

Article

Price-Guided Peer-To-Peer Trading Scheme and Its Effects on Transaction Costs and Network Losses

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Abstract: Distributed energy resources (DERs), such as small-scale renewable energy generators, storage systems, and controllable loads, have been attracting great attention. Accordingly, interest in peer-to-peer (P2P) energy trading between prosumers with DERs is growing. The prosumers may perform the P2P electricity trading within the loss-guided framework, where network losses are primarily considered during the peer matching process. However, the loss-guided framework has limitations in that prosumer welfare is neglected in favor of prioritizing the network losses caused by the P2P transactions. Thus, in this study, a price-based framework for P2P electricity trading is suggested, where the prosumer welfare is considered by including not only network loss costs but also energy costs in the matching procedure. The effects of the suggested price-based framework on network efficiency, prosumer welfare, and social welfare are examined by comparing simulation results with the loss-guided framework and the random transactions. Further, how those three properties are affected by the change in loss price is analyzed and a guideline for the suitable choice of the loss price is suggested.

Keywords: peer-to-peer(P2P) electricity trading; loss management; transaction guide; electricity market



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1. Introduction

In conventional power systems, electricity has mainly been generated from large-scale generators located far from the load centers. As many of those large-scale generators use fossil fuels such as oil, gas, and coal, conventional power systems are regarded to be not carbon-neutral, contrary to the global awareness of climate change and environmental problems [1]. Further, as perceptions on the issue of constructing high-voltage electric lines, which are of importance for the efficient transmission of electricity, vary by interest groups, it is well-known that efforts to mediate social conflict are always necessary for maintaining conventional power systems [2].

Distributed energy resources (DERs), such as renewable energy generators, storage systems, and controllable loads that do not use fossil fuels are usually regarded to be “carbon positive” and free from environmental problems. Additionally, as most DERs are connected to low/medium voltage networks close to load centers and can contribute to the balance of generation and consumption in the electricity network with advanced measurement infrastructure (AMI) and information and communications technologies, external costs for constructing a large-scale transmission network and associated possible social conflicts can be avoided [3–9].

Therefore, many countries worldwide are facilitating the spread of DERs through energy policies, and in this context, peer-to-peer (P2P) electricity trading is attracting attention as an option that can boost countries' efforts to facilitate the spread of DERs. Under the power system where P2P electricity trading is possible, traditional passive customers can become prosumers who actively pursue benefits by installing DERs following the

possibility of profit creation [3–9]. Some electricity companies, such as Brooklyn Microgrid in US and Piclo in the UK, have already made P2P electricity trading platforms in their distribution networks [9–12]. However, most P2P electricity trading projects are at the beginning stage, and there are still challenges to be addressed before the advantages of P2P electricity trading can be fully enjoyed.

To achieve the intended goal of introducing P2P electricity trading—the widespread adoption of DERs—the P2P trading framework must satisfy two conditions [13]. First, the P2P trading framework must be able to attract the active participation of prosumers to maintain the P2P economy of the trading framework itself. The framework needs to be easily accessible and open to prosumers. The framework also needs to help prosumers predict the benefits of participating in the P2P transaction while reassuring them that economic surplus or any possible costs will be distributed fairly and reasonably. Second, as the transaction of electricity is made under physical network constraints unlike other goods, the P2P trading framework needs to consider the state of the network while managing transactions between prosumers. That is, even if P2P electricity trading is permitted, the network should be stable, reliable, and efficiently operated.

In these perspectives, Ref. [14] suggested a P2P transaction mechanism that maximizes social welfare considering the uncertainty and profit fairness of the players. Ref. [15] proposed a photovoltaic energy-sharing model under the feed-in tariff scheme which is more economical than the independent operation. Ref. [16] presented a P2P market structure that allows multi-bilateral trading and product differentiation based on prosumer preferences. Ref. [17] proposed a P2P electricity trading method based on an iterative peer-matching process that allows prosumers not to reveal their private information. Ref. [18] and [19] present a P2P pricing mechanism that considers voltage and line congestion management. Ref. [20] also suggests a methodology based on sensitivity analysis to guarantee energy exchanges do not violate network constraints. Ref. [21] suggests a P2P trading framework based on the fast dual ascent, which makes transactions to be proceeded not only considering network constraints but also considering the fair allocation of transaction cost and network privacy.

Taking the two important conditions that the P2P trading framework must satisfy, we suggested the loss-guided P2P trading framework in our previous work [13]. In the proposed framework, which is designed in a decentralized manner, electricity prosumers can easily access the system and submit bids or offers whenever they wish, and the framework automatically matches a bid and offer pair in real-time, minimizing the change of network losses when the dispatch is completed. Through the simulation in [13], it is shown that, under the suggested framework, network losses, which are usually regarded as one of the important performance indexes of operating electricity network, can be effectively decreased compared with a centralized loss management framework based on the optimal power flow method that many conventional power systems use. However, the loss-guided P2P trading framework suggested in the previous work has limitations in that prosumer welfare and preference are rather neglected—it is not the prosumers themselves but still, automated system operators (SOs) that match bids and offers, and it is the management of network losses that is the supreme task for the SOs.

Therefore, in this research, a new price-guided P2P trading framework that guides prosumers to be matched taking into account network losses as well as the price of bids and offers is suggested considering the limitation of previous work. The contributions of this paper are as follows:

- A new price-guided P2P electricity trading framework that premises the autonomous decision of prosumers and considers both prosumer welfare and network losses is suggested;
- A methodology of setting the appropriate loss price and reflecting it in bids and offers under the price-guided P2P electricity trading framework is suggested;
- Effects of the new price-guided framework on network efficiency, prosumer welfare, and social welfare are examined through simulation;

- Effects of various loss prices on the new price-guided framework are examined through the simulation.

The remainder of the paper is organized as follows. In Section 2, the suitable form of the auction for P2P electricity trading is examined. In Section 3, the new price-guided P2P trading framework is suggested after reviewing the limitations of the loss-guided framework in the previous paper. The two frameworks are compared with each other in a simple 6-bus example. Further, a methodology for managing network losses by setting the appropriate loss price under the price-guided framework is suggested. In Section 4, the simulation conducted in this study to check the effects of the price-guided framework is described. The results of the simulation are discussed in Section 5. Finally, concluding remarks are provided in Section 6.

2. Continuous Double Auction in P2P Trading

In the conventional power system, electricity is usually traded under the centralized market structure in which the operator first gathers all bids and offers until the market closes, and simultaneously matches them. The centralized market structure has widely been adopted in many countries as it is convenient for the operators in running the network efficiently and distributing any operating costs to network users at a stroke under a single rule.

Despite the advantages, the centralized market is not suitable for P2P electricity trading. Under the P2P economy, also known as the sharing economy, which is the principle of P2P electricity trading, individuals or groups seek to maximize their profits by directly trading underused or overproduced resources. However, the conventional centralized market is operated with the market participants' commitment to their amount of generating or consuming of electricity at the time appointed, which is not suitable for trading underused or overproduced resources that are difficult to predict the time of occurrence. In addition, under the centralized market structure, the operator may bill the overhead costs to participants for their efforts spent on the stable and efficient operation of power systems, and this could lead to the reduction of prosumers' profit. Further, the centralized market framework may bring a heavy burden of collecting detailed information on market participants to the operator [22].

What market structure, then, is suitable for the P2P electricity transaction? In [11,20,23,24], a decentralized market structure and management scheme that "allow for a bottom-up approach to empower prosumers" unlike those of the conventional centralized electricity market are suggested as requirements for the P2P electricity transaction. Drawing on existing studies, in our previous study [13], we discussed the requirements that a decentralized market for P2P electricity trading must satisfy as follows:

Requirement 1. *Peers should be able to participate in the market at any time in case of surplus or demand for electricity.*

Requirement 2. *Network operators' mediation on the transaction should be minimized.*

Requirement 3. *Peers should be able to calculate the benefits of participating in the market before proceeding the P2P electricity trading.*

Requirement 4. *The market must not undermine the prerequisite of the stable and efficient operation of power systems.*

Considering the requirements, the continuous double auction (CDA) mechanism can be considered a suitable market structure for P2P electricity trading. Under the CDA mechanism, the transactions can occur at any time the prosumers wish, and the bid and offer match, therefore, prosumers can maximize their utility by trading excess electricity following their initiative. Further, as the operator does not manage the market schedule directly or actively arrange the matching of bids and offers, the overhead costs that may be required under the centralized market structure can be decreased.

