REAL-TIME PRICING SYSTEM FOR DEMAND-SIDE MANAGEMENT IN FRIENDS

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Abstract – This paper presents a methodology for the demand-side management (DSM) considering the Flexible, Reliable and Intelligent ENergy Delivery System (FRIENDS) proposed by the authors. The proposed DSM is based on a real-time pricing system executed by third parties called Quality Control Centers (QCC) in FRIENDS, which are allocated close to consumers. The economic use of distributed generators (DG) or distributed energy storage systems (ESS) installed in the QCC is also considered in the DSM. A logistic sigmoid function is used for modeling the real-time pricing system and a couple of parameters in the function are optimized using the Genetic Algorithm (GA) so that profit of the QCC is maximized. The effectiveness of the proposed DSM is ascertained by evaluating the profit or the load factor of QCC through simulations using model systems.

Keywords: Demand-side Management, Real-time pricing system, FRIENDS, Distributed Generator, Distributed Energy Storage System

1 INTRODUCTION

An effective use of electric energy to save the limited natural resources has been one of the most important concerns in the world. Demand Side Management (DSM) is a way for inducing electric consumers to reschedule their energy consumption from viewpoints of the social benefit. The several methodologies for DSM such as peak clipping, valley filling, load shifting have been investigated [1].

In Japan, the energy consumption of business consumer or residential consumer has been increased recently. Therefore, a time-of-use pricing system which is a kind of DSM has been executed for their consumers by the utility. However, it has been reported that the effect of the DSM is not large because different needs of consumers are not considered, but the prices for electricity are set uniformly for every consumer. In fact, their energy consumption depends greatly on their individual life style or every company's economical policy. Therefore, equipments for effective use of energy such as electric water heaters [2], heat pumps have been installed individually. Or, it would be more effective to use the latest information and communication technology such as optical fibers spread to every building or every home.

The authors have proposed the Flexible, Reliable and Intelligent ENergy Delivery System (FRIENDS) as a concept of future electric power systems [3]. The concept of FRIENDS takes into account the deregulation of the electric power industry and progress of technologies such as power electronics, distributed generators (DG), distributed energy storage systems (ESS), information and communication. One of the most important characteristics of FRIENDS is that new facilities called Quality Control Centers (QCC) are installed between distribution systems and electric consumers as shown in Fig.1. The distributed generators, distributed energy storage systems and power electronics devices are installed in QCC so that the multi-quality power supply considering different needs of consumers can be realized. Another important characteristic of FRIENDS is that powerful information and communication network exists between QCCs and consumers. The network can be used not only for exchanging information about the electricity, but also for offering variable information services to consumers.

This paper presents a methodology for DSM based on a real-time pricing system through the information and communication network in FRIENDS. The economic use of DG and ESS in QCC is also considered in the proposed DSM. The logistic sigmoid function is used for modeling the real-time pricing system and a couple of parameters in the function are optimized by the Genetic Algorithm (GA) so that the profit of QCC is maximized.

In [4], a method for determining the real-time prices so that a social benefit defined by sum of supplier's cost and consumer's benefit is maximized has been

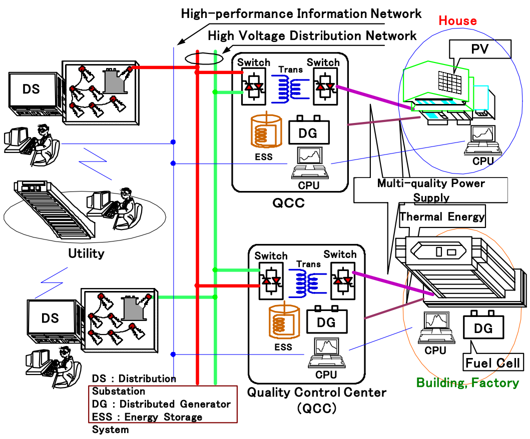


Figure 1: Concept of FRIENDS

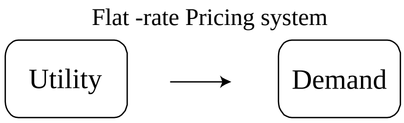


Figure 2: Conventional system

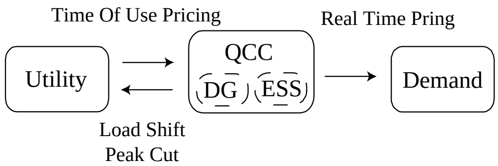


Figure 3: Proposed system

presented. In this case, depreciation expense, repair expense and personnel expense caused by load changes are included in the supplier's cost.

