DISTRIBUTED P2P ENERGY TRADING SYSTEM USING MATCHING MECHANISM

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ABSTRACT

In this research, we propose a new decentralized power distribution system. Producers and the consumers are connected bi-directionally with a power line and are able to trade electric power in real time. For this, they submit bids freely based on personal preferences to spot markets. In this paper, we not only conceptually design the power distribution system, but also simulate the system for a given case study. We could confirm the behavior of the market by reproducing the bidding strategies and the power transactions of the system. We show that trading can significantly reduce curtailment of solar energy, especially if batteries are included.

INTRODUCTION

Currently in Japan, one electric power company per region is covering almost all of the electricity demand in that area.
In the existing power distribution system, electric power companies buy the surplus power which is not consumed by the houses. The Feed-in-Tariffs (FIT) are fixed by the Japanese government. The power company then sells this electric power is then sold to other customers. Currently, the vast majority of electricity however is transmitted one way from power plants over feeders to the end consumers. The grid itself is unable to store electricity which means that the grid works as a just-in-time distribution system, in which electricity generation must match demand all the time. If that is not the case, a penalty fee is imposed as an imbalance.
In such a power distribution system, producers including prosumer cannot sell electricity freely, and the merit of installing your own power generation is significantly reduced. In order to incentivize local power generation, it is necessary to build a new distribution system which allows prosumers and consumers to trade equally.
In this research, we propose a new P2P-based power distribution system, in which a large number of prosumers and consumers are interconnected and can exchange power freely.

Literature review

Zhang[1] used the Nash equilibrium to show that the market participant's supply and demand can be balanced by means of P2P transactions.
Namerikawa[2] and his colleagues showed an example of decentralized real-time electricity price determination mechanism and conducted a real-time market from using a fixed price contract. However, the cost functions of consumers and suppliers are predefined, meaning that the price is fixed when solving the optimization problem. Thus, it does not allow dynamic, market-based pricing.
An innovative distribution system based on packet power trading is proposed by Inoue[3]. It allows trading electricity on a network where customers with storage are connected to each other. However, the proposed system requires customers to own batteries to join. Also, bidding strategies for the market cannot reflect individual preferences.

Motivation and approach

To complement the shortcomings of existing research, this research proposes a distributed power distribution system with the following features:

1. Prosumers and consumers are connected via bi-directional power lines.
2. It is possible to send a bid to buy or sell electricity to the market following individual preferences.
3. Power can be traded for current and future timeslots.

Thanks to these features, we aim at building a distributed electricity distribution system that incentives the installation of renewable energy. To achieve our goal, we designed a decentralized model for a power distribution network and an electricity trading market. Then, we implement a simulator to evaluate the system using case studies.

CONCEPTUAL DESIGN OF A DECENTRALIZED POWER DISTRIBUTION SYSTEM

Distributed network structure

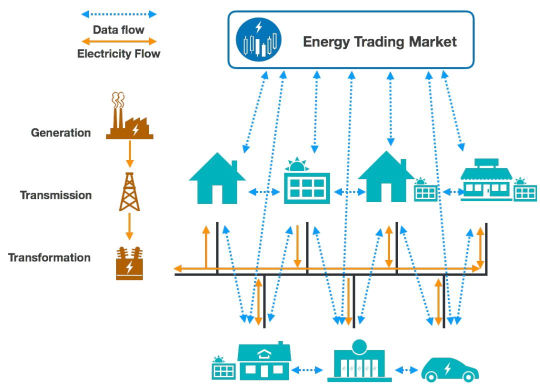

Figure 1 Distributed Network

The proposed system is illustrated on Figure 1. All consumers and prosumers can communicate with each other and exchange power bi-directionally. The market is managed by one or more super nodes.

Electricity market

For the decentralized market mechanism, each node locally takes measurements, calculates prediction and generated the bidding information that is sent to the market. The market mechanism then runs to determine potential power matches. In the case when a power trade is concluded in the market, electricity accommodation is executed. Details of each function are described in next section.

Participants in Distributed Energy Trading System

Participants in the distributed power distribution system are classified as shown in Figure 2. Depending on their abilities of handling electric power, they implement a function that simulates the consumption of electric power, a function for power generation and function that stores electric power. Participants may implement one or more of these functions.

