

An Economic Evaluation for an Autonomous Independent Network of Distributed Energy Resources

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Abstract

This paper proposes a method for the economic evaluation of an autonomous independent network of distributed energy resources. There are existing proposals for such networks; the system that we are proposing and analyzing in this study is called Microgrid. Microgrid is a new framework of power delivery system that is formed by small, modular generation systems connected to each other to create a small autonomous grid. This paper estimates the total costs to consumers in a Microgrid with optimized operation of distributed generators and energy storage systems. This estimation includes not only installation and operation costs but also the additional expenses to construct the Microgrid itself. In addition, power interruption costs are also taken into account to consider the reliability enhancement created by the Microgrid. The paper attempts to determine whether or not it is economical for consumers to form this kind of autonomous independent network.

Keywords: Autonomous independent network; Distributed generator; Economic evaluation; Energy storage systems; Fuel cell; Microgrid

1. Introduction

Distributed generators (DG) are becoming increasingly attractive to consumers, and in the future a great number of them will be installed at consumer's sites. In this situation, conventional distribution networks that accept the DG connections may face serious difficulty in control and protection as their required functions may become very complicated. This incurs a burden to the network operation and some technical limitations will appear when installing a great number of DGs. Therefore, new concepts for energy delivery systems have been proposed [1–3]. Microgrid is one of them: it is a novel energy delivery system formed to provide reliable electricity and heat delivering services by connecting DGs and loads to each other within a small area.

However there are two concerns that may affect the feasibility of Microgrids: technical issues and economic issues. Technical issues include: how to establish the interconnection schemes between the upper network and the Microgrid, voltage control schemes within the Microgrid, frequency regulation control when islanding, as well as several other issues [3–6].

On the other hand, economic evaluation is also a significant factor when considering practical implementation of a Microgrid. Some research has previously been done on this issue, but the majority of studies did not consider economic evaluation of newly built Microgrids. For example, the authors of reference [7] considered an economic dispatch problem for a Microgrid to achieve minimized fuel consumption; however, this study focused on the real time operation of DGs after the Microgrid was built. To the best of our knowledge, there is no similar research to what we propose for the economic evaluation of Microgrids.

Several types of DGs can be operated as combined heat and power (CHP) systems and achieve remarkable energy efficiency. A consumer-owned Microgrid can be operated according to a consumer's own policy, as long as it does not have an undesirable impact on the upper grid. In this paper, an economic evaluation of a Microgrid from the consumer's point of view is presented. A fuel cell is adopted as a DG; an optimal operation problem of fuel cells, energy storage systems and heat sources is formulated in a linear programming manner. The total cost function for constructing the Microgrid is evaluated in some typical cases through several numerical simulations. In addition, the reliability of the Microgrid is also evaluated by integrating a power interruption cost into the cost function being minimized. The results obtained are compared with the conventional case in which each consumer makes its own respective contract with the utility.

In this report, section 2 explains what a Microgrid is, and its cost function is formulated in section 3. Section 4 describes the numerical simulations and the obtained results are summarized and examined in section 5.

2. Microgrid

Various types of new DG network systems have previously been proposed to effectively reduce DG potential: typical examples are Virtual Power Plant [1], Power Park [2], Microgrid [3], amongst others. These new types of DG network system are different in their technical or economic advantages. Microgrid, discussed in this paper, is a new energy delivery system for providing reliable electricity and heat by integrating and controlling various new types of energy sources. The major advantages of Microgrid can be summarized as follows [3]:

- Microgrid can provide an efficient way for integrating

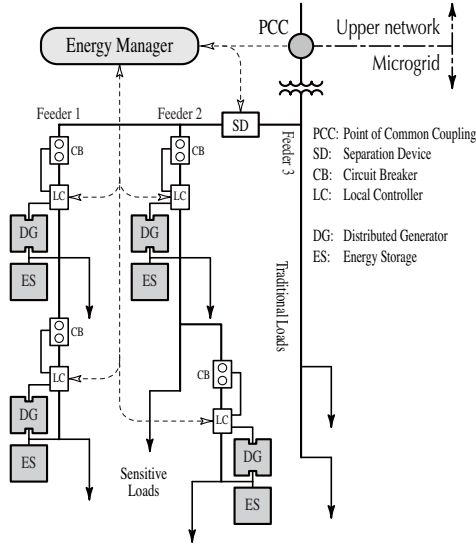


Fig. 1. An example of a Microgrid.

DGs and loads.

- Microgrid can provide a flexible way for DGs to connect and disconnect.
- Microgrid can be a “grid-friendly” entity that does not have undesirable influences on the distribution grid.
- Microgrid can operate independently without connecting to the upper grid when a fault occurs (islanding mode).

Overall, the above advantages can be classified as either environmental or economic advantages. Renewable energy types of DGs can be effectively integrated in a Microgrid, which contributes greatly to a reduced environmental impact. On the other hand, co-generation types of DGs have great potential to reduce energy costs due to high-efficiency and CHP functions. The former DGs, such as photovoltaic generators or wind turbines, are promising options but they have technical and economic difficulties as their outputs are not stable and their generation costs are still high compared to other types of DGs.

A Microgrid may be designed, installed and controlled by consumers according to their technical and economic needs. In this study the authors have focused on co-generation systems, whose generation costs are becoming lower due to mass-production, and have performed economic evaluations of some variations of Microgrids. Fig. 1 shows an example of a Microgrid formed by DGs (CHP), energy storage systems, heat sources and loads. The connection point to the upper distribution network is called PCC (Point of Common Coupling) and the breaking point is called SD (Separation Device): the SD can achieve immediate islanding when a fault occurs. The Energy Manager plays an important role in monitoring the demand-supply balance and allows the most efficient operation planning for DGs.

3. Economic efficiency and formulations

In order to build a Microgrid, various additional equipment such as power electronics devices, dedicated distribution lines and communication networks are required, as well as distributed energy resources (DER) such as DGs, energy storage systems and heat sources. In addition, after the Microgrid is built, consumers have to pay additional

expenses for the operation and maintenance of DERs. Therefore it is necessary to minimize the total cost of installation as well as operation.

3.1 Optimal operation planning of DERs

An optimal operation planning problem of DERs is formulated in this section. Typical operation of DGs already adopted is a tracking-based method in which the DGs control their output to match the electrical or thermal load. Daily variation of industrial factory and office loads, examined as examples in this study, is very small and can be modeled as stable load profiles without significant error. In this paper the modeled load can be regarded as given data which is constant during a unit time. In order to minimize the total cost, the optimal operation planning of DERs is formulated as a linear programming problem.

3.2 Objective function for the optimal operation problem

Equation (1) is the objective function for the optimal operation problem that expresses the annual total cost to consumers. In this study, three types of costs are considered: operation costs of DERs, capital costs of DERs and an electricity charge that should be paid by consumers. The operation costs include fuel costs, inspection and maintenance costs. The capital costs are necessary to install DGs. The electricity charge should be paid when a Microgrid purchases electricity from a utility.

In equation (1), the first three terms correspond to the operation costs of DGs, heat sources and energy storage systems respectively. The fourth and fifth terms express the charge for electricity supplied from the utility and the income from selling electricity to the utility respectively. The following three terms are the initial costs of all DERs, and the last term is the base rate of electricity to be charged by the utility. In addition, α , β and γ correspond to the depreciation rate of each DER, which are necessary to convert gross cost to annual one.

$$\begin{aligned}
 z_1 = & \sum_{l=1}^n \sum_{j=1}^m S_j \sum_{i=1}^l \{ (f_{dg} + m_{dg}) p_{dg}(i, j, l) \\
 & + (f_{bl} + m_{bl}) p_{bl}(i, j, l) + 2m_{st} \cdot pr_{st}(i, j, l) \\
 & + e_e(i, j) p_e(i, j, l) - e_s(i, j) p_u(i, j, l) \} \\
 & + \sum_{l=1}^n \{ \alpha \cdot c_{gs} \cdot gs(l) + \beta \cdot c_{st} \cdot ss(l) + \gamma \cdot c_{bl} \cdot bs(l) \} \\
 & + 12e_b \cdot es \quad , \quad (1) \\
 es = & \max \left\{ \sum_{l=1}^n p_e(i, j, l) \mid i = 1, L, t, j = 1, L, m \right\} , \\
 \alpha, \beta, \gamma = & \frac{u(1+u)^{n_{\alpha, \beta, \gamma}}}{(1+u)^{n_{\alpha, \beta, \gamma}} - 1} .
 \end{aligned}$$

3.3 Constraints to optimal operation problem

The following equations presented are constraints to the formulation of optimal operation. Equation (2) is the electricity supply-demand balancing constraint, and equation (3) is the thermal supply-demand balancing constraint. Equation (4) ensures that the energy storage systems cannot discharge power beyond the charged energy

Table 1
Values of a_i and b_i for each type of consumer (l).

Load Type (l)	a_i	b_i
Hotel	0.7930	0.2341
Sports Center	0.7930	0.2341
Office	0.5291	0.5543
Hospital	0.7930	0.2341
Factory	0.7173	0.3272
Grocery Store	0.7930	0.3272

in advance. Upper and lower limits of DG output are expressed in equation (5) and the limits for other DERs are shown in equations (6) to (8). Equation (9) ensures that all given variables are positive.

$$\sum_{l=1}^n L_e(i, j, l) = \sum_{l=1}^n \{p_{dg}(i, j, l) + pr_{st}(i, j, l) - pc_{st}(i, j, l) + p_e(i, j, l) - p_s(i, j, l)\} \quad (2)$$

$$\sum_{l=1}^n L_h(i, j, l) \leq \sum_{l=1}^n \{hr \cdot p_{dg}(i, j, x) + p_{bl}(i, j, y)\} \quad (3)$$

$$-h \cdot ss(l) \leq \sum_{i=1}^T \{pr_{st}(i, j, l) - pc_{st}(i, j, l)\} \leq 0 \quad (T = 1, L, t) \quad (4)$$

$$lv \cdot gs(l) \leq p_{dg}(i, j, l) \leq gs(l) \quad (5)$$

$$0 \leq p_{bl}(i, j, l) \leq bs(l) \quad (6)$$

$$0 \leq pr_{st}(i, j, l) \leq ss(l) \quad (7)$$

$$0 \leq pc_{st}(i, j, l) \leq ss(l) \quad (8)$$

$$0 \leq p_e(i, j, l), p_s(i, j, l), gs(l), ss(l), bs(l), es \quad (9)$$

3.4 Microgrid construction cost

The expenses incurred by the consumers include not only the installation and operation costs of DERs but also the construction cost of the Microgrid itself. Microgrids need special facilities such as an Energy Manager (EM), Separation Device (SD), and private distribution and communication lines in order to achieve full function. In this paper, the cost to form a Microgrid is defined as follows:

$$z_2 = \delta \cdot C_{SD} + \eta \cdot C_{EM} + \lambda \cdot C_{DL}(dl_{total}) + \sigma \cdot C_{SD}(cl_{total}), \quad (10)$$

$$\delta, \eta, \lambda, \sigma = \frac{u(1+u)^{n_{\delta, \eta, \lambda, \sigma}}}{(1+u)^{n_{\delta, \eta, \lambda, \sigma}} - 1}$$

This cost function is the sum of initial costs of all facilities necessary for building a Microgrid. The coefficients δ , η , λ and σ are the depreciation rate of each facility.

3.5 Power interruption cost

Power Interruption Cost (PIC) is the equivalent cost to consumers of damages caused by power interruptions. This cost depends mainly on the duration of the interruption, the types of consumers, and geographical attributes. Power interruption is very difficult to forecast and prevent. However, even when a fault occurs in the upper grid, a Microgrid can continue supplying high-quality power to important loads (in islanding mode).

In this paper the improved reliability created by a

Microgrid is expressed as the reduction of the interruption cost, and it is integrated into the formulation as follows [8]:

$$IC(i, j, l) = \begin{cases} 0, & LoL(i, j, l) \leq 0 \\ \frac{120d^{a_i}}{10^{b_i}} LoL(i, j, l), & 0 \leq LoL(i, j, l) \end{cases}, \quad (11)$$

$$LoL(i, j, l) = L_e(i, j, l) - \{gs(l) + ss(l)\}.$$

The values of PIC expressed in equation (11) depend on the type of consumers, which are characterized by parameters a_i and b_i ; the values of parameters are shown in Table 1.

Forecasting power interruptions is almost impossible and the induced damages cannot be exactly evaluated. Therefore in this paper the probability of power interruption is assumed to be the same over a year, and the PIC is evaluated by using uniform distribution of the probability, as shown in the following equation:

$$z_3 = \sum_{l=1}^n \sum_{j=1}^m \sum_{i=1}^t \{IC(i, j, l) \cdot prob(i)\} \quad (12)$$

The PIC is adopted as an index for reflecting power supply reliability in the objective function. However, other indices can be used for the same purpose depending on a consumer's policy.

In conclusion, the total cost function to be minimized is expressed in equation (13) as the sum of equations (1), (10) and (12).

$$z = z_1 + z_2 + z_3 \quad (13)$$

4. Numerical simulations

4.1 Test system

In this study, six types of consumers (a Hotel, Sports Center, Office, Hospital, Factory, and Grocery Store) are assumed to form a Microgrid. Several cases of economic evaluation are performed in which each consumer can install DGs, energy storage systems, and heat sources. Fig.