In the DSM proposed in this paper, QCC determines the real-time prices so that its profit can be maximized subject to a condition where consumer’s satisfaction does not change. Further, QCC can implement the DSM economically and flexibly by its owned DG and ESS. The effectiveness of the proposed DSM is ascertained by evaluating profit and load factor of QCC through simulations using model systems.

2 OUTLINE OF PROPOSED DEMAND-SIDE MANAGEMENT

2.1 Models of Proposed DSM

In the conventional power systems before FRIENDS is introduced, the utility supplies electric energy to consumers with a flat-rating pricing system as shown in Fig. 2. On the other hand, after the concept of FRIENDS has been introduced, a number of QCC would exist between utility’s distribution systems and electric consumers. This paper assumes that every QCC is a third party which is different from the utility and the electric energy for every consumer is supplied only by the QCC as shown in Fig.3. The utility just supplies the electric energy to every QCC. Further, QCC procures the electric energy from the utility under a conventional time-of-use pricing system in which the price for electricity is lower in the nighttime and higher in the daytime. After that, QCCs supply the electric energy to every consumer based on the proposed real-time pricing system in which the price for electricity changes in every period. Since the QCC owns DG and ESS, it can not only enhance its load factor by operating DG and ESS appropriately, but also would get more profit. Also, the enhancement in load factor of every QCC contributes to an efficient use of utility’s equipments such as transformers, transmission lines, generating plants. Therefore, the proposed DSM would be effective for the utility.

In this paper, two DSM models are considered as operation of facilities in QCC. One is a model in which DG is used for a peak shaving. The other is a model in which ESS is used for a load leveling.

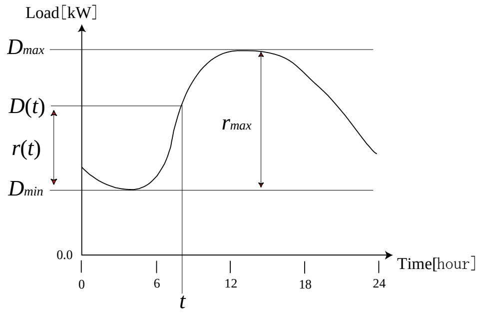


Figure 4: Reference load curve

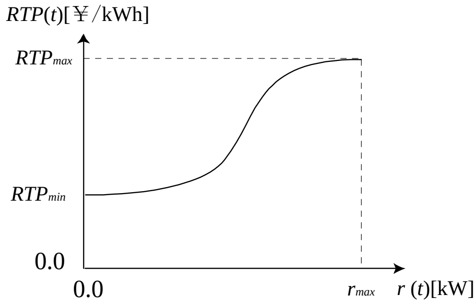


Figure 5: Real-time pricing curve using sigmoid logistic function

2.2 Formulation of proposed real-time pricing system

Generally, to enhance the load factor through cost consciousness, it is necessary to set a higher price in a period of heavy load and a lower price in a period of light load. The proposed DSM changes the prices for electricity in real-time using a sigmoid logistic function with three parameters. More specifically, the real-time prices can be determined according the following steps.

① QCC forecasts load patterns of residential consumer and business consumer before one day.

② QCC determines prices in every period based on the forecasted load patterns.

③ QCC informs to each consumer the real-time prices of the next day.

Here, it is assumed that load patterns of consumers when the price for electricity is free (0 yen) can be forecasted by QCC from the past experience. The load pattern is called a reference load curve in this paper (Fig.4). The real-time price, $RTP(t)$ can be determined by the following sigmoid logistic function as shown in Fig.5.

$$RTP(t) = RTP_{min} + \frac{a}{1 + b\exp(-cr(t))} \quad (1)$$

$$r(t) = D(t) - D_{min} \quad (2)$$

where, $D(t)$ is energy consumption at period t in the reference load curve. D_{min} is minimum value in the reference load curve. RTP_{min} is minimum value of $RTP(t)$. a, b and c are parameters which influence the shape of the sigmoid logistic function.

