Nurturing a New Low Carbon Sector under Uncertainty of Fuel Economy and Renewable Sources Development

Tak Niimura[a] , Hiroshi Takamori[b], Daiki Yamasita[c], Ti Wang[d], and Ryuichi Yokoyama[e]

[a] *Faculty of Economics, Hosei University*

[b] *Waseda University Environmental Research Institute*

[c] *Dept. of Environment and Energy Engineering, Waseda University*

[d] *Dept. of Environment and Energy Engineering, Waseda University*

[e] *Dept. of Environment and Energy Engineering, Waseda University*

Abstract:

This paper explores avenues for nurturing a new energy-saving sector under uncertain development of renewable energy sources and energy storage facilities. In particular, we addresses designing a smart-grid scheme that would make crowds of EV users the part of the energy management optimizers of a smart community. A collected mass of electrical vehicles provides the capacity as cushions for absorbing erratic energy disturbances caused by renewable sources. The main instrument is to exercise the dynamic pricing and induce various types of users, including EV users, to respond to the electricity price driven their own incentives. This study aims to draw on the dynamism of competitive market mechanisms.

Keywords: charging infrastructure; renewable energy risk; smart-gird

1. A Model of Energy Management in the Smart Community

Figure 1 shows an image of the smart community, the energy management of which is to be studied in this paper. Energy in the form of electricity is of main concern. Up to today, electricity has traditionally been supplied by an electric power company or a utility company that serve as a regional monopolist. While the electric power company enjoys the monopoly position, it operations have been regulated in many ways. In particular, under this scheme, the price of electricity was under rigid control by the government. With electricity price fixed, the demand typically fluctuates in erratic manners. It has been the utility companies' mission and responsibility that they are prepared to meet whatever high demand for electricity with sufficient capacity at hand. This requires for the electricity company to invest heavily in capacity in preparation for the peak demand. This seems to be a source of inefficiency in the firm's operation, because most generation facilities remain idle in low demand periods.

In contrast to the traditional practice, Figure 1 shows a new type of business players in electric power enterprises, called the "Load Serving Entity (LSE)", or sometimes the "Electricity Aggregator". The firms in the category of what is called the "PPS (Power Producer and Supplier) are most likely to enter this new enterprise.

An important difference between the LSE and the electric utility company is that the LSE seeks to trade electricity with price responsive users in the community. The LSE may have its own generation facility such as a gas turbine generator or some renewable generation facilities as seen in Figure 1. It may also have a contract with some outside sources like an electric utility or another PPS firm to procure electricity for a pre-arranged price when needed.

It is widely known that there are quite different types of electricity users in the community. Some type of users adjusts the quantity of electricity they use responding to the price changes, and some users do not.

This paper presents a model of energy management with an LSE as a business coordinator in a community.