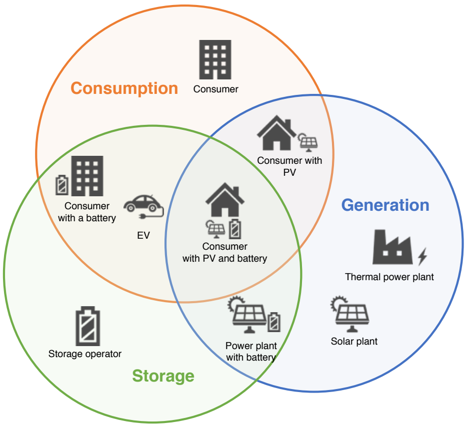

Figure 2 Type of System Participants

DESIGNING ELECTRICITY MARKET

One day is divided into 48 timeslots of 30 minutes each. Each timeslot is associated to an independent market able to carry out transactions. All power transactions must coincide precisely with the 30 minutes of one of the 48 timeslots.

The trading method in the proposed electricity market adopts a continuous double auction approach.

Each market participant is composed of a measurement agent, a prediction agent and bidding agent:

a)***[Measurement Agent]*** Collects measurement information describing present system state. We also measure past demand and amount of generated electricity. In addition to it, we collect past weather, temperature and humidity data.

b)***[Prediction agent]*** Predicts user's demand and power generation using data obtained from the measurement agent. At the beginning of each timeslot, it predicts electricity consumption and generation during the 30 minutes market trading period.

The energy amount for bidding is calculated based on the confidence levels. We divide the levels in 10 levels of 10% each from 0% to 100%. For instance, if the confidence level is 90%, we will select the bidding parameters corresponding to 90% chance of occurrence.

For consumption prediction, we used clustering and multiple regression analysis as proposed in [4]. This defines the probability density function of the predicted value for every 30 minutes and calculates the predicted value for each occurrence rate. The method for getting the mean value of the probability density function is described below.

Initially, we separate the input 11 months data of demand, supply, temperature and humidity into weekday, weekend and holiday. After that, we get 4 segments using k-means clustering algorithm. The total clustering number becomes 12. We used the following formula defined in [4].

$$D_{predict_t} = a_0 + a_1 T_t + a_2 T_t^2 + a_3 H_t \quad (1)$$

$D_{predict_t}$: Demand prediction at time *t*
T_t: Temperature at time t
H_t: Humidity at time t
$a_0 \sim a_3$: Parameters for multiple regression

By substituting temperature and humidity into the prediction expression of the cluster linked to the day of the week, it is possible to obtain the average value of the probability density function.

The variance of the probability density function can be obtained from the difference between the value of the training data and the calculation result using the above equation

c)***[Bidding agent]*** Determines the quantity and the price of electricity bid. The bidding strategy is determined in advance by the individual preferences of each participant. The amount and price of the electricity are automatically determined depending on the predicted consumption or generation. The bidding strategy for nodes with batteries are from the ones without. Each bidding strategy is described below:

- **Forecast-based bidding**
  When a node without a storage unit decides the bid price, the probability of occurrence of the predicted value and the time difference from the current time and the future market are taken into account as shown in Table 1. For example, when issuing a buy bid to the market three hours from now, the electricity price up to the predicted amount with a confidence level 100% is 33.5 yen, and the electricity price for the amount with a confidence level of 90% to 100% is going to be 32.4 yen.

Table 1 Bidding Strategy Based on Prediction

	Bidding timing(t)						
Probability	16<t≤24	8<t≤16	4<t≤8	2<t≤4	1<t≤2	0.5<t≤1	0<t≤0.5
1 ~	20.0	24.5	29.0	33.5	38.0	44.0	50.0
0.9 ~ 1	18.0	22.8	27.6	32.4	37.2	43.6	44.0
0.8 ~ 0.9	18.0	22.8	27.6	32.4	37.2	43.6	43.6
0.7 ~ 0.8	14.0	19.4	24.8	30.2	35.6	42.8	43.6
0.6 ~ 0.7	14.0	19.4	24.8	30.2	35.6	42.8	42.8
0.5 ~ 0.6	10.0	16.0	22.0	28.0	34.0	42.0	42.8
0.4 ~ 0.5	6.0	10.4	14.7	19.1	23.4	29.2	42.0
0.3 ~ 0.4	6.0	10.4	14.7	19.1	23.4	29.2	29.2
0.2 ~ 0.3	2.0	1.7	1.4	1.1	0.8	0.4	29.2
0.1 ~ 0.2	2.0	1.7	1.4	1.1	0.8	0.4	0.4
0 ~ 0.1	1.0	0.9	0.7	0.6	0.4	0.2	0.4

- **SOC-based bidding**
  For nodes having a storage battery, the bidding price depends primarily on the predicted value of the State of Charge (SOC) for the time of the bidding. Therefore, as shown in Table 2, the price changes according to the SOC at the time of bidding. When the SOC is predicted to exceed a preset upper limit value or falls below a lower limit value 4 hours after the concerned bidding timeslot, the prices are modified in order to take into account not only the predicted SOC but also the rate of change in SOC (i.e. the SOC 4 hours later).