The QCC determines three parameters a, b and c in eq.(1) so that its profit can be maximized. However, it is preferable not to give any influence on consumers’ satisfaction after the real-time pricing system was

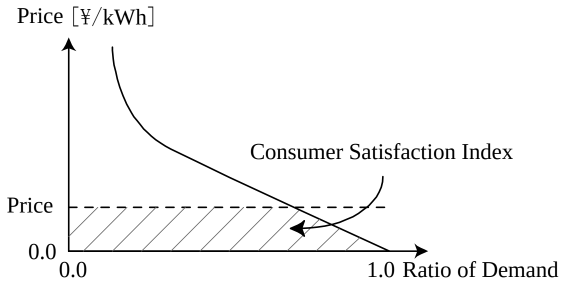


Figure 6: Price-demand curve

introduced. Moreover, the prices for electricity charged by QCC should not be higher than prices set by the utility. Therefore, the proposed real-time prices are constrained by the following conditions:

・Consumers' satisfactions before and after the real-time pricing system is introduced are identical.

・The maximum and minimum values of the real-time price are equal to prices when the QCC buys the electric energy from the utility in the daytime and nighttime respectively.

2.3 Models of Consumers

The change in energy consumption by setting real-time prices can be obtained by a simplified price-demand curve as shown in Fig.6. More specifically, if the energy consumption when the price is free is regularized by 1.0, the horizontal axis in this figure means a ratio of how much the demand decreases by setting a certain price. Therefore, the actual demand after setting the real-time prices can be calculated by multiplying the ratio derived from the demand curve to the reference load curve. Also, the consumers' satisfaction for a certain price can be calculated by losses of consumer surplus as shown in the shaded area of Fig.6 [5].

2.4 Optimization of Real-time Price

The proposed real-time prices are obtained by determining parameters *a* ,*b* and *c* in eq.(1). This paper determines these three parameters so that the profit of QCC is maximized. The concrete objective functions and constraints are defined in Chapters 3 and 4 respectively. The Genetic Algorithm (GA) is used for the optimization. A flow chart of GA is shown in Fig.7. Three parameters are coded in a single chromosome and the value of the objective function is evaluated as gene fitness.

3 DSM MODEL CONSIDERING OPERATION OF DG

3.1 Method for determining real-time price

As described in Chapter 2, QCC buys electric energy from the utility based on the conventional time-of-use pricing system in which the price for electricity is lower in the nighttime and higher in the daytime. Here, if the price in the daytime is higher than the marginal cost of DGs in QCC, the QCC can supply the electric energy

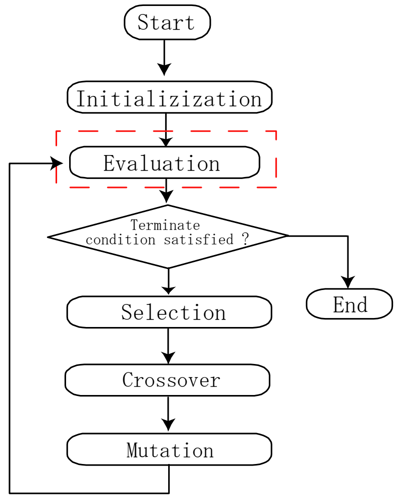


Figure 7: Flow chart of genetic algorithm

by operating its DGs to their upper limits and buying the insufficient energy from the utility. The QCC can get a profit by difference between the revenue from consumers based on the real-time price and the cost for supplying the electric energy which is called supply cost in this paper. Here, the supply cost, $C_{supply}(t)$[¥/kWh] can be expressed as follows:

$$C_{supply}(t) = \frac{C_{DG}(t)W_{DG}(t) + C_{buy}(t)W_{buy}(t)}{W_{DG}(t) + W_{buy}(t)} \quad (3)$$

where, $C_{DG}(t)$[¥/kWh] is the marginal cost of DG, $W_{DG}(t)$[kWh] is the electric energy produced by DG, $C_{buy}(t)$ is price for electricity charged by the utility, $W_{buy}(t)$ is the electric energy that QCC buys from the utility.

The QCC determines real-time prices so that its owned profit becomes maximum according to eq.(4). The decision variables are *a*, *b* and *c* in eq.(1).

Objective function: Maximization of profit of QCC

$$\max\{\sum_{t=1}^{24}(RTP(t) - C_{supply}(t)) \times W_{demand}(t)\} \quad (4)$$

Constraint conditions:

The maximum and minimum values of real-time prices are fixed to time-of-use prices charged by the utility.

$$RTP_{max} = C_{buy}(t_{=day}) \quad (5)$$
$$RTP_{min} = C_{buy}(t_{=night})$$

Consumer's satisfaction does not change before and after introducing the real-time pricing system.

$$\sum_{t=1}^{24} u_{before}(t) = \sum_{t=1}^{24} u_{DSM}(t) \quad (6)$$

where, $W_{demand}(t)$[kW] is the actual demand after $RTP(t)$ was set, $C_{buy}(_{t=day})$ and $C_{buy}(_{t=night})$ [¥/kWh] are prices when QCC buys electric energy from the utility based on the time-of-use pricing system. The variables, $u_{before}(t)$ and $u_{DSM}(t)$ mean consumer's satisfactions before and after the real-time pricing system is introduced.