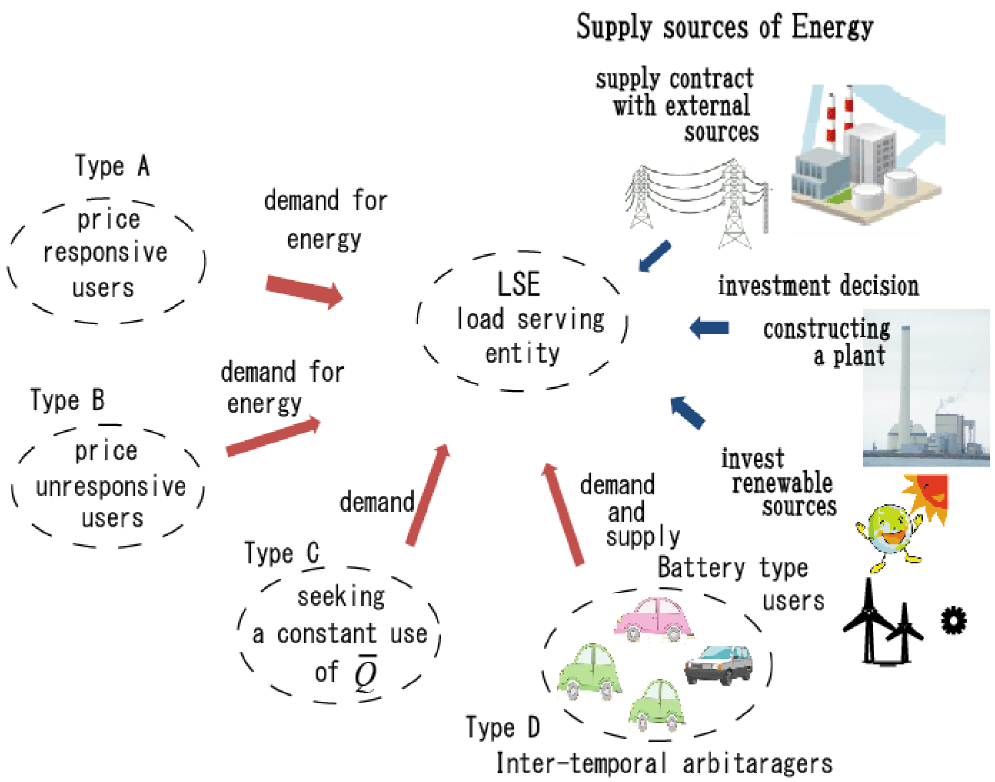

Figure 1 An image of smart Community

1.1 Demand Response Characteristics of Various Electricity Users in the Community

This section considers a model of the smart community as shown in Figure 2. A load serving entity (LSE) aggregates and coordinates, a day in advance, demands for electricity of various types of users in the community for each period of the next day. The purpose of the LSE is to achieve efficient energy supply and consumption via signaling electricity price for each period, to which users adapt their consumptions.

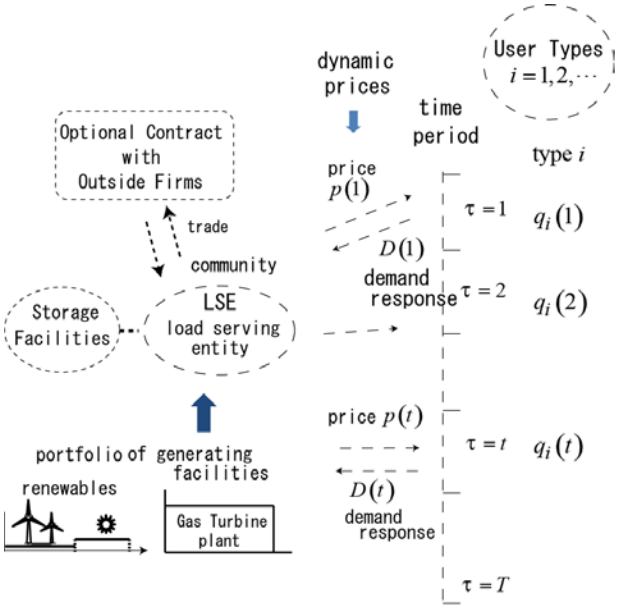

Figure 2 A Model of Daily Arrangements of Dynamic Pricing and Consumptions

The consumption behavior of each user type is modeled by their demand function for electricity:

$$q_{it} = A_{it} \cdot p_t^{\alpha_i}, \quad t = 1, 2, \ldots, T \tag{1}$$

where the coefficient α_i stands for the price elasticity of consumption of type i users and the coefficient A_{it} represents the demand shift parameter. The dynamic demand changes over periods in a day are represented by changing values of A_{it}.

The inverse demand function of (1) is as follows.

$$p_i = M_{it}\; q_{it}^{h_i}, \quad t = 1, 2, \ldots, T \qquad \text{where } M_{it} = 1/A_{it},\; h_i = 1/\alpha_i \tag{2}$$

The theory of Economics stipulates that the inverse demand function represents the marginal value, or utility function, namely,

$$\frac{dU_{it}(q_{it})}{d\, q_{it}} = M_{it}\, q_{it}^{h_i} \tag{3}$$

where $U_{it}(q_{it})$ is the value function of the type i users consuming electricity in the amount of q_{it}. Thus, we can derive the value function by taking the integral of (3):

$$U_{it}(q_{it}) = \int_0^{q_{it}} M_{it}\, x^h dx = \frac{M_{it}}{\gamma_i}\, q_{it}^{\gamma_i}, \quad t = 1, 2, \ldots, T \qquad \text{where } \gamma_i = h_i + 1 \tag{4}$$