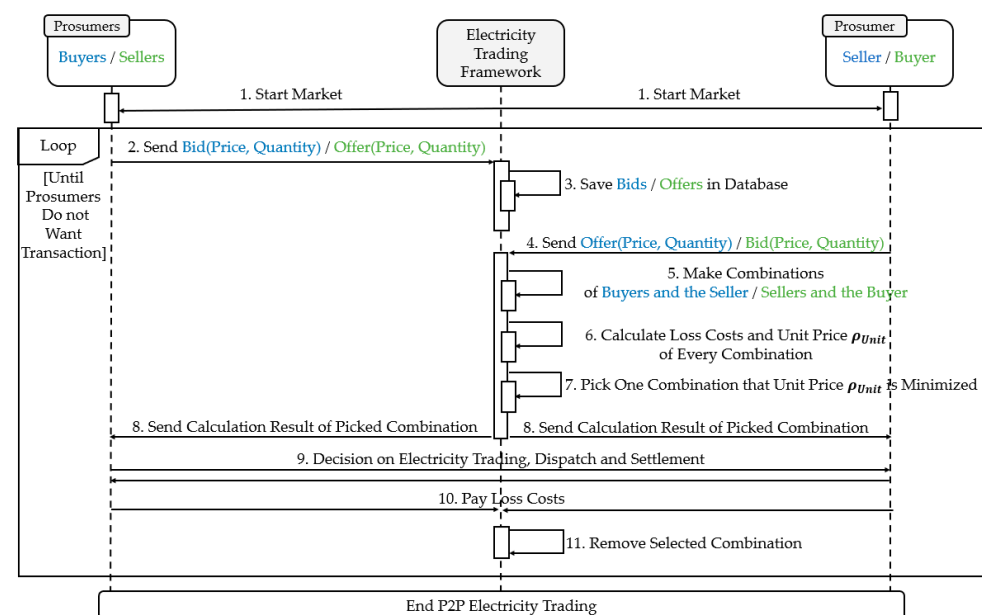
3. Two Frameworks for P2P Electricity Trading

Even with the CDA mechanism, it is obvious that the electricity network should retain its stability, reliability, and efficiency during P2P electricity trading. However, as the P2P electricity market under the CDA mechanism operates in a decentralized manner and the role of the operator in the market is minimized, there is a possibility that the P2P transactions could affect the physical characteristics of the network. Therefore, it is necessary to prepare provisions to keep the stability, reliability, and efficiency of the electricity network before invigorating P2P electricity trading.

One of the important physical characteristics of the electricity network that should be considered in introducing P2P electricity trading is network losses. As network losses inhibit the efficient use of energy and cause social costs, managing and allocating them have always been essential issues in the power system. Generally, the optimal power flow method has been utilized in minimizing network losses, and the pro-rata procedure, the proportional sharing procedure, and the marginal procedure have been representative methods for allocating loss costs to network users [25–29]. However, those methods coordinate with the conventional market mechanism, which operates on the periodic schedule that opening, closing, dispatching, and settlement times are pre-fixed and repeated. Therefore, new methods of managing and fairly allocating network losses are needed for the P2P electricity market under the CDA mechanism in which the periodic schedule does not exist.

3.1. Loss-Guided P2P Trading

As a solution for the network losses that aligns with the CDA, the loss-guided electricity trading framework suggested in [13], our previous study, can be used which automatically matches the bids and offers in real-time considering the minimization of losses. That is, after combining all unmatched bids and offers one by one and calculating every possible network loss cost that can be generated in every combination, the framework picks a set of prosumers with the minimum network losses and confirms the transaction. Then, the prosumers proceed with the transaction and settle the energy costs with each other and the loss costs with the network operator. The sequence diagram of the loss-guided electricity trading framework is shown in Figure 1.



Case Blue: A seller tries to purchase electricity from buyers. / Case Green: A buyer tries to purchase electricity from sellers.

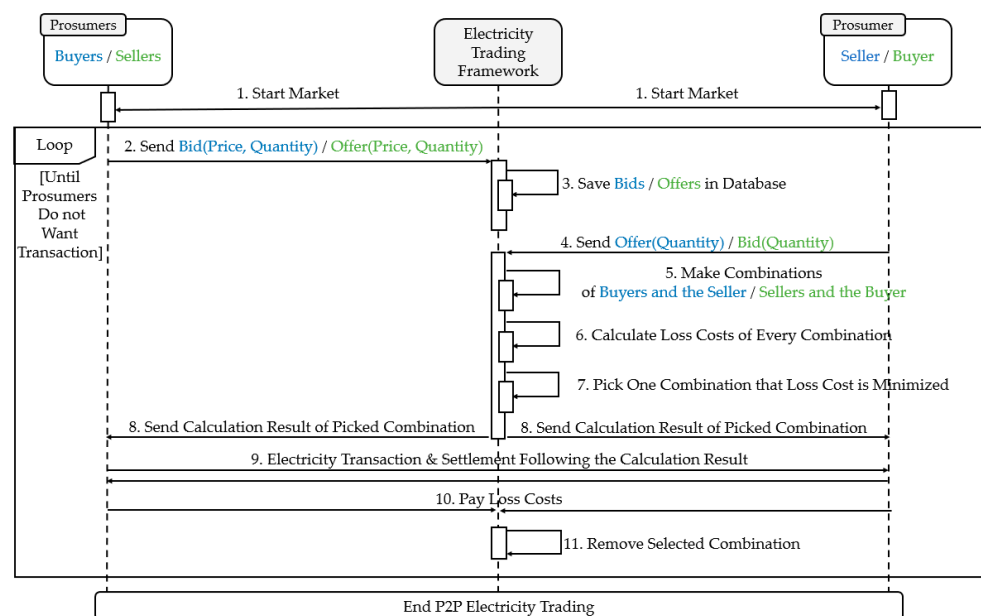
Figure 1. Sequence diagram of the loss-guided P2P trading.

3.2. Price-Guided P2P Trading

The aforementioned framework may be effective in loss minimization as it only allows transactions between prosumers with minimal network losses, but it has a weakness in that it is the network status that is prioritized rather than the prosumers' preference. For example, a prosumer who wants to buy electricity at a cheaper price may have to select a prosumer who sells electricity at an expensive price but is located electrically near following the automatic decision of the loss-guided electricity trading framework.

As an alternative, a price-guided electricity trading framework that lets prosumers be matched according to, not the loss cost alone, but the sum of the energy cost and loss cost, can be considered. When the prosumer conveys buying/selling intent, the framework makes the combinations of all possible matches, calculate ρ_{unit} , the unit price of the sum of the energy cost and loss cost in every match, and pick the offer/bid with the minimum/maximum unit cost. Then, the prosumers who participate in the transactions decide whether to accept the framework's calculated combination. The unit price of the sum of the energy cost and loss cost, ρ_{unit} , is expressed in (1) where $\rho_{trading}$ stands for the unit price of offer/bid; $p_{trading}$, the volume of offer/bid; ρ_{loss} , the unit price of network loss; and p_{loss} , the volume of network loss. The sequence diagram of the price-guided electricity trading framework is shown in Figure 2.

$$\rho_{unit} = \frac{\rho_{trading} \times p_{trading} + \rho_{loss} \times p_{loss}}{p_{trading}} \quad (1)$$



Case Blue: A seller tries to purchase electricity from buyers. / Case Green: A buyer tries to purchase electricity from sellers.

Figure 2. Sequence diagram of the price-guided P2P trading.

The suggested price-guided trading framework can be regarded to generally satisfy requirements for the decentralized P2P transaction discussed in Section 2. First, a transaction between prosumers can be established due to prosumers' needs for electricity trading. Prosumers also do not need to follow the market schedule or decision that the operator suggests unlike in the conventional market (Requirements 1&2). Second, from the database, prosumers can watch the pool of bids and offers, predict the benefits, and reflect the prediction in deciding their participation in the electricity market (Requirement 3). Third, the framework not only considers prosumers' benefits but also considers network losses in calculating, which is used in picking a preferable combination among bids and offers (Requirement 4).

3.3. Example for Loss-Guided and Price-Guided Frameworks

To compare the two frameworks, we suppose a 6-bus network from Wood and Wollenberg [30] as in Figures 3 and 4, where the generator in bus 1 supplies 100 MWh of electricity; the generator in bus 2, 50 MWh; and the generator in bus 3, 60 MWh; while the loads in bus 4, bus 5, and bus 6 consume 70 MWh each. In the example, the generator in bus 1 submits an offer of 10 MWh of electricity at \$80/MWh; the generator in bus 2, \$100/MWh; and the generator in bus 3, \$120/MWh.

