, $E_{k,i}[n-1] + G_{k,i}[n] - C_{k,i}[n] > E_{k,\text{max}}$. In this case, the amount of energy to be sold to the main grid is $(E_{k,i}[n-1] + G_{k,i}[n] - C_{k,i}[n]) - E_{k,\text{max}}$, and will be denoted by $S_{k,i}[n]$.

III. Proposed Metrics

In this section, we present a new metric that can be used to measure the energy independence of an energy trading mechanism in a microgrid, which becomes an island. As mentioned earlier, the energy self-reliance of an island should be evaluated as high when it is operated with only the internal energy produced by the island itself, without receiving the power from the main grid. Simply from this perspective, the energy independence is largely influenced by the average percentage of the energy purchased from the main grid to the energy consumed by prosumers on the island. In this sense, we can define a new energy independence metric $\psi$ as follows:

$$\psi = 1 - \frac{\sum_{k,i,n} B_{k,i}[n]}{\sum_{k,i,n} C_{k,i}[n]}.$$

In the remainder of this paper, we will examine an energy trading mechanism in terms of energy independence through simulation. The trading systems to simulate are those presented in [2].

IV. Numerical Results & Discussion

For the evaluation of an energy independence, an island composed of 45 prosumers was assumed. Each prosumer has a power consumption profile measured in units of 30 minutes. The power consumption profile is the simulated load profiles for the US. Department of Energy (DOE) commercial reference buildings, including 15 different types of buildings such as office, hotel, restaurant, and school [6]. The power generation profile is designed using solar radiation and wind speed information [7] according to the consumption profile of each prosumer. To this end, each prosumer is assumed to have an average ratio of the amount of energy produced to the amount of energy consumed. It depends on the types of renewable energy generator and scale. At this time, $r_k$ denotes this ratio of the kth prosumer. For example, $r_k$ is 0.7 means the kth prosumer can produce 70% of the amount of energy consumed. In the process of designing the power generation profile, each $r_k$, $k \in \{1, 2, \ldots, L\}$, is randomly determined as a value between 0.7 and 1.2. The ratio of the prosumer with $r_k > 1$ was set to be almost the half. Fig. 2 is an example of the kind of power generation and consumption profiles used in this paper.

In this island, the energy independence is measured through a 30-day energy trading simulation. The energy trading simulation consists of the trade with main grid and the trade among prosumers. At this time, prosumer can buy energy from main grid at any time according to its energy state, or can sell energy that can not be stored due to ESS capacity. When there is an energy trade among prosumers at the specified time interval, the prosumer predicts energy production and consumption until the next energy trading, and takes part in as provider or consumer considering its current amount of energy. To predict the power consumption, the cross-sectional method was used [8]. In this method, an autocorrelation of the consumption profile of each prosumer is used. The prediction is performed using the profile of the past time point (e.g., one week before) at which the autocorrelation becomes
maximum. On the other hand, to predict the power generation, the prediction accuracy of the weather information is referred. It means that all prosumers in the island predicts the power generation with one predicted meteorological information. Fig. 3 is an example of prediction profiles.

The following is the result of applying the trading mechanism [2] to the above simulation environment. First, we examined the energy independence of each prosumer when there is no energy trading among prosumers. Fig. 4 shows the energy independence of each prosumer measured in 100 simulations with different simulation environment. For every simulation, \( r_k, k \in \{1, 2, \cdots, L\} \) is randomly selected again, between 0.7 and 1.2. Clearly, Fig. 4 indicates that energy independence is proportional to \( r \). From this result, we can confirm that the proposed metric will show reasonable energy independence for the prosumer or island that can produce energy. However, there is a difference in energy independence despite of same \( r \). It is due to the difference of prosumer’s energy production and consumption patterns. This difference is illustrated in Fig. 5. Fig. 5a shows the case where the pattern of production and consumption is aligned well, thus the energy independence is almost same with \( r \). Conversely, Fig. 5b shows the case where despite the high \( r \), production and consumption patterns are not aligned, thus the energy independence is low. The situation as in Fig. 5b can occur because of the uncertainty of the renewable energy. However, if there are prosumers with surplus energy at this time, the energy independence can be improved through energy trading between prosumers.

Next, we examined the change in energy independence of the island when the energy trading among the prosumers occurs at the specified time interval. In the simulation with energy trading among prosumers, there were a factor that had to be considered carefully, which is the amount of energy the prosumer currently has. The prosumer predicts the amount of energy produced and consumed up to the next energy trade and decides how much energy to buy or sell based on the predicted results. In this decision process, the amount of energy currently in the ESS also has to be considered. However, in existing energy trading researches, there were not enough consideration for this. Without proper consideration for this, the following situations may occur. First, even if the surplus energy is expected due to energy generation until the next trading, if the prosumer has a small amount of energy now, the prosumer can sell only that small energy. Also, even if the energy shortage is expected until the next trading, energy...
shorter the trading cycle, the higher the degree of reduction ratio. However, if you have a certain amount of ESS capacity, the reduction ratio in the amount of energy purchased from main grid is the greatest when the trading among microgrid occurs twice a day.

Therefore, given the cost of ESS and the cost of energy trading among prosumers, it would be most appropriate to have a certain amount of ESS capacity (e.g., 10) and to have energy trade twice a day, in this energy trading mechanism. However, this is a limited solution to the one trading mechanism where the prosumer’s ESS capacity is not optimized. Despite of this limitation, the energy independence metric proposed in this paper makes it possible to evaluate and compare the energy trading systems. Furthermore, energy trading simulation is used to remind of factors that should be considered in order to operate the energy trading mechanism.

V. CONCLUSION

In this paper, the authors have proposed a new metric to measure the energy independence of an energy trading system in a microgrid. The proposed metric makes it possible to evaluate and compare the energy trading mechanism, especially in the microgrid within the island where energy independence is an important consideration. To shows this, we build a microgrid and performed energy trading simulation. First, the proposed metric is validated as an indicator of energy independence through simulation, and energy independence is discussed in various simulation environments. In addition, we identified factors that should be considered important in the energy trading system by simulating the actual energy trading situation.

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