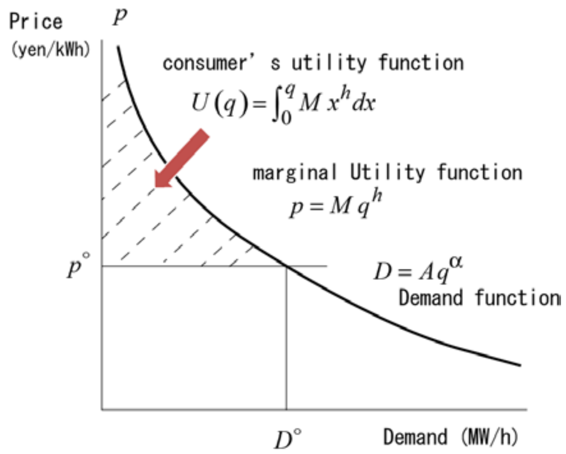

Figure 3　Demand function and Utility function

For simplicity, we consider three types of typical electricity users as described below.

✧ Type A Users

This type of users are price responsive, for example, with the elasticity of $\alpha_A = -1.5$. The second row of Table 1 shows the demand level $q_a(t)$ of type A users for price $p_t = 10$ (Yen/kWh), $t = 1, 2, \ldots, 6$. The corresponding demand shift parameters $A_{da}(t)$ are determined from (1) as:

$$A_{it} = q_{it} / \left(p_t^{\alpha_t} \right),\ t = 1, 2, \ldots, T \tag{5}$$

The second row shows the demand shift thus determined.

Table 1　Demand for price 10 (yen/kWh) and Shift Parameters: Type A

Period t	1	2	3	4	5	6
Demand D for p=10	3	1	8	2	1	4
A_{at}	94.4	31.6	253	63.2	31.6	126

Figure 2 draws the curve of the inverse demand function derived from (1) for each period.

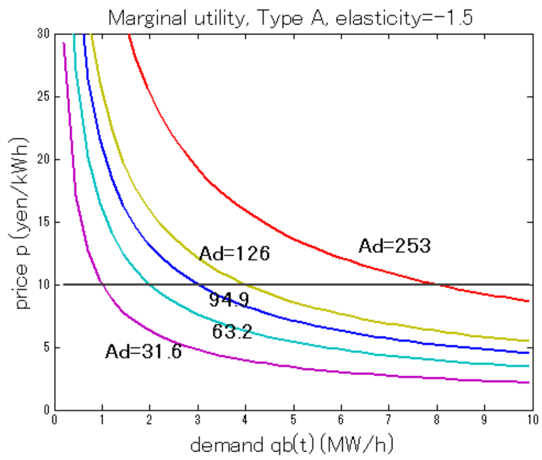

Figure 4　Demand curve and elasticity of Type A

✧　Type B Users

This type of users are price irresponsive with the elasticity, for example, of $\alpha_B = -0.2$ Table 2 shows the demand level $q_b(t)$ of type B users for price $p_t = 10$ (Yen/kWh), $t = 1, 2, \ldots, 6$, and the corresponding demand shift parameters A_{bt}.

Table 2　Demand for price 10 (yen/kWh) and Shift Parameters: Type B

Period t	1	2	3	4	5	6
Demand D for p=10	1.2	0.3	5	1	0.5	1.0
A_{bt}	1.9	0.476	7.92	1.58	0.792	1.58

Figure 5 draws the curve of the inverse demand function for each period. As seen in the figure, the curves are close to vertical lines around the price of $p = 10$ (yen/kWr), indicating that the demands $q_b(t)$'s are price inelastic for the type B users.

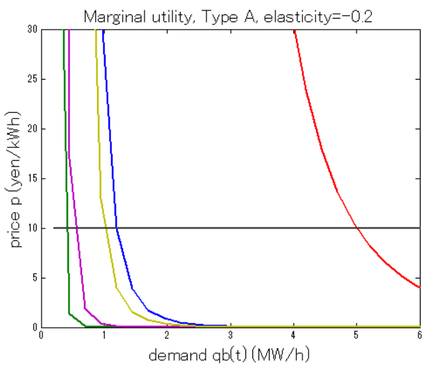

Figure 5　A Dynamic Demand Shift of Type B Users

✧　Type C Users

The consumption behavior of this type is driven by a preference different from the demand function of A and B. These users seek to minimize the total cost of consumption upon achieving the total consumption $\sum_{t=1}^{T} q_{ct}$ being equal to Q

$$w_C = \max\ K\left(\sum_{t=1}^{T} q_{ct} - Q\right) - \sum_{t=1}^{T} p_t q_{ct} \tag{6}$$

where $q_c(t)$ is the electricity consumption in period t, and Q is the total consumption during a day. The parameter p_t is the price of electricity in period. Electricity vehicle users typical belong to this group.