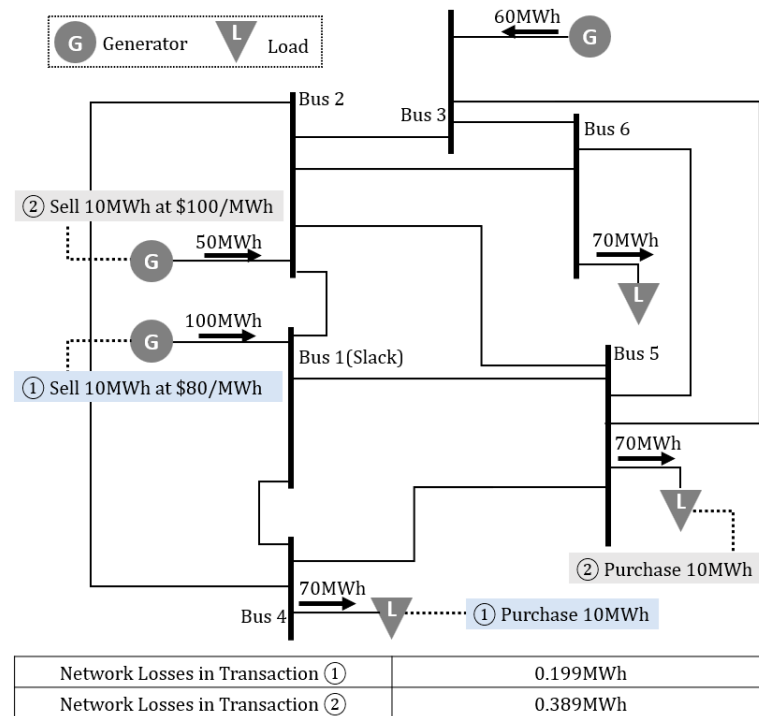


Figure 3. 6-bus network example of the loss-guided trading framework.

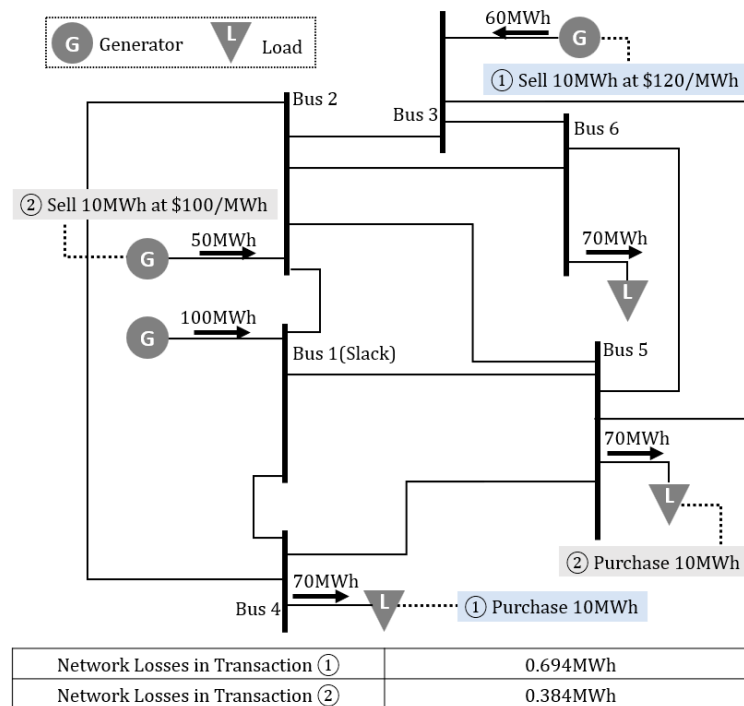


Figure 4. 6-bus network example of the price-guided trading framework.

When the load in bus 4 tries to purchase 10 MWh of electricity under the loss-guided framework, the framework automatically calculates network losses assuming a transaction between the load in bus 4 and each generator in bus 1, bus 2, and bus 3, which is, 0.694 MWh, 0.259 MWh, and 0.199 MWh, respectively, when calculated using MATPOWER [31,32]. If the unit cost of losses is set to be \$100/MWh, a median of the offer prices, the loss cost of each possible transaction will be \$69.40 ($=0.694 \text{ MWh} \times \$100/\text{MWh}$), \$25.90 ($=0.259 \text{ MWh} \times \$100/\text{MWh}$), and \$19.90 ($=0.199 \text{ MWh} \times \$100/\text{MWh}$). Then, the framework confirms the transaction between the load in bus 4 and the generator in bus 3. Following the framework's decision, the generator in bus 3 put 10 MWh of electricity into the grid and the load in bus 4 pays \$1200 ($=10 \text{ MWh} \times \$120/\text{MWh}$) to the generator in bus 3. Further, both the generator and load should pay the loss cost caused by their transaction to the network operator.

If the load in bus 5 tries to purchase 10 MWh under the loss-guided framework, following the transaction between the load in bus 4 and the generator in bus 3, the framework again automatically calculates network losses assuming a transaction between the load in bus 4 and each remaining generator in bus 1 and 2, which is 0.805 MWh and 0.389 MWh, respectively. Then, through the same process, the load in bus 5 will be matched with the generator in bus 2. The load in bus 5 pays \$1000 ($=10 \text{ MWh} \times \$100/\text{MWh}$) to the generator in bus 2. The loss costs that the prosumers need to bear will be \$38.90 ($=0.389 \text{ MWh} \times \$100/\text{MWh}$).

When the price-guided electricity trading framework is applied, the matching results go differently, as described in Figure 4. If the load in bus 4 tries to purchase 10 MWh, the price-guided framework calculates network losses, and the result is 0.694 MWh, 0.259 MWh, and 0.199 MWh, which is the same as the result of the loss-guided framework. However, the price-guided framework also calculates P_{Unit} , the unit price of the sum of the energy cost and loss cost by applying the formula in (1), supposing a transaction between the load in bus 4 and generators in bus 1, 2, and 3, which is \$86.941/MWh, \$102.591/MWh, and \$121.991/MWh, respectively. Then, based on the calculated results of P_{Unit} , the price-guided framework approves the transaction between the load in bus 4 and the generator in bus 1, unlike the loss-guided framework, which matches the load in bus 4 with the generator in bus 3. Following the framework's approval, the generator in bus 1 put 10 MWh of electricity into the grid and the load in bus 4 pays \$800 ($=10 \text{ MWh} \times \$80/\text{MWh}$) to the generator in bus 1. Further, both the generator and load should bear the loss cost caused by their transaction to the network operator, which is \$69.400 ($=0.694 \text{ MWh} \times \$100/\text{MWh}$).

If the load in bus 5 tries to purchase 10 MWh, following the transaction between the load in bus 4 and the generator in bus 1, the price-guided framework again automatically calculates network losses assuming a transaction between the load in bus 4 and each remaining generator in bus 3 and 4, which is 0.384 MWh and 0.310 MWh each, respectively. Then, through the same process, the unit price will be calculated, which is \$103.841/MWh and \$123.098/MWh, respectively. Based on the calculation results, the load in bus 5 will select the generator in bus 2. Finally, the load in bus 5 pays \$1000 ($=10 \text{ MWh} \times \$100/\text{MWh}$) to the generator in bus 2. The loss costs that the prosumers need to bear will be \$38.40 ($=0.384 \text{ MWh} \times \$100/\text{MWh}$).

The costs spent under the loss-guided framework and the price-based framework are summarized in Table 1. In the loss-guided framework where loss minimization is prioritized, the total loss cost is calculated as \$58.80 which is 54.54% of the loss cost of the price-guided framework. In the price-guided framework, where network loss as well as prosumers' preferences are considered, the total energy cost is calculated as \$1800 which is 81.82% of the energy cost of the loss-guided framework. This implies that in a P2P electricity market under the CDA mechanism, there is a trade-off relationship between the energy cost and the loss cost—when the network loss is focused more than the prosumers' preference and welfare, the energy cost increases while the loss cost decreases, and vice versa. It should be noted that the low total cost of the price-guided framework, \$1907.82, does not mean that the framework always brings more social benefits to network users as

the result may change following the unit price of the loss cost, which is set as \$100/MWh for the convenience.

Table 1. Loss-guided and Price-guided Electricity Trading Framework Result.