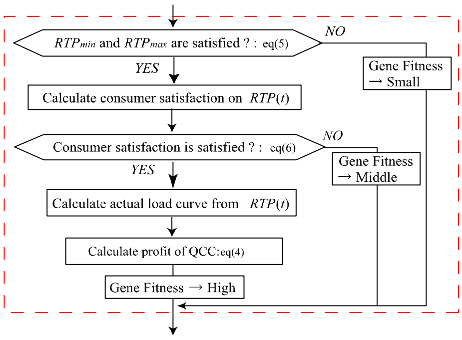


Figure 8: Fitness evaluation on each chromosome for DSM considering DG operation

3.2 Flow chart for calculation

Figure 8 shows a flow chart for determining the real-time prices considering the operation of DG. The process in this figure is applied to one chromosome of GA. The chromosome with the largest profit or the largest fitness is selected as the optimal solution of the problem.

3.3 *System Evaluation for the installation of DG*

The daily profit and the load factor of QCC were evaluated changing the capacity of DG introduced in QCC. Here, the capacity of DG is defined by the ratio to the peak value in a daily load after the real-time price was introduced.

○*Simulation conditions*

It is assumed that the QCC can be dealt with the utility based on a time and season differential tariff for a business consumer as shown in Table 1. The "daytime" in this table means time periods from AM8:00 to PM10:00 and the "nighttime" means the other periods. Also, the "summer" means July, August and September. These values were set using an actual tariff of Tokyo Electric Power Company in Japan. Under such a condition, the QCC supplies the electricity to its business consumer and residential consumer. The maximum and minimum values of the real-time prices to business and residential consumers were also set based on a tariff of Tokyo Electric Power Company as shown in Table 2 [6]. The other data for simulation is summarized in Table 3. Table 4 shows the load factor before the real-time pricing system is introduced. In this paper, simulations were executed for typical four kinds of reference load curve as shown in Figure 9. These reference load curves were made by the standard model developed in the Institute of Electric Engineers in Japan.

○*Simulation results*

Simulation results are shown in Fig. 10.

・*Load factor of QCC*

When DG was installed by 10 % to the peak load, the load factor of QCC became maximum in every residential consumer. And, for the business consumer, when the ratio is 50 %, the load factor of QCC became maximum. However, this figure shows that excessive

Demand charge[¥/kW]			1560.00
Energy charge[¥/kWh]	Daytime	summer	14.70
		the others	13.65
	Nighttime		6.05

Table 1: Contract between QCC and Utility

		RTPmax[¥/kWh]	RTPmin[¥/kWh]	Flat-rate price[¥/kWh]
Business	summer	14.70	6.05	12.02
	other seasons	13.65		10.93
Residential		19.95	5.95	15.58

Table 2: Parameters in real-time pricing system

The marginal cost of DG[¥/kWh]	11.0
The slope of price-demand curve[¥/kWh]	-100

Table 3: Other data for simulation

	Load factor[%]
Residential (Summer)	83.9
Residential (Spring, Autumun)	79.7
Residential (Winter)	77.9
Business (Summer)	60.9

Table 4: Load factor for conventional system

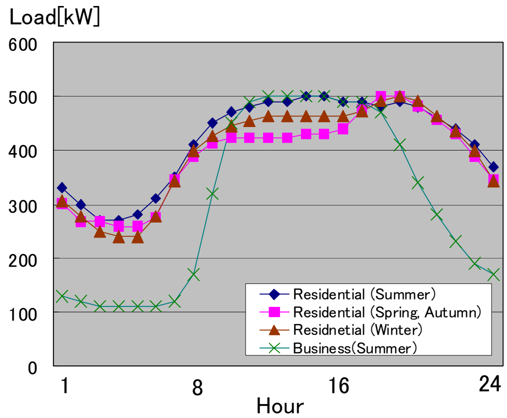


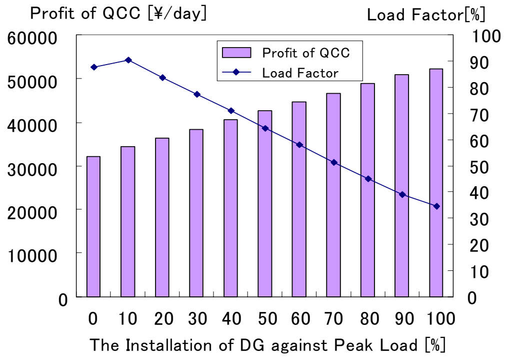
Figure 9: Reference load curves for simulation

installation of DG results in a lower load factor than before the real-time pricing system is introduced. This is because that load in the daytime was decreased considerably by operating DG.