These users simply wish the total consumption to be Q, and they are indifferent about when to consume during the day as far as their total consumption is Q. For the type C users, we cannot draw the demand curve period-wise independently. Their entire demand $\mathbf{d} = (d_1, d_2, \ldots, d_T)$ over the all periods depends upon the vector of the entire prices $\mathbf{p} = (p_1, p_2, \ldots, p_T)$. In other words, the demand in each period is a function of the vector $\mathbf{p} = (p_1, p_2, \ldots, p_T)$, $d_t(\mathbf{p})$, $t = 1, 2, \ldots, T$. This functional relationship is written as follows:

$$\mathbf{d}_c(\mathbf{p}) \equiv \left(d_1(\mathbf{p}), d_2(\mathbf{p}), \ldots, d_T(\mathbf{p})\right)$$

From the community's stand point, these users contribute greatly to mitigating demand and supply crunch of the peak periods.

✧ Type D users: Inter-temporal arbitragers

This type of users acts like batteries with some storage capacity for energy. Typically, we imagine electric vehicle users purchasing electricity in low price periods and selling it in higher price periods. While they are acting driven by their own benefits, their arbitrage type of behaviors contribute greatly to smooth out erratic fluctuation of prices within a span of different periods.

$$S_t = S_{t-1} + s_t^+ - s_t^-, \quad t = 1, 2, \ldots, T$$
$$s_t^+,\ s_t^-,\ S_t \ge 0, \quad S_t \le \overline{S}$$

S_t : Level of energy charge of the storage facility at the end of period t.

s_t^+ : Amount of discharge of electricity during period t.

s_t^- : Amount of charge of electricity during period t

These users' objective is defined by

It is also to be noted here that this welfare maximization problem is for a given price vector $\mathbf{p}$.

2. Dynamic Pricing for the Energy Management in the Community

2.1 Welfare Maximization of All the Agents in the Community

Let $\mathbf{q}_i \equiv (q_{i1}, q_{i2}, \ldots, q_{iT}),\ \ i = A, B$ be the vector of energy consumption of Type i users.

Given a price vector $\mathbf{p} = (p_1, p_2, \ldots, p_T)$, these two types of users seek to maximize

$$
\begin{aligned}
W_i(\mathbf{p}) &= \max_{q_{i1},\ldots,q_{iT}} \ w_i(\mathbf{q}_i : \mathbf{p}), \qquad i = A, B \\
\text{where} \ \ w_i(\mathbf{q}_i : \mathbf{p}) &= \sum_{t=1}^{T} U_{it}(q_{it}) - \mathbf{p} \cdot \mathbf{q}_i
\end{aligned} \tag{7}
$$

where $\mathbf{p} \cdot \mathbf{q}_a$ stands for the **inner product** of a pair of vectors $\mathbf{p}$ and $\mathbf{q}_a$.

The first order condition of (7) is

$$
\frac{dU_{it}(q_{it})}{dq_{it}} - p_t = 0, \ \ i = A, B, \ \ t = 1, 2, \ldots, T \tag{8}
$$

where $\mathrm{dU}_{it}(q_{it}) / dq_{it}$ stands for the marginal utility function represented by the inverse demand function (3).