Loss-Guided Electricity Trading Framework							Price-Guided Electricity Trading Framework						
S T E P	Peers		Cost				S T E P	Peers		Cost			
	Load	Gen.	Energy		Loss			Load	Gen.	Energy		Loss	
			Price	Volume	Price	Volume				Price	Volume		
			[\$/MWh]	[MWh]	[\$/MWh]	[MWh]				[\$/MWh]	[MWh]		
1	Bus4	Bus1	1	10	100	0.694	1	Bus4	Bus1	80	10	100	0.694
	Bus4	Bus2	100	10	100	0.259		(Matched)	Energy Cost: \$800		Loss Cost: \$69.40		
	Bus4	Bus3	120	10	100	0.199		Bus4	Bus2	100	10	100	0.259
	(Matched)	Energy Cost: \$1200		Loss Cost: \$19.900		Bus4		Bus3	120	10	100	0.199	
	Total Cost in Step 1: \$1219.900							Total Cost in Step 1: \$869.400					
2	Bus5	Bus1	80	10	100	0.805	2	Bus5	Bus2	100	10	100	0.384
	Bus5	Bus2	100	10	100	0.389		(Matched)	Energy Cost: \$1000		Loss Cost: \$38.40		
	(Matched)	Energy Cost: \$1000		Loss Cost: \$38.900		Bus5		Bus3	120	10	100	0.310	
	Total Cost in Step 2: \$1038.900							Total Cost in Step 2: \$1038.400					

3.4. Appropriate Loss Price under the Price-Guided Electricity Trading Framework

As the price-guided electricity trading framework focuses more on prosumers' preferences and welfare, it can be regarded to have a weakness in managing network losses compared to the loss-guided electricity trading framework. However, managing network losses is important even under the price-guided electricity trading framework as too many network losses can finally lead to a decrease in prosumers' overall utility. Fortunately, by setting the appropriate loss costs, total network losses can also be managed under the price-guided electricity trading framework.

Suppose an example described in Figure 5, where prosumers A and B try to sell the same volume of electricity, P_D , at different prices, $\rho_{D,min}$ and $\rho_{D,max}$ each, to prosumer C through the price-guided electricity trading framework. In this example, as an extreme case, suppose that what A suggests for the price of electricity, $\rho_{D,min}$, is the cheapest among all offers, while the amount of network losses can be caused when the offer is selected, $P_{L,max}$, is the biggest. On the contrary, suppose that what B suggests for the price of electricity, $\rho_{D,max}$, is the most expensive among all offers, while the amount of network losses that can be caused when the offer is selected, $P_{L,min}$ is the smallest.

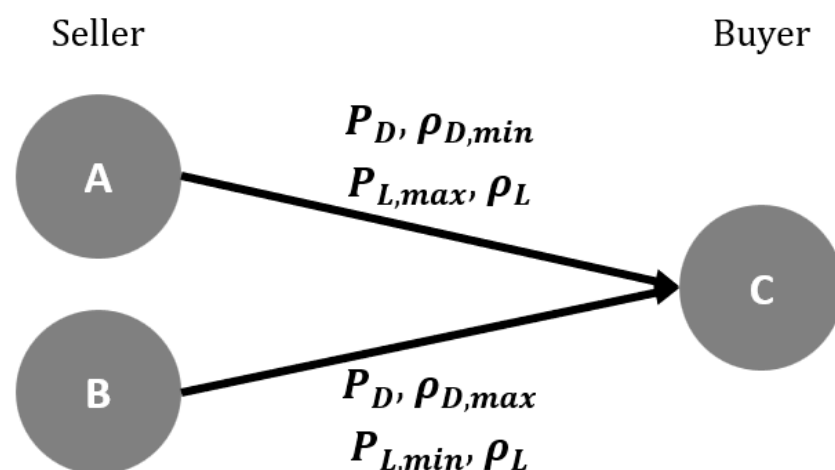


Figure 5. Loss price example under the price-guided electricity trading framework.

If the transaction is processed under the loss-guided trading framework, prosumer (buyer) C will be matched with prosumer (seller) B for the minimization of network losses. But, if the transaction is processed under the price-guided trading framework, there is a possibility that prosumer (buyer) C could choose prosumer (seller) A, and the network loss on the transaction could be maximized. However, by setting the appropriate loss

price, ρ_L , and making the unit price of prosumer A close to the unit price of prosumer B, $\rho_{unit}^A \cong \rho_{unit}^B$, prosumer (buyer) C can be induced to select prosumer (seller) B. This condition for minimizing network losses under the price-guided trading framework can be described as (2) and can be simplified as (3):

$$\frac{\rho_{D,min} \times P_D + \rho_L \times P_{L,max}}{P_D} \cong \frac{\rho_{D,max} \times P_D + \rho_L \times P_{L,min}}{P_D} \quad (2)$$

$$\rho_L \cong \frac{(\rho_{D,max} - \rho_{D,min}) \times P_D}{P_{L,max} - P_{L,min}} = \frac{\rho_{D,max} - \rho_{D,min}}{\varepsilon_{L,max} - \varepsilon_{L,min}} \quad (3)$$

where $\varepsilon_{L,max}$ and $\varepsilon_{L,min}$ are the maximum and minimum ratio of network loss in a transaction, respectively.

4. Simulation Setup

4.1. Test Cases and Algorithms

To examine the effect of the price-guided framework in P2P electricity trading, a simulation on the IEEE 33 bus system was carried out using MATLAB [31] and MATPOWER [32]. The total demand and available supply at each bus in the IEEE 33 bus system used in this simulation are described in Table 2. The original IEEE 33 bus system is a radial network with only 1 generator and 37 lines. To implement P2P trading in the simulation, 12 more generators were added referring to previous studies [13,33]. In this bus system, as in our previous work [13], it is assumed that only the prosumers with excess electricity become bidders, and prosumers who lack electricity just select offers through the framework.

Table 2. Demand and Supply of Each Bus in the IEEE 33 Bus System [13,33].

Bus Number	Total Demand [kWh]	Available Supply [kWh]	Bus Number	Total Demand [kWh]	Available Supply [kWh]	Bus Number	Total Demand [kWh]	Available Supply [kWh]
1	0	100	12	60	500	23	90	0
2	100	500	13	60	0	24	420	500
3	90	0	14	120	500	25	420	500
4	120	500	15	60	0	26	60	0
5	60	0	16	60	0	27	60	0
6	60	0	17	60	0	28	60	0
7	200	500	18	90	500	29	120	500
8	200	0	19	90	0	30	200	500
9	60	0	20	90	0	31	150	0
10	60	0	21	90	0	32	210	500
11	45	0	22	90	0	33	60	500

In our previous study [13] where the loss-guided framework is suggested, the focus of the simulation was to show the effectiveness of the loss-guided framework in managing network losses. Therefore, with the loss-guided framework, two cases were compared, the centralized loss management case and the random transaction case. In the centralized loss management case, a matching algorithm, not for the P2P electricity trading, but for the centralized electricity trading is used, which is based on the power flow equations and is already being utilized in many centralized electricity markets. The results of the centralized loss management case were used as a benchmark to check the loss-managing performance of the suggested case, which was the loss-guided framework [13]. In the random transaction case, a matching algorithm that is based on the CDA mechanism but matches prosumers randomly was used to show the benefit of applying the new algorithm in the P2P market [13]. The three cases simulated in this paper focusing on the price-guided framework are slightly different from each other, as follows:

1. (The loss-guided case) As the simulation in this paper focuses on the limitation of the loss-guided framework suggested in [13], that, even if it has merit in loss management, it has a demerit in considering prosumers' preference and welfare, the loss-guided framework is used as a benchmark in this paper. As noted in Section 3.1, the framework is for the CDA-based P2P market, and therefore, the prosumers can

bid or offer at any time. The selection and match of bid and offer are proceeded by the framework. The framework automatically selects and matches bid and offer in real-time, which minimizes the increase in network losses. Algorithm 1 below is the pseudocode of the logic we used for the loss-guided case. The algorithm is coded using MATLAB and Line 5 and Line 6 in Algorithm 1, which is the procedure of solving power flow and calculating added network losses each, are implemented using the MATPOWER function.

Algorithm 1: Matching algorithm at time t_τ under the loss-guided framework.