Table 2 Bidding Strategy Based on SOC

	Normal		Upper limit		Lower limit		Both limit	
SOC	Buy	Sell	Buy	Sell	Buy	Sell	Buy	Sell
0.9 ~ 1.0	0.0	7.0	0.0	7.0	0.0	7.0	0.0	7.0
0.8 ~ 0.9	2.5	21.4	0.0	7.0	5.0	25.7	0.0	7.0
0.7 ~ 0.8	5.0	25.7	2.5	21.4	7.5	30.0	0.0	100.0
0.6 ~ 0.7	7.5	30.0	5.0	25.7	10.0	34.3	0.0	100.0
0.5 ~ 0.6	10.0	34.3	7.5	30.0	25.0	38.6	0.0	100.0
0.4 ~ 0.5	25.0	38.6	10.0	34.3	27.5	42.9	0.0	100.0
0.3 ~ 0.4	27.5	42.9	25.0	38.6	30.0	100.0	0.0	100.0
0.2 ~ 0.3	30.0	100.0	27.5	42.9	50.0	100.0	0.0	100.0
0.1 ~ 0.2	50.0	100.0	30.0	100.0	50.0	100.0	50.0	100.0
0.0 ~ 0.1	50.0	100.0	50.0	100.0	50.0	100.0	50.0	100.0

d) [Market function and power integration] After determining the bidding parameters, the bid is transmitted to the market. Since the market uses continuous double auction mechanism, the bid is immediately treated and judged whether or not it could be matched.
The physical power transfer of executed bids is started when the concerned market is opened.

MODEL DESIGN OF PARTICIPANTS

Participants in the electricity market prepare the parameter tables used for the bidding strategy as defined in previous section based on each participant's individual preferences. We modelled the participant's preferences and how the preferences are reflected in the bidding strategy.

Consumer

The consumer determines the bidding strategy using the indicators listed in Table 3.
There is a parameter indicating how much the customer trusts the predicted value which influences the bidding price. If a customer trusts the predicted value almost as much as an actually measured value, the bidding strategy will set a bidding price close to the one for the actual value. In order to express such a feature, an indicator of confidence is set and the bid price of the one hour ahead market is specified. We also defined an indicator of risk tolerance and designed it so that the future market buy price will decline together with the risk tolerance value.

Table 3 Indices for Consumer

Index	Unit	Min	Max
Target Price	Yen	Market min price	Market max price
Max price	Yen	Market min price	Market max price
Price range	Yen	0	∞
Prediction reliability	-	0	10
Risk torlerance	-	0	1

Producer

The producer determines the bidding strategy using the indicators listed in Table 4.
Using the predicted confidence levels similarly to the consumer, the bid price other than the target price and the lowest price one hour ahead market is determined. Using the risk preference as an indicator, bid prices for the one hour ahead market is determined.

Table 4 Indices for Generator

Index	Unit	Min	Max
Target Price	Yen	Market min price	Market max price
Max price	Yen	Market min price	Target price
Price range	Yen	0	∞
Prediction reliability	-	0	10
Risk torlerance	-	0	1

Prosumer with PV

Customers with PV have bidding strategies for both consumers and producers (PV). We first define the probability distribution of power consumption / generation. Then, the probability distribution of electricity generation is subtracted from the consumption which is then used as the forecast for the net demand. If the average of the probability distribution is positive, the buy bid is submitted, and when the average of the probability distribution is negative, the sell bid is submitted.

Prosumer with PV and battery

The customers with both PV and battery determine the bidding strategy using the indicators listed in Table 5.
We assume two types of prosumer: the ones who wish to use the electricity between the lower limit and the upper limit of SOC flexibly for trading energy on the market, and the ones who want to keep a stable SOC level in order to always have sufficient stored energy in case of a power outage etc. Therefore, an indicator for the desired stability of SOC is specified. Using this index, we define the range of variation of the bid price between SOC lower limit and upper limit.