Community Welfare

This subsection describes the welfare that each type of users seeks to maximize responding to a given price vector $\mathbf{p}$. These users adjust their consumption levels $\mathbf{q}_a, \mathbf{q}_b, \mathbf{q}_c, \mathbf{q}_d$ to maximize their welfares that are defined below.

i. Type A and B: $w_i(\mathbf{q}_i : \mathbf{p}) = \max_{\mathbf{q}_i} \left[\sum_{t=1}^{T} U_{it}(q_{it}) - \mathbf{p} \cdot \mathbf{q}_i \right], \ \ i = A, B$

ii. Type C: $w_C(\mathbf{q}_c : \mathbf{p}) = \max_{\mathbf{q}_c} \left[U_c(\mathbf{q}_c) - \mathbf{p} \cdot \mathbf{q}_c \right]$, where the utility function of this type of users are in the following form

$U_c(\mathbf{q}_c) = -K\left(\sum_{t=1}^{T} q_{ct} - Q\right)^2$, the coefficient K is very large positive number so

that $U_c(\mathbf{q}_c)$ is maximized when $\sum_{t=1}^{T} q_{ct} - Q$.

iii. Type D: $w_D\left(\mathbf{s}^+, \mathbf{s}^-; \mathbf{p}\right) = \max_{\mathbf{s}^+, \mathbf{s}^-, \mathbf{S}} \left(\sum_{t=1}^{T} p_t s_t^+ - \sum_{t=1}^{T} p_t s_t^- \right)$

iv. Welfare of the community (LSE) is $w_L(\mathbf{x}:\mathbf{p}) = \max_{\mathbf{x}} \left[\mathbf{p}\cdot\mathbf{x} - \sum_{t=1}^{T} \mathrm{C}_t(x_t) \right]$, where $C_t(x_t)$ is the total cost of supplying x_t in period t.

The community welfare maximization is now written as follows.

$$
\begin{aligned}
\mathrm{W}_{\mathrm{COM}}(\mathbf{q}_i, \mathbf{s}_i, \mathbf{x};\, \mathbf{p}) &= w_A(\mathbf{q}_a;\mathbf{p}) + w_B(\mathbf{q}_b;\mathbf{p}) + w_C(\mathbf{q}_c;\mathbf{p}) \\
&\quad + w_D\left(\mathbf{s}_d^-, \mathbf{s}_d^+;\mathbf{p}\right) + w_L(\mathbf{x};\mathbf{p}) \\
&= \max_{\mathbf{q}_i, \mathbf{s}_i, \mathbf{x}} \sum_{t=1}^{T} \mathrm{U}_{at}(q_a(t)) + \sum_{t=1}^{T} \mathrm{U}_b(q_b(t)) - \sum_{t=1}^{T} C(x_t) \qquad (9) \\
&\text{subject to:} \\
&\text{market clearing condition:} \quad \mathbf{q}_a + \mathbf{q}_b + \mathbf{q}_c + \mathbf{q}_d = \mathbf{x}
\end{aligned}
$$

where $\mathbf{x}$ stands for the supply vector of electricity that the LSE needs to procure by generation from renewable sources, or by generation from its own plant or by outsourcing. As seen in (9), summing up all the welfares of the all agents involved in the system results in disappearance of the price vector $\mathbf{p}$ from the problem.

The cost term $\sum_{t=1}^{T} C(x_t)$ depends upon the supply management on the part of the LSE, the coordinator of the community. The next section models the planning and operational decision problem of the supply-side LSE.

2.2 Planning and Operational Decision Problem of the Supply-side LSE

We consider a day-ahead planning problem of the LSE. However, adjusting to the real-time realization of uncertain generation from renewable sources, the problem involves some real-time decision variables as well.