Input 1: Set of matches of selected bids and buyers M
Input 2: Total network losses L and total energy costs E
Input 3: $B_{t_\tau} := \{b_{1,t_\tau}, b_{2,t_\tau}, \dots, b_{3,t_\tau}, \dots, b_{N_b,t_\tau}\}$ for set of buyers
Input 4: $S_{t_\tau} := \{s_{1,t_\tau}, s_{2,t_\tau}, \dots, s_{j,t_\tau}, \dots, s_{N_s,t_\tau}\}$ for set of sellers
Input 5: $P_{t_\tau}^s := \{(p_{1,t_\tau}^s, \rho_{1,t_\tau}^s), (p_{2,t_\tau}^s, \rho_{2,t_\tau}^s), \dots, (p_{j,t_\tau}^s, \rho_{j,t_\tau}^s), \dots, (p_{N_s,t_\tau}^s, \rho_{N_s,t_\tau}^s)\}$ for set of selling bids from sellers

- 1: **while** $S_{t_\tau} \neq \emptyset$:
- 2: randomly choose buyer b_{k,t_τ} from the set B_{t_τ} ;
- 3: define a temporary set $T_{t_\tau} := \{\}$;
- 4: **for** $j = 1$ to N_s :
- 5: solve power flow for the case $M \cup (p_{j,t_\tau}^s, \rho_{j,t_\tau}^s, b_{k,t_\tau})$;
- 6: calculate added network losses p_{j,t_τ}^L and total energy costs E_{j,t_τ} ;
- 7: $T_{t_\tau} \leftarrow T_{t_\tau} \cup (p_{j,t_\tau}^L, E_{j,t_\tau})$;
- 8: **end**
- 9: pick j' that minimizes p_{j',t_τ}^L from the set T_{t_τ} ;
- 10: $M \leftarrow M \cup (p_{j',t_\tau}^s, \rho_{j',t_\tau}^s, b_{k,t_\tau})$;
- 11: $L \leftarrow L + p_{j',t_\tau}^L$; $E \leftarrow E_{j',t_\tau}$;
- 12: $B_{t_\tau} \leftarrow B_{t_\tau} - b_{k,t_\tau}$;
- 13: $S_{t_\tau} \leftarrow S_{t_\tau} - s_{j',t_\tau}$;
- 14: $P_{t_\tau}^s \leftarrow P_{t_\tau}^s - (p_{j',t_\tau}^s, \rho_{j',t_\tau}^s)$;
- 15: **Return** M, L, E ;
- 16: **end**

2. (The price-guided case) As also noted earlier, the new price-guided framework in this paper aims to overcome the limitation of the loss-guided framework by reflecting not only network losses but also prosumers' preference in the unit cost and letting the transaction proceed based on the unit cost while maintaining the CDA structure. The energy costs, network losses, and total costs under this framework will be calculated and compared with those of cases 1 and 3. Algorithm 2 below is the pseudocode of the logic we used for the price-guided case. The algorithm is coded using MATLAB and Line 5 and Line 6 in Algorithm 2, which is the procedure of solving power flow and calculating added network losses each, are implemented using the MATPOWER function.

Algorithm 2: Matching algorithm at time t_τ under the price-guided framework.

Input 1: Set of matches of selected bids and buyers M and total network losses L
Input 2: Total network losses L , total energy costs E and loss price ρ_{loss}
Input 3: $B_{t_\tau} := \{b_{1,t_\tau}, b_{2,t_\tau}, \dots, b_{3,t_\tau}, \dots, b_{N_b,t_\tau}\}$ for set of buyers
Input 4: $S_{t_\tau} := \{s_{1,t_\tau}, s_{2,t_\tau}, \dots, s_{j,t_\tau}, \dots, s_{N_s,t_\tau}\}$ for set of sellers
Input 5: $P_{t_\tau}^s := \{(p_{1,t_\tau}^s, \rho_{1,t_\tau}^s), (p_{2,t_\tau}^s, \rho_{2,t_\tau}^s), \dots, (p_{j,t_\tau}^s, \rho_{j,t_\tau}^s), \dots, (p_{N_s,t_\tau}^s, \rho_{N_s,t_\tau}^s)\}$ for set of selling bids from sellers

- 1: **while** $S_{t_\tau} \neq \emptyset$:
- 2: randomly choose buyer b_{k,t_τ} from the set B_{t_τ} ;
- 3: define a temporary set $T_{t_\tau} := \{\}$;
- 4: **for** $j = 1$ to N_s :
- 5: solve power flow for the case $M \cup (p_{j,t_\tau}^s, \rho_{j,t_\tau}^s, b_{k,t_\tau})$;
- 6: calculate added network losses p_{j,t_τ}^L ;
- 7: calculate unit cost $\rho_{j,t_\tau}^{unit} = \frac{\rho_{j,t_\tau}^s \times p_{j,t_\tau}^L + \rho_{loss} \times p_{j,t_\tau}^L}{p_{j,t_\tau}^s}$;
- 8: $T_{t_\tau} \leftarrow T_{t_\tau} \cup (p_{j,t_\tau}^L, E_{j,t_\tau}, \rho_{j,t_\tau}^{unit})$;
- 9: **end**
- 10: pick j' that minimizes ρ_{j',t_τ}^{unit} from the set T_{t_τ} ;
- 11: $M \leftarrow M \cup (p_{j',t_\tau}^s, \rho_{j',t_\tau}^s, b_{k,t_\tau})$;
- 12: $L \leftarrow L + p_{j',t_\tau}^L$; $E \leftarrow E_{j',t_\tau}$;
- 13: $B_{t_\tau} \leftarrow B_{t_\tau} - b_{k,t_\tau}$;
- 14: $S_{t_\tau} \leftarrow S_{t_\tau} - s_{j',t_\tau}$;
- 15: $P_{t_\tau}^s \leftarrow P_{t_\tau}^s - (p_{j',t_\tau}^s, \rho_{j',t_\tau}^s)$;
- 16: **Return** M, L, E ;
- 17: **end**

3. (The random transaction case) The price-guided framework suggested in this paper may improve some characteristics of the loss-guided case. However, after applying the new framework, it is possible that some characteristics could be impaired. Therefore, the random transaction case, which does not consider network losses as well as prosumers' preferences, but is just based on the CDA structure, is tested to see if adopting the price-guided framework itself has any benefit. Algorithm 3 below is the pseudocode of the logic we used for the random transaction case which is also used in the previous study. The algorithm is coded using MATLAB and Line 3 and Line 4 in Algorithm 3, which is the procedure of solving power flow and calculating added network losses each, are implemented using the MATPOWER function.

Algorithm 3: Matching algorithm at time t_τ under the random transaction.

Input 1: Set of matches of selected bids and buyers M
Input 2: Total network losses L and total energy costs E
Input 3: $B_{t_\tau} := \{b_{1,t_\tau}, b_{2,t_\tau}, \dots, b_{3,t_\tau}, \dots, b_{N_b,t_\tau}\}$ for set of buyers
Input 4: $S_{t_\tau} := \{s_{1,t_\tau}, s_{2,t_\tau}, \dots, s_{j,t_\tau}, \dots, s_{N_s,t_\tau}\}$ for set of sellers
Input 5: $P_{t_\tau}^s := \{(p_{1,t_\tau}^s, \rho_{1,t_\tau}^s), (p_{2,t_\tau}^s, \rho_{2,t_\tau}^s), \dots, (p_{j,t_\tau}^s, \rho_{j,t_\tau}^s), \dots, (p_{N_s,t_\tau}^s, \rho_{N_s,t_\tau}^s)\}$ for set of selling bids from sellers

1: **while** $S_{t_\tau} \neq \emptyset$:
2: randomly choose buyer b_{k,t_τ} from B_{t_τ} and seller $s_{j,t_\tau}, (p_{j,t_\tau}^s, \rho_{j,t_\tau}^s)$ from $S_{t_\tau}, P_{t_\tau}^s$;
3: solve power flow for the case $M \cup (p_{j,t_\tau}^s, \rho_{j,t_\tau}^s, b_{k,t_\tau})$;
4: calculate added network losses p_{j,t_τ}^L and total energy costs E_{j,t_τ} ;
5: $M \leftarrow M \cup (p_{j,t_\tau}^s, \rho_{j,t_\tau}^s, b_{k,t_\tau})$;
6: $L \leftarrow L + p_{j,t_\tau}^L$; $E \leftarrow E_{j,t_\tau}$;
7: $B_{t_\tau} \leftarrow B_{t_\tau} - b_{k,t_\tau}$;
8: $S_{t_\tau} \leftarrow S_{t_\tau} - s_{j,t_\tau}$;
9: $P_{t_\tau}^s \leftarrow P_{t_\tau}^s - (p_{j,t_\tau}^s, \rho_{j,t_\tau}^s)$;
10: **Return** M, L, E ;
11: **end**

4.2. Simulation Descriptions

Based on the test cases and algorithms described in Section 4.1, two experiments are executed. First, network losses, energy costs, and total costs under the three cases, the loss-guided framework, the price-guided framework, and the random transaction case, are examined with various ranges of offer prices, supposing a CDA-based P2P market environment where offers of prosumers can be varied. The purpose of the first experiment is to check the effect of the price-guided framework on network efficiency and prosumer welfare. The results of the first experiment are described in Section 5.1. Second, network losses, costs on network losses, and total costs under the three cases are examined with various loss prices. The purpose of the second experiment is to discuss the appropriate loss price for the P2P market that the price-guided framework applied. The results of the second experiment are described in Section 5.2.