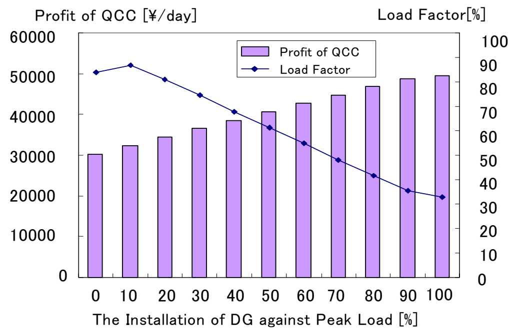
・*Profit of QCC*

The QCC can obtain more profits as the capacity of DG increases. More specifically, the supply cost defined in eq.(3) can be reduced by operating DG because the marginal cost of DG is lower than the price for electricity charged by the utility in the daytime. However, the revenue obtained by a real-time pricing system is not almost different from before. Further, when the proposed DSM is applied to the business consumer, the QCC can obtain a positive profit by installation of more than 30% of DG to the peak load. Also, when it is applied to residential consumers, a positive profit can be obtained, even though QCC does not install DG. This is because that the QCC can procure the electric energy from the utility based on the tariff for a business consumer in which the price is lower than the tariff for the residential consumer.

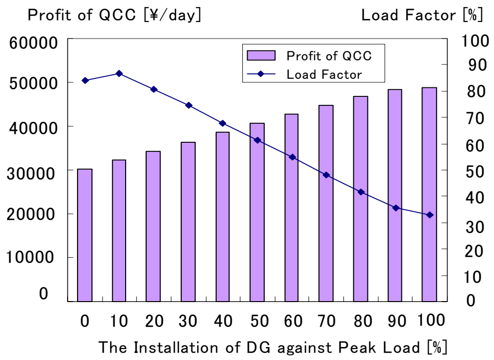
As a result, a positive profit of QCC and enhancement in load factor of QCC were realized simultaneously by applying the proposed DSM.



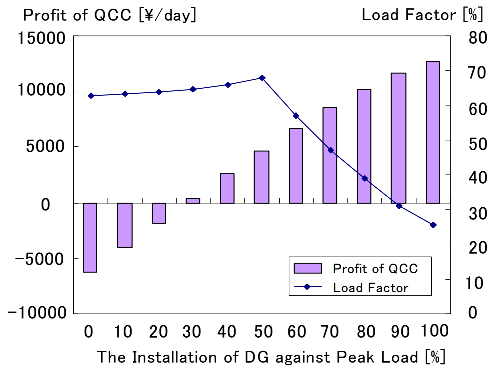
(a) Residential(Summer)



(b) Residential(Spring, Autumn)



(c) Residential(Winter)



(d) Business(Summer)

Figure 10: Profit of QCC and load factor on a day against the installation of DG

4 DSM MODEL CONSIDERING OPERATION OF ESS

4.1 The method for determining real-time price

Generally, QCC needs to deal with the utility about the contracted power which means the maximum power that QCC can purchase from the utility. The larger contracted power results in an increase in the demand charge to be paid to the utility. The QCC can reduce the demand charge by operating the ESS in the daily cycle. The revenue and expense of QCC can be expected by eqs.(7) and (8) respectively.

Revenue:

$$\sum_{t=1}^{8760} RTP(t)\times W_{demand}(t) + C_{base}\times W_{cut}\times 12 \qquad (7)$$

Expence:

$$\sum_{t=1}^{8760} (C_{buy}(t)\times(W_{demand}(t)\pm ESS(t))) + Cons\times rate \qquad (8)$$

where, W_{cut}[kW] is the reduced contracted power. C_{base}[¥/kW/month] is the demand charge based on the contracted power. $C_{buy}(t)$[¥/kWh] is the price for electricity when QCC buys electric energy from the utility based on the time-of-use pricing system. $W_{dmand}(t)$[kWh] is the actual load determined by $RTP(t)$, $ESS(t)$[kWh] is the charged/discharged energy of ESS, *Cons*[¥/kW] is the capital cost of ESS and *rate* is the rate of annual charge.