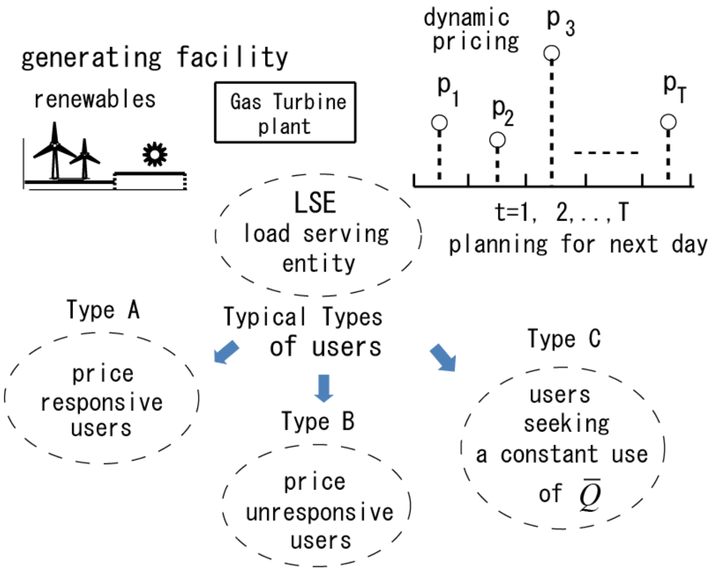

Figure 6 A Day-Ahead Coordination of Energy Management in a Community

Nomenclature

General Parameters

T : Total number of periods in a day

Δt : Number of hours in a period , $\Delta t = 24 / T$

p_t Market price of electricity in period t . This is determined a day-ahead by contract. [10^3 yen/MWh]

(i) LSE's variables and parameters related to long term decision

G : Generation capacity to construct (MW): decision variable

I_C : Investment cost per capacity of generation (10^6 yen/MW)

c_h : Hpurly equivalent of Investment cost per capacity (10^3 yen/MW/h)

(ii) LSE's annual decision variables and parameter

z : Capacity contract for outsourcing (MW)

C_z : Contract cost per outsourcing capacity (10^6 yen/MW)

c_z Daily equivalent of contract cost per outsourcing capacity (10^6 yen/day)

A Day-ahead Variables, Contract Decisions

(i)Users' Decision Variables

q_{it} : Electricity demand level of user type i in period t [MW/hr.]

α_i : Demand elasticity of user type i , $i = a, b$

A_{it} : Demand shift parameter of user type i in period t

(ii) LSE's Decision Variables

x_t : Supply level in period t [MW/hr.]

z_t : Capacity contract for outsourcing in period t. [MWh]

c_a : Capacity price for outsourcing in period t. [MWh]

LSE's Real-time Decision Variables and Parameters in the Current Day

Decisions depend on the realization of the state of nature

ω_t^i	State of nature in period t, *e.g.*, $i=1$: fine weather, $i=1$: cloudy weather
r_t^i	Renewable energy generation level for ω_t^i in period t [MW/hr.]
ρ_t^i	Probability of realization of state i
g_t^i	Generation level by LSE's plant [MW/hr.]
c_g	Marginal cost of generation by LSE's plant, [10^3 yen/MW/hr.]
c_y	Electricity cost per MW/hr. for outsoucing in period t [10^3 yen/MWh]
y_t^i	Outsourcing level per hour [MW/hr.]
o_t^i	Purchasing amount exceeding the contract capacity z [MW/hr.]
c_o	Purchasing cost in the contract over-run [10^3 yen/MWh]