In the first experiment, the prices that prosumers offer are assumed to follow the normal distribution. By increasing the standard deviation gradually for a total of 11 steps, from 0 to 10% of the mean, while maintaining the mean of distributions to be \$100/MWh, price ranges that prosumers can offer under and intensity of price competition are adjusted as shown in Table 3. Under each standard deviation, the loss price is assumed to be \$100/MWh, which is the same as the mean of all 11 distributions.

Table 3. Range of Offer Prices Used in the first experiment.

Step No.	Mean [\$/MWh]	Standard Deviation [\$/MWh]	Step No.	Mean [\$/MWh]	Standard Deviation [\$/MWh]
1	100	0 (0% of mean)	7	100	6 (6% of mean)
2	100	1 (1% of mean)	8	100	7 (7% of mean)
3	100	2 (2% of mean)	9	100	8 (8% of mean)
4	100	3 (3% of mean)	10	100	9 (9% of mean)
5	100	4 (4% of mean)	11	100	10 (10% of mean)
6	100	5 (5% of mean)			

In the second experiment, the loss price is designed to increase for a total of 151 steps, from 0 to \$3000/MWh (30 times \$100/MWh), with increments of \$20/MWh (0.2 times \$100/MWh). To make offer prices vary and prosumers compete, the prosumers' offer prices are assumed to follow the normal distribution with a mean of \$100/MWh and a standard deviation of \$10/MWh (10% of the mean).

The two experiments have three things in common. First, as the Algorithms 1–3, in Section 4.1, used in both experiments have random characteristics in choosing one buyer from the set of buyers who bid at the same time, those algorithms are executed 100 times for each step in each experiment to reduce the randomness and make the results clearer. Therefore, for the first experiment, each algorithm is executed 1100 times, and for the second experiment, each algorithm is executed 15,100 times. At each execution, each algorithm outputs a set of results, network losses, loss costs, energy costs, and total costs. One hundred sets of results of each algorithm in each step are displayed using the box-and-whisker plot (Figures 6 and 7) or by calculating the average (Figures 8–10).

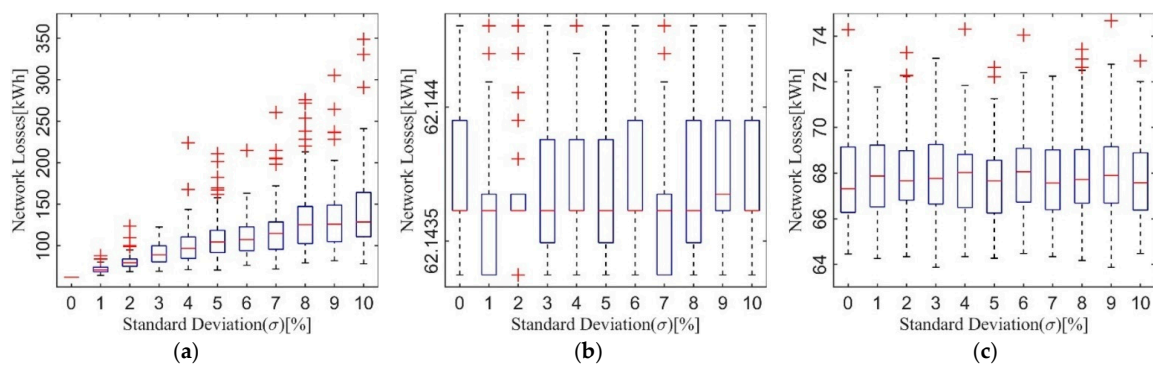


Figure 6. Distribution of Network Losses: (a) Price-guided Case; (b) Loss-guided Case; (c) Random Case.

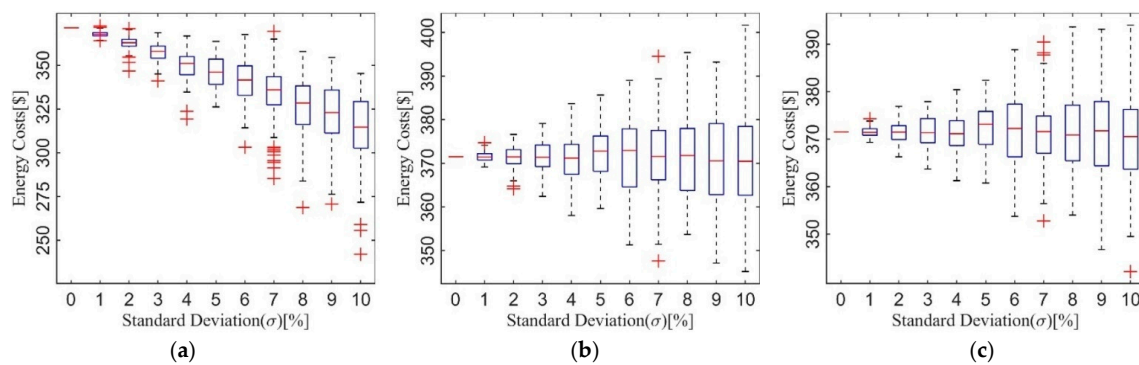


Figure 7. Distribution of Energy Costs: (a) Price-guided Case; (b) Loss-guided Case; (c) Random Case.

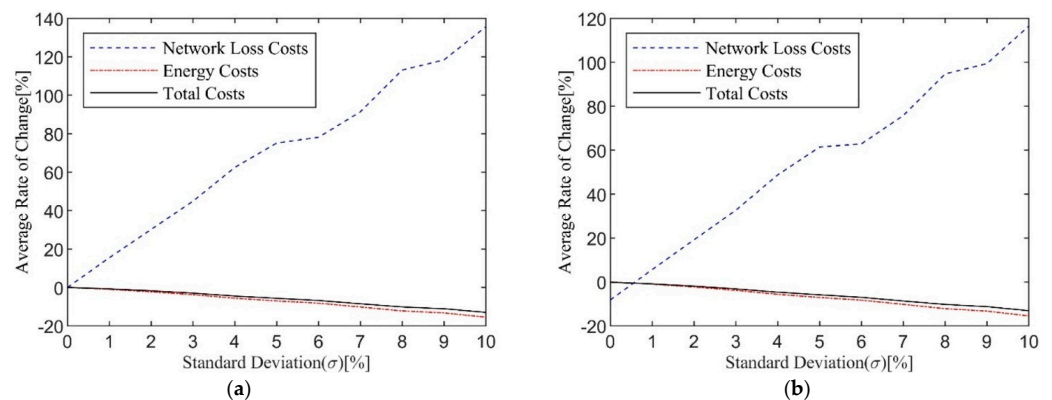


Figure 8. Average Rate of Change in Costs between (a) Price-guided Case and Loss-guided Case; (b) Random Transaction Case and Price-guided Case.

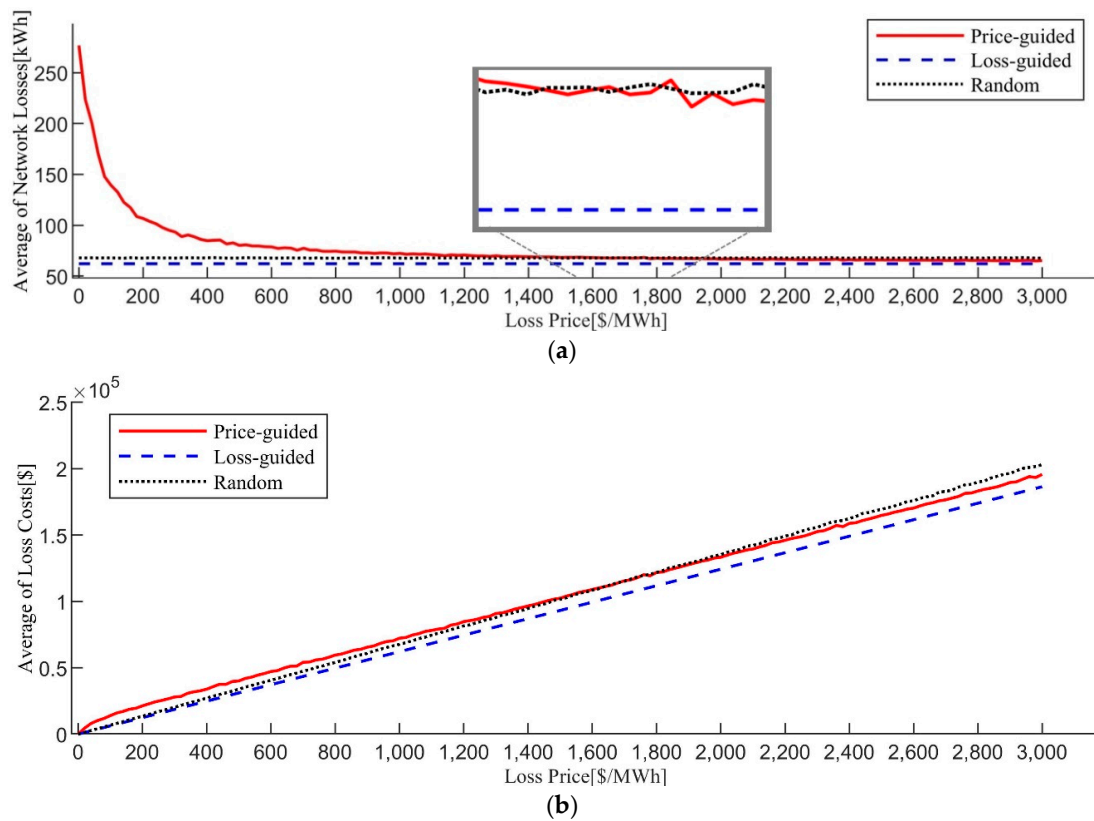


Figure 9. Average of (a) Network Losses and (b) Loss Costs with Increase in Loss Price.