Table 5 Indices for Consumer with PV

Index	Unit	Min	Max
Target SOC	%	0%	100%
Target buy price	Yen	Market min price	Target sell price
Target sell price	Yen	Target buy price	Market max price
Max SOC	%	0%	100%
Min SOC	%	0%	100%
SOC stability	-	0	10
Change sensitibity	-	0	10

Grid

The grid has a very simple strategy: it always submits sell bids for unlimited amounts of energy at a given upper limit price (the market price) and submits buy bids for an unlimited amount of energy at the lower limit price (Feed-in-Tariff).

CASE STUDY

Decentralized Power Distribution Simulation

In this research, we simulated the proposed power distribution system and observed the superiority of the energy market trading system by reproducing the power flows and the bidding strategies. Figure 4 shows the flow of distributed power flow simulation.

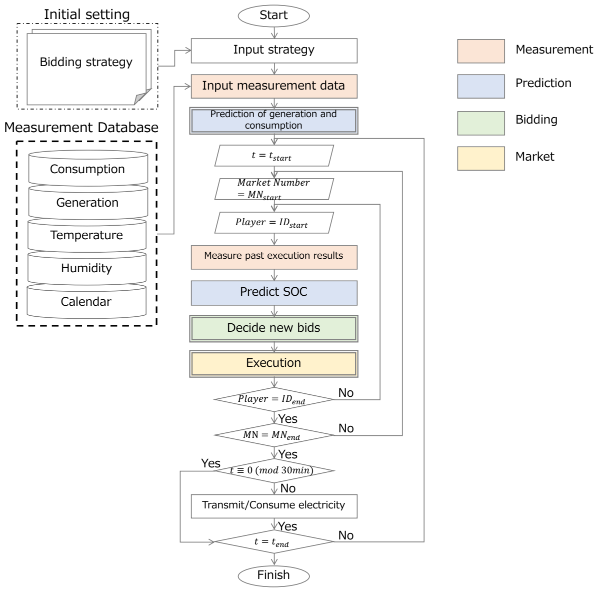

Figure 3 A Simulation of Distributed Electricity Trading System

The number of markets is 48, and the simulation period is two days. In addition, an upper limit price and a lower limit price for all buy and sell bids is introduced. This case study includes 11 participants: the 5 are prosumers with PV (N1-N5), 4 are simple consumers (N6-N10), and one acts as power grid (N11).

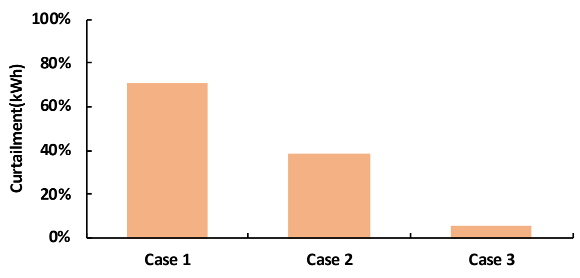

Figure 4 Surplus electricity percentage

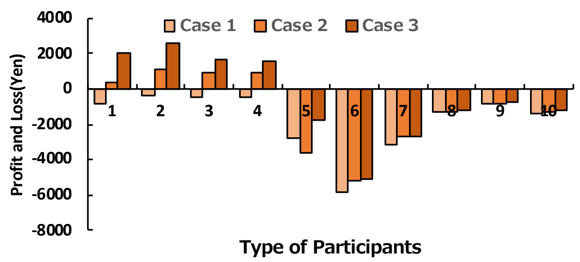

Figure 5 Profit and Loss

In this case study, we assumed following 3 cases:
(1) each participant cannot trade with each other.
(2) each participant can trade with each other.
(3) each participant can trade with each other and three of the prosumers have storage batteries.
The average ratio of curtailed electricity for each of the three cases is shown in Figure 4 , and the profit and loss for each participant except the grid is shown in Figure 5.
The simulations show that the existing power distribution system without trading results in 71% of the solar power generation being curtailed. With the here proposed power market model and decentralized power distribution system the curtailment was reduced to 39%. In addition, we showed that it is possible to reduce curtailment to a mere 6% by using storage batteries for 3 of the prosumers.
For the existing power distribution model, the average electricity bill of all participants was 17270 yen, while when using the decentralized power distribution model including storage units for 3 prosumers it was reduced to 4868 yen.

CONCLUSION

In addition to conducting conceptual design of the power distribution system, we modeled the system and conducted simulations to reproduce the actual energy transactions to confirm the behavior of the market.
We conducted a case study of such a decentralized power distribution system which consisted of five prosumers with PV, and five regular consumers.
Our future work will include predictions of users' behavior and calculate future consumption and generation. This will allow us to also take EVs into account and simulate V2G. In addition to that, we are planning to build physical infrastructure to test actual electricity transmission.

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