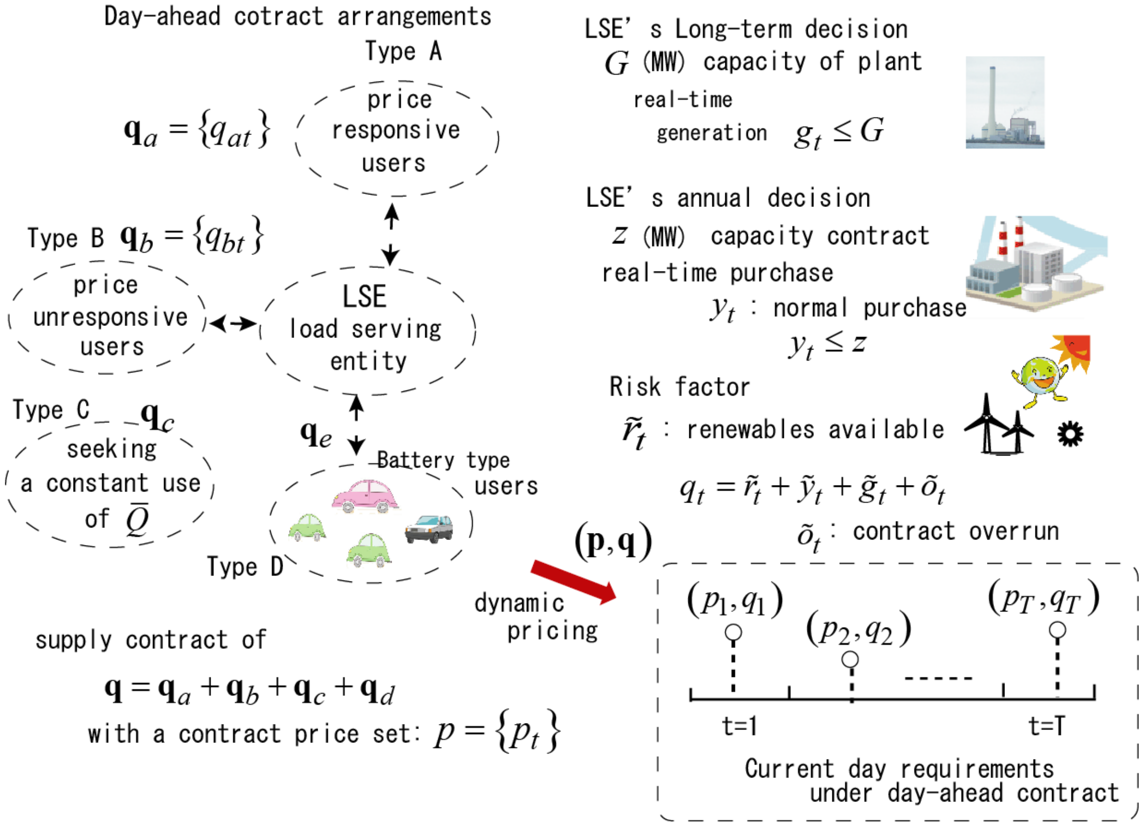

Figure 7 Long-term decision and short-term decision

Long-term Investment Decision on the Generating Plant

The LSE makes a long-term decision on the capacity G (MW) of its own generation plant. It costs I_c (10^6 yen/MW) per one Megawatt of capacity to construct a generating facility of its own. Assuming that the plant will be in operation for $n = 8$ year and the capital cost for the investment is $i = 0.08$ (8%). The capital cost I_c is transformed to annual equivalent I_a by

$$I_a = I_c \times F_{i,n}, \qquad F_{i,n} = \frac{i(1+i)^n}{\left[(1+i)^n - 1\right]} = \frac{.07(1.07)^8}{\left(1.07^8 - 1\right)} = 0.167 \tag{10}$$

where $F_{i,n}$ is the annual equivalent cost factor. The annual cost c_I (10^6 yen/MW/yr.) is further transformed to the hourly equivalent investment cost c_H by

$$c_h = \frac{c_I}{360 \times 24} \times 10^3 \qquad (10^3 \text{ yen/MW/h}) \tag{11}$$

Thus, if the LSE or the community decides to construct G megawatt of plant, it will cost $c_H \times G$ (10^3 yen) hourly. The generation levels, g_t, $t = 1, 2, \ldots, T$, are constrained by

$$g_t \le G, \; t = 1, 2, \ldots, T \tag{12}$$

Capacity Procurement from External Suppliers: An annual decision on contract with the outside source of supply

The LSE purchases a capacity on a contract annually. The capacity are expressed by z (MW). This is a decision variable made once in a year. In other words, the LSE can purchase hourly up to the amount z (MW), which is procured at the beginning of the year for the capacity price of C_a (10^6 yen/MW). This cost of purchasing a unit of capacity is transformed to the capacity cost per day by $c_a = (C_a / 365) \times 10^3$ (10^3 yen/MW/day).

Let

$$\tilde{\mathbf{y}} = \left(\tilde{y}_1, \tilde{y}_2, \ldots, \tilde{y}_T\right) \tag{13}$$

be the vector of the real-time purchase from the outside source. Then, the decision variables $\tilde{y}_t$'s are constrained by

$$\tilde{y}_t \le z, \quad t = 1, 2, \ldots, T \tag{14}$$

The cost c_y (10^3 yen/MW/h) applied to y_t is considerably low compared with the cost c_o (10^3 yen/MW/h) applied to O_t which is the purchase in the amount of the capacity over-run.

2.3 The Cost Minimization of the Supply-side LSE

This subsection describes the cost minimization problem to meet a given supply vector $\mathbf{x} = (x_1, x_2, \ldots, x_T)$.

The LSE has its own generating plant. The unit cost of generation is c_H (10^3 yen/MW/h). The variable cost of generation $C_t(g_t)$ for the generation level of g [MW/hr.] is

$C_t(g_t) = C_g \cdot g_t$, where $C_g = c_g \cdot \Delta t$, Δt = the number of hours in a period.