The real-time prices, $RTP(t)$ in the above formulation can be determined so that the daily profit of QCC defined by eq.(9) is maximized. The decision variables are a, b and c in eq.(1).

Objective function: Maximization of a profit by the daily operation of QCC

$$\max\{\sum_{t=1}^{24}(RTP(t)\times W_{demand}(t) - \min\{C_{buy}(t)\times W_{receive}(t)\})\} \qquad (9)$$

Here, $W_{receive}(t)$[kW] means the electric energy which QCC buys from the utility. The value of the second term in the above function can be evaluated by solving the following problem.

Objective function: Minimization of the operation cost for ESS

$$\min\{\sum_{t=1}^{24} C_{buy}(t)\times W_{receive}(t)\} \qquad (10)$$

$$W_{receive}(t) = W_{demand}(t) \pm ESS(t) \qquad (11)$$

Constraint conditions: In addition to the constraints of eqs.(5) and (6), the following constraints on the operation of ESS are considered.

- Constraints on the maximum power which QCC buys from the utility

$$0 \le W_{receive}(t) \le W_{contract} \qquad (12)$$

- Constraints on the minimum and maximum powers charged/discharged in ESS

$$-ESS_{limit} \le ESS(t) \le ESS_{limit} \qquad (13)$$

- Constraints on capacity of energy stored in ESS

$$0 \le State_{ESS}(t) \le State_{\max} \qquad (14)$$

- Constraints on the boundary condition

$$State_{ESS}(t_{=0}) = State_{ESS}(t_{=24}) \qquad (15)$$

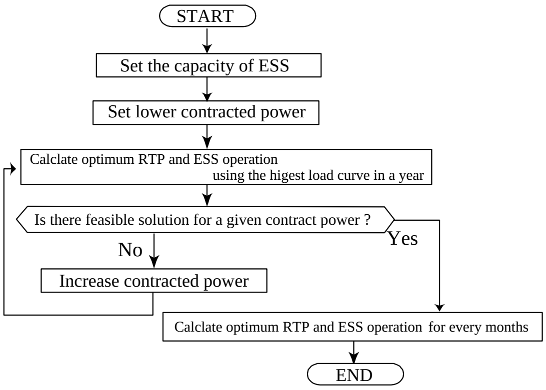


Figure 11: Overall flow chart for determining the real-time prices.

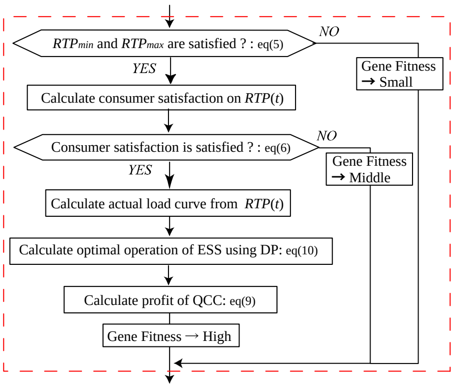


Figure 12: Fitness evaluation on each chromosome for DSM considering ESS operation

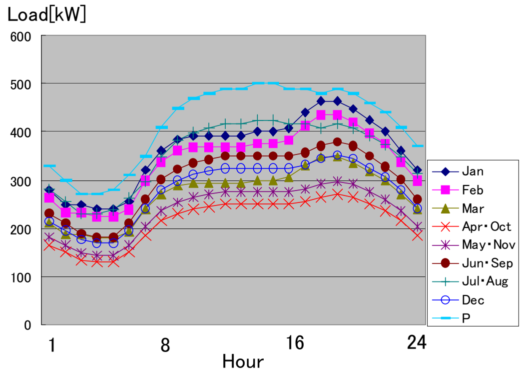
where, $W_{contract}$[kW] is the contracted power between QCC and the utility, $ESS(t)$[kWh] is a power charged/discharged in ESS, $State_{ESS}$(t) is the energy stored in ESS in the period t.

The above problem can be solved easily by the Dynamic Programming (DP) [7].

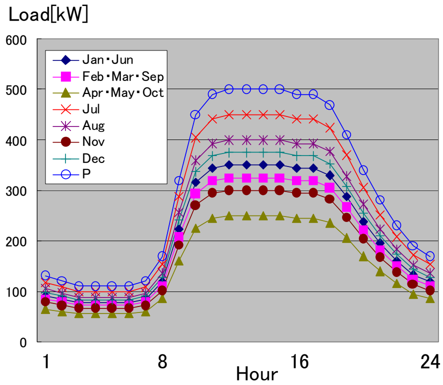
4.2 Flow chart for calculation

Figure 11 shows the overall flowchart for determining the real-time prices considering the operation of ESS. As seen from the flowchart, first, a capacity of ESS introduced and a contracted power are assumed. Here, the contracted power is started with a relative low value. Next, the feasibility of the assumed contracted power is checked. More specifically, whether or not the QCC can supply the electric energy to its consumers for the assumed contracted power is evaluated. If it is infeasible, the larger contracted power is set. The contracted power is updated until a feasible solution is obtained. Next, the optimization of real-time prices and operation of ESS is implemented by GA. The above calculations are executed changing the capacity of ESS. In general, the lower the contracted power, the larger income based on the reduction in the demand charge. Therefore, the lowest contracted power under a given capacity of ESS can be found by this calculation.

Figure 12 shows a flowchart for optimizing the real-time prices and operation of ESS using GA. This process is applied to one chromosome of GA. Here,



(a) Residential



(b) Business

Figure 13: Reference load curves for simulation

System output[kW]	parameter
Storage Capacity[kWh]	System output × 7.2h
Total battery efficiency	78%
Rate of anuual charge	0.0778
Capital cost[¥/kW]	250,000

Table 5: Simulation data for ESS

note that the constrained conditions on the operation of ESS are added depending on the assumed contracted power. In this calculation, the chromosome with the largest fitness is selected as the optimal solution.

4.3 System Evaluation for the installation of ESS

○*Simulation conditions*

Since the contracted power is considered, simulation over a year is needed. The reference load curves on a typical day in every month are shown in Fig.13. In this figure, "P" means the peak load in a year which contains five days at the end of July. The condition for determining real-time prices and the contract between QCC and utility are same as those described in paragraph 3.3. The simulation data for ESS are shown in Table 5.

○*Simulation results*

Simulation results are shown in Table 6 and Fig.14.

・*Load Factor of QCC*

The deterioration of load factor was found when ESS more than 100kW is installed to the residential

	ESS[kW]	Load Factor [%]											
		Jan	Feb	Mar	Apr	May	Jun	Jul	P	Aug	Sep	Oct	Nov	Dec
Conventional		77.9	77.9	77.9	79.7	79.7	79.7	83.4	83.4	83.4	83.4	79.7	79.7	79.7
Proposed	0	81.9	81.9	82	83.9	83.8	83.8	87.7	87.7	87.7	87.7	83.9	83.8	83.9
model	25	84.2	84.4	84.9	87.9	85.4	86.7	89.4	90.1	89.4	89.4	87.9	85.4	86.9
	50	86.4	86.0	84.1	85.8	88.5	86.6	88.8	94.2	88.8	88.0	85.8	88.5	86.3
	75	86.4	83.4	83.3	81.2	83.0	86.8	88.9	96.3	88.9	87.9	81.2	83.0	85.6
	100	84.8	84.0	77.7	74.5	76.6	81.2	88.1	96.3	88.1	82.0	74.5	76.6	79.8
	125	86.5	83.5	73.2	68.9	71.2	76.8	88.1	96.8	88.1	77.2	68.9	71.2	75.1
	150	86.5	83.5	73.2	68.9	71.2	76.8	88.1	96.8	88.1	77.2	68.9	71.2	75.1
	175	86.3	83.5	68.4	59.8	62.3	76.3	88.1	96.8	88.1	74.7	59.8	62.3	72.5
	200	87.4	83.3	68.4	57.9	62.2	76.4	88.1	96.4	88.1	74.5	57.9	62.2	72.5

(a) Residential

	ESS[kW]	Load Factor [%]											
		Jan	Feb	Mar	Apr	May	Jun	Jul	P	Aug	Sep	Oct	Nov	Dec
Conventional		60.9	60.9	60.9	60.9	60.9	60.9	60.9	60.9	60.9	60.9	60.9	60.9	60.9
Proposed	0	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7
model	25	65.0	65.1	65.1	64.0	64.0	65.0	64.4	64.3	64.6	65.1	64.0	64.0	64.8
	50	68.6	64.0	64.0	67.2	67.2	68.6	64.0	69.0	64.0	64.0	67.2	66.6	64.7
	75	68.7	69.0	69.0	66.6	66.6	68.7	66.8	72.8	66.8	69.0	66.6	72.6	66.1
	100	71.7	75.0	75.0	76.2	76.2	71.7	70.1	77.7	68.9	75.0	76.2	72.5	74.2
	125	68.7	72.1	72.1	68.5	68.5	68.7	74.5	81.6	66.7	72.1	68.5	74.1	70.7
	150	74.9	71.9	71.9	65.2	65.2	74.9	78.7	86.8	70.3	71.9	65.2	64.0	68.9
	175	72.0	71.7	71.7	64.6	64.6	72.0	81.3	89.8	71.7	64.6	74.5	65.2	74.5
	200	67.3	64.0	64.0	64.3	64.3	67.3	81.4	89.7	72.7	64.0	64.3	65.2	71.6
	225	74.1	69.0	69.0	58.7	58.7	74.1	84.2	92.9	75.9	69.0	58.7	67.9	71.6

(b) Business

Table 6: Load factor comparison
(Conventional vs DSM model [Parameter: ESS capacity])

consumers or when ESS more than 225kW is installed to the business consumer. Marked values in Table 6 mean that the load factor became lower than before. The optimal operation of ESS is decided by the Dynamic Programming to maximize profit of QCC; therefore, the purpose of the operation of ESS is not to maximize the load factor. As seen from Fig.13, reference load curves for residential and business consumers on April are lowest in a year. If larger energy is charged/discharged by ESS on April, excessive load would shift from daytime to nighttime. Therefore, the load factor of QCC in the nighttime becomes higher than in the daytime.

・*Profit of QCC*

The profit in Fig.14 is defined by the difference between eq.(7) and eq.(8). As seen from this figure, the QCC can obtain the maximum profit under the condition where the load factor is not decreased every month. More specifically, the installation of 50kW of ESS gives the maximum profit of QCC for residential consumers and 175kW of ESS gives the maximum profit of QCC for business consumer. These values are smaller than the capacity when the load factor becomes lower than before. When the proposed DSM model considering ESS is applied to the residential consumers, a positive profit can be obtained for QCC, even though ESS is not introduced. This is because that the QCC can procure the electric energy from the utility based on a tariff for business consumers which is lower than that for residential consumers.

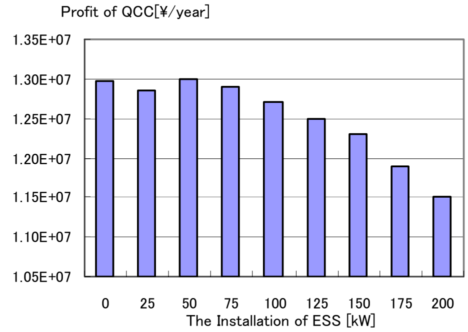
As a result, obtaining a positive profit for QCC and enhancing the load factor can be realized simultaneously by applying the proposed DSM to the residential consumer. However, it is not preferable for QCC to apply the DSM to the business consumer.

5 CONCLUSION

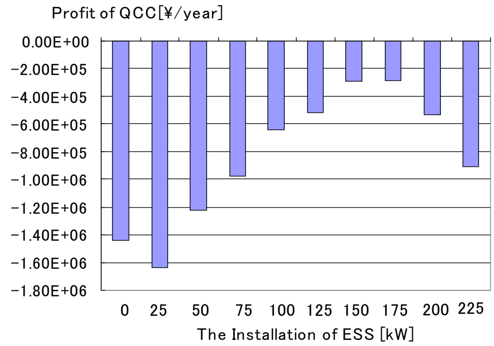
This paper presented a novel DSM based on the real-time pricing system considering the FRIENDS proposed by the authors. Two DSM models were presented, one is a model considering operation of DG and the other is a model considering operation of ESS. The QCC sets real-time prices based on demand pattern of the next day and uses its owned DG and ESS economically.

The effectiveness of the proposed DSM was evaluated by calculating profits and load factor of QCC using model system. By the proposed DSM, the enhancement in load factor of QCC and increase in the profit of QCC were achieved simultaneously. However, it was difficult to obtain a positive profit for QCC when the DSM considering ESS operation is applied to the business consumer.

As a future study, the authors would like to model DSM program considering coordinate operation of DG and ESS or priority service on power quality in FRIENDS. Further, there is also a way of determining the real-time prices based on the market prices when QCC purchases the electricity from an energy market, while this paper assumes that the QCC purchases it for a constant price from the utility. Thus, the authors would like to investigate the other possibilities for determining the real-time prices.



(a) Residential



(b) Business

Figure 14: Profit of QCC on a year against the installation of ESS

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