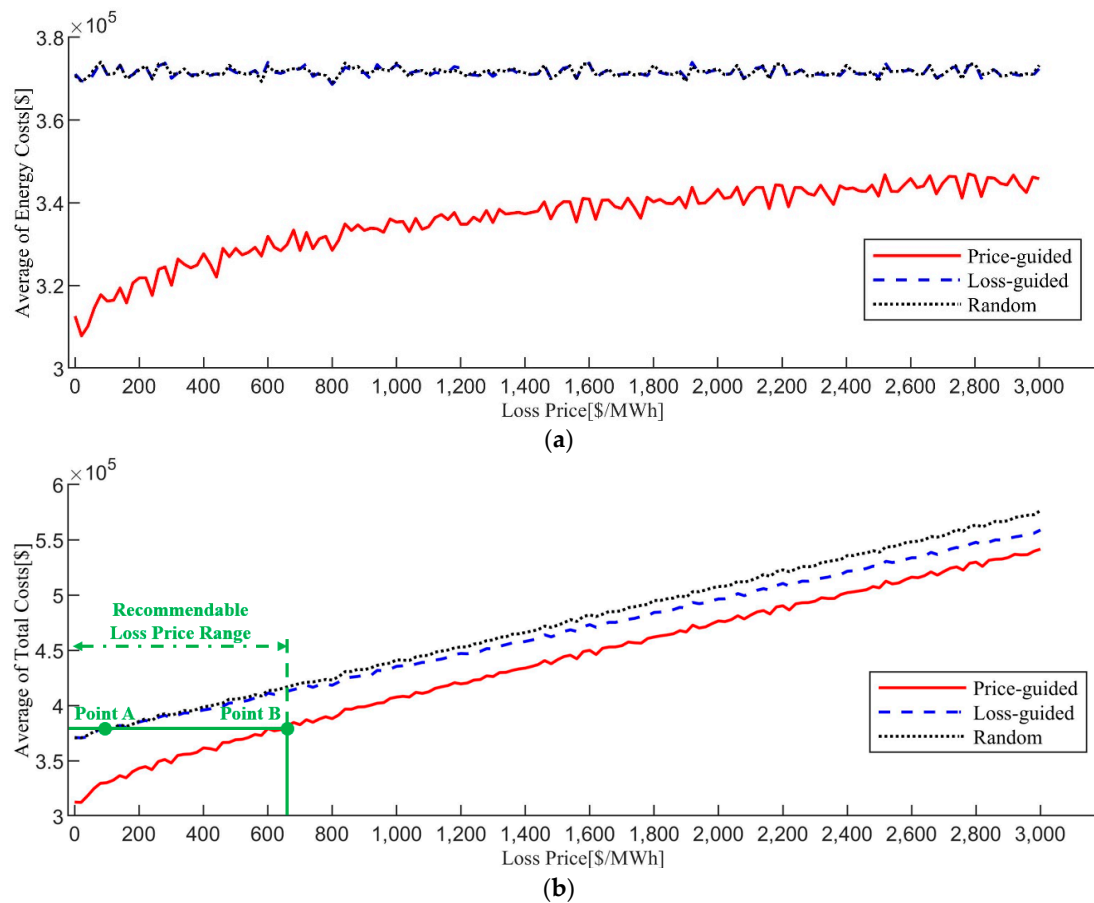


Figure 10. Average of (a) Energy Costs and (b) Total Costs with Increase in Loss Price.

Second, during the simulation, only transactions that do not violate network constraints are considered, as in our previous work [13]. Therefore, the tested case, the IEEE 33 bus system, keeps its stability from the beginning to the end during the simulation [13]. Third, the volume of electricity that can be traded in one transaction is limited to 10 kWh to evenly distribute the chance of participating in the P2P electricity trading to prosumers. If not, a buyer with a big demand could distort the results of the experiments. Under the transaction limit, prosumers who want to trade more than 10 kWh need to buy or sell electricity through multiple transactions.

5. Simulation Results

5.1. The Effect of the Price-Guided Framework with Different Ranges of Offer Prices

Network losses and energy costs in the price-guided case, the loss-guided case, and the random transaction case in the IEEE 33 bus system are shown in Figures 6 and 7 as box plots. As can be seen from the decreasing trend of energy costs in Figure 7a, under the price-guided framework, the existence of price options lets prosumers pursue benefits during P2P electricity trading. The more widespread the price options become as the standard deviation increases, the higher the possibility that the buyer can be matched with cheaper offers. Therefore, it leads to a decrease in energy costs spent in the P2P market. However, as can be seen from the increasing trend of network losses in Figure 6a, the pursuit of benefits among prosumers makes managing network losses difficult. The more widespread the price options become, the higher the difficulty in managing network losses.

Unlike the price-guided case, an increase in the price options does not affect the network losses in the loss-guided case, as the framework always tries to minimize the network losses regardless of price. Thus, the network losses converge to a value between 62.143 kWh and 62.145 kWh at all times, as shown in Figure 6b. It should be mentioned here that the network losses under the conventional centralized market framework, which can be calculated by not applying any algorithms in Section 4.1 and just using MATPOWER functions on the IEEE 33 bus system in Table 2, is 62.136 kWh. The network losses under the loss-guided case, which prioritizes managing network efficiency, described in Figure 7b, are only 0.011% to 0.014% larger than those under the conventional case. The energy costs under the loss-guided case in Figure 7b do not show an increasing or decreasing trend as the framework does not consider the price of offers during the matching process. Instead, its range of fluctuation becomes wider following the diversification of price. The energy cost under the random case in Figure 7c shows a similar result as Figure 7b the same token. However, the range of fluctuation of network losses in Figure 6c, which is from 63.873 kWh to 74.678 kWh, is larger than the loss-guided case in Figure 6b. This is because the minimization of network losses is not a matter of concern under the random trading framework.

The effect of the price-guided framework is detailed in Figure 8. Figure 8a describes the average rate of change in network loss costs, energy costs, and total costs of the price-guided case when those costs in the loss-guided case are used as set points. Likewise, Figure 8b describes the average rate of change in network loss costs, energy costs, and total costs of the price-guided case when those costs in the random transaction case are used as set points. The changing trends of graphs in Figure 8a,b are similar, as the network losses in the price-guided case are a lot bigger than those in the loss-guided and random cases, as shown in Figure 6, and the energy costs in the loss-guided and random cases are close to each other, as shown in Figure 7.

As shown in Figure 8a, the average rate of change in network loss costs between the price-guided framework and the loss-guided framework is positive, and the average rate of change in energy costs between the price-guided framework and the loss-guided framework is negative regardless of the standard deviation, except when the standard deviation is 0% of the mean. When the standard deviation is 0%, it is p_{loss} alone that varies in calculating ρ_{unit} in (1), as the loss price as well as the offer price, ρ_{loss} and $\rho_{trading}$, are fixed at \$100/MWh. In this case, the price-guided framework operates just the same as the

loss-guided framework, and thus, the average rate of change in all three costs when the standard deviation is 0% is zero.

The average rate of change in both network losses and energy costs between the price-guided and loss-guided frameworks diverges when the price options become wider following the increase in the standard deviation. This implies that the price-guided framework uses the trade-off relationship between the energy costs and the loss costs in P2P electricity trading, which was already mentioned in the example in Section 3.3. By exchanging network efficiency with prosumer welfare, the price-guided framework resolves the limitation of the loss-guided framework in our previous work [13]. The more energy costs decrease, the more network losses increase.

However, as the price-guided framework considers both energy costs and network losses simultaneously, careful consideration will be needed in applying the framework to the P2P electricity market. The results in Figure 8b are the reason for this. The results imply that, when the loss price is set to \$100/MWh, the price-guided framework prioritizes prosumer welfare more than network costs, not by just considering them, but by allowing prosumers' active profit-seeking, even though prosumers' decisions may lead to the inefficient use of the network. The reason why this favoritism happens is on the decision process of unit price, ρ_{unit} , described in (1). With the loss price of \$100/MWh, the weight of loss costs $\rho_{loss} \times p_{loss}$ in calculating ρ_{unit} is so light that it is the energy costs that dominate the price-guided framework's matching procedure. But the increase in loss price, p_{loss} , much heavier than \$100/MWh, does not always lead to an increase in $\rho_{loss} \times p_{loss}$, as the framework will consider the minimization of network losses, p_{loss} , more, and therefore, it can be said that setting the appropriate loss price is important but intricate work in applying the price-guided framework. Section 5.2 deals with this matter under the price-guided framework.

In this simulation, it can be said that, among the three cases simulated, the total costs, which is the sum of loss costs and the energy costs that correspond to the social welfare, are minimized under the price-guided case as an average rate of change of total costs in both Figure 8a,b are negative. However, the results do not lead to the conclusion that the price-guided framework always increases social welfare. The loss price in this simulation is fixed as \$100/MWh for convenience, which is the median value of ranges of offer prices, but as mentioned above, different loss prices will affect the network loss as well as the matching procedure, and the result could become different. This will also be dealt with in Section 5.2.

5.2. The Effect of Different Loss Prices on the Price-guided Framework

As discussed in Figure 8 in Section 5.1, setting the loss price is an important procedure in applying the price-guided framework to the P2P electricity market, as it can affect the matching mechanism, network efficiency, prosumer welfare, and social welfare. The impact of loss prices on network losses, loss costs, energy costs, and total costs on the price-guided framework is described in Figures 9 and 10. The impact of loss prices on the loss-guided framework and the random transaction case is also described for comparison.

Under the loss-guided framework, it is not loss costs but network loss itself that determines transactions among prosumers. Therefore, as can be observed in Figure 9a, the average of network losses is independent of the loss price. Further, as the loss-guided framework is based on the power flow equation, even though there is randomness in the buying order, the loss value converges to a constant, 62.143 kWh. As with the loss-guided framework, under the random transaction case, loss price does not affect trading between prosumers. Therefore, as can be observed in Figure 9a, the average of network losses under the random transaction case is independent of the loss price. As the random transaction case does not use any algorithm, such as power flow equations, the network losses rather fluctuate unlike the loss-guided case, but still converge between 67.469 kWh and 68.134 kWh. As the average of the network losses is almost constant regardless of the loss price under both cases, the loss costs of the loss-guided framework and the random

transaction case, which are the network losses multiplied by the loss price, looks directly proportional to the loss price as in Figure 9b.

Under the price-guided framework, however, the average of network losses is inversely proportional to the loss price. When the loss price is set to \$0/MWh, the average of total network losses is 276.834 kWh, which is a lot bigger than those of the loss-guided framework and random transaction case, but when the loss price is \$200/MWh, network losses decrease to 106.638 kWh, still bigger than those of loss-guided framework and random transaction case, and, when it is more than \$1800/MWh, the value starts to become lower than that of the random transaction case as in Figure 9a. With a lot bigger loss price, the price-guided framework will work the same as the loss-guided framework, as the weight of loss costs $\rho_{loss} \times p_{loss}$ in calculating ρ_{unit} , (1), will become much heavier than the energy costs, $\rho_{trading} \times p_{trading}$. Therefore, the average of network losses in Figure 9a of the price-guided framework will finally converge to that of the loss-guided framework. The average of loss costs in Figure 9b will also converge.

The overall results in Figure 9 imply that, under the price-guided framework suggested in this paper, the loss price works well as a controller of the network losses—with a small loss price, prosumers pursue their welfare actively with little consideration of network losses, but when the loss price goes up, network efficiency on losses can be improved. In this experiment, the effectiveness of the controller is maximized when the loss price is small, between 0 and around 6 times the median of the offering range, \$100/MWh. However, as can be seen from Figure 9a,b, the increase rate of average network losses is always negative, while the increase rate of average loss costs is always positive. This implies that the decrease rate of average network losses is much smaller than the increase rate of average loss price. As the increase in loss price may not lead to a desirable decrease in network losses, careful consideration is needed in setting the loss price under the price-guided framework.

The average of energy costs under the loss-guided framework and random transaction case is independent of loss price just as with the average of network losses under both cases, as can be seen in Figure 10a. Especially, as energy price is not considered during the matching process under both loss-guided framework and random transaction, it looks as if the averages of energy costs of both cases are almost the same regardless of the loss price. As the price-guided framework uses the trade-off relationship between the energy costs and the loss costs, average energy costs under the price-guided framework are always under the value of the loss-guided and random transaction cases as shown in Figure 10a, contrary to the average network losses described in Figure 9a. Following the increase in loss price, the energy costs under the price-guided framework increase, as in Figure 10a, and this supports the former discussion on prosumers' behavior according to the loss price—prosumers pursue their welfare actively without considering network losses when the loss price is small, and rather passively, whether it is a true intention or not when the loss price increases.

As with the network losses discussed in Figure 9a, as the loss price increases, the average energy costs under the price-guided framework will also finally converge to those of the loss-guided framework. But the average energy costs of the price-guided framework cannot exceed those of the loss-guided framework, just as the average network losses of the price-guided framework cannot go under those of the loss-guided framework. Therefore, it is obvious that adopting the price-guided framework will definitely cause some amount of exchange between network losses and prosumer welfare, which we called a trade-off relationship in Section 3.3. To what amount, then, can the network losses and prosumer welfare be exchanged?

In the P2P electricity trading market that allows free transactions among prosumers, network losses in the distribution network will be compensated using the electricity that the network operator purchases from the mother grid. Therefore, the contract price of electricity for loss compensation will be the minimum loss price that the network operator can notify prosumers. Under the price-guided framework, the operator may put emphasis on the efficiency of the network by raising the loss price more than the contract price and

sacrificing prosumer welfare or may put emphasis on social welfare, by remaining the loss price around the contract price and keeping the total costs small. However, in raising the loss price, a limitation is needed, as it can cause an excessive increase in total costs and an excessive decrease in prosumer welfare. In this case, the total costs under the loss-guided case when the loss price is the contract price between the network operator and the mother grid can be used as a reference. For example, suppose a contract price between the network operator and the mother grid is \$100/MWh, the median of the offering range among prosumers in this simulation. As marked as point A in Figure 10b, the average total costs of the loss-guided case when the loss price is \$100/MWh is \$379,053 and this will be the marginal total costs that it is recommended not to exceed, even if the operator increases the loss price under the price-guided framework. To follow the recommendation, the operator needs not to increase the loss price more than the x value of Point B in Figure 10b, which seems to be between 6 and 7 times the median \$100/MWh. If not, the average total costs under the price-guided framework will become even larger than that of the loss-guided framework and the price-guided framework will become less meaningful.

6. Conclusions

As DERs are a matter of great interest in electricity networks these days, accordingly, interest in P2P electricity trading using DERs is growing. Therefore, many studies have focused on the requirements that the P2P trading framework should fulfill. The P2P trading framework must not only be able to attract the active participation of prosumers but also be able to manage network status. In this respect, in our previous work, a loss-guided framework based on the CDA mechanism that matches prosumers considering network losses was suggested [13]. However, as the loss-guided framework has the weakness of not considering prosumer welfare, a price-guided framework for P2P electricity trading that makes up for the weakness by taking into account network loss costs, as well as energy costs, is suggested.

In the paper, the impact of the price-guided framework is examined through a simple 6-bus example. After that, the price-guided framework is compared with the loss-guided framework and the random transaction case through two experiments on the IEEE 33 bus network. In the first experiment, network losses, energy costs, and total costs under three cases, the price-guided case, the loss-guided case, and the random transaction case, are calculated with various ranges of the offer price. From the first experiment, the basic principle that the price-guided framework is based on is examined, which is the trade-off relationship between the energy costs and the network losses. By using the trade-off relationship, prosumer welfare can be improved under the price-guided framework.

In the second experiment, network losses, network loss costs, and total costs under the same three cases are calculated with various loss prices. From the second experiment, it was concluded that, if prosumer welfare is a major concern under the price-guided framework, it would be better to set the loss price as low as possible, close to the contract price between the network operator and the mother grid. However, if the network losses need to be considered as well, setting a loss price to be around 6 times the contract price is suggested to achieve both low network losses and low total costs, which corresponds to both network efficiency and social welfare.

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