Let

$$\tilde{\mathbf{g}} = (\tilde{g}_1, \tilde{g}_2, \cdots, \tilde{g}_T) \tag{15}$$

be the vector of generations for all the periods in the current day. The decision on $\tilde{g}_t$ depends upon the realization of the renewable generation $\tilde{r}_t$. In meeting the power demand x_t in period t, the LSE attempts to supply with the purchase $\tilde{y}_t$ under the day-ahead capacity contract and with the generation from the renewables $\tilde{r}_t$. The balance $\tilde{g}_t$ needs to be generated by its own costly plant. Both the self-generation $\tilde{g}_t$ and the purchase from outsource $\tilde{y}_t$ are bounded by the longer term decision and contract. Therefore, the requirement and constraints for periods are written as

$$\begin{aligned} &\tilde{r} + \tilde{g}_t + \tilde{y}_t + \tilde{o}_t = x_t, \\ &\tilde{y}_t \le z, \quad \tilde{g}_t \le G, \quad t = 1, 2, \ldots, T \end{aligned} \tag{16}$$

where the supply level x_t is not a random variable since it is predetermined a day-ahead, while other variables are real-time random variables depending upon the realization of the renewable energy availability $\tilde{r}_t$.

The cost function $C_t(x_t)$ in (9) is expressed as follows.

$$C_t(x_t) = c_h G + c_z z + \left[\sum_{t=1}^{T} \mathbf{E}\left(c_g \vartriangle t \tilde{g}_t + c_y \vartriangle t \tilde{y}_t + c_o \vartriangle t \tilde{o}_t \right) \right] \tag{17}$$

This is the expected cost for one day. Since $\tilde{g}_t, \tilde{y}_t, \tilde{o}_t$ are interdependent variables resulting from the real-time decision, the expected value operation $\mathbf{E}[\cdot]$ cannot be distributed among terms within the bracket. To simplify this operation, we assume that the random variables $\tilde{r}_t$ takes a value out of two possible values as follows.

Energy generation by renewable source

The LSE owns a renewable generation plant, and the renewable generation levels during a day are represented by

$$\tilde{\mathbf{r}} = \left(\tilde{r}_1, \tilde{r}_2, \ldots, \tilde{r}_T\right). \tag{18}$$

The generation level $\tilde{r}_t$ in period t has a binomial distribution as follows:

$$\begin{array}{ccc} & & \text{probability} \\ \tilde{r}_t = & \left\{\begin{array}{l} r_t^1 \\ r_t^2 \end{array}\right. & \begin{array}{c} \rho_t \\ 1-\rho_t \end{array} \end{array}, \quad t = 1, 2, \ldots, T$$

The cost function $\sum_{t=1}^{T} C_t\left(x_t\right)$ in (9) results from the following minimization:

$$\begin{aligned} C(\mathbf{x}) = \min_{\mathbf{g}^i, \mathbf{y}^i, \mathbf{o}^i} \Big[& c_z z + c_z G - \overline{c}_g \boldsymbol{\rho} \cdot \mathbf{g}^1 + \overline{c}_g \left(\mathbf{1} - \boldsymbol{\rho}\right) \cdot \mathbf{g}^2 \\ & + \overline{c}_y \cdot \left(\boldsymbol{\rho} \mathbf{y}^1 + \left(1 - \boldsymbol{\rho}\right) \mathbf{y}^2\right) + \overline{c}_o \left(\boldsymbol{\rho} \mathbf{o}^1 + \left(1 - \boldsymbol{\rho}\right) \mathbf{o}^2\right) \Big] \end{aligned}$$

subject to :constraints on generation with the LSE plant

$$\begin{aligned} & r_t^k + g_t^k + y_t^k + o_t^k = x_t, \\ & y_t^k \le z, \qquad k = 1, 2, \quad t = 1, 2, \ldots, T \\ & g_t^k \le G, \qquad k = 1, 2, \quad t = 1, 2, \ldots, T \\ & g_t^k, y_t^k, \ o_t^k \ge 0, \quad k = 1, 2, \quad t = 1, 2, \ldots, T \\ & x_t \ge 0, \qquad t = 1, 2, \ldots, T \end{aligned}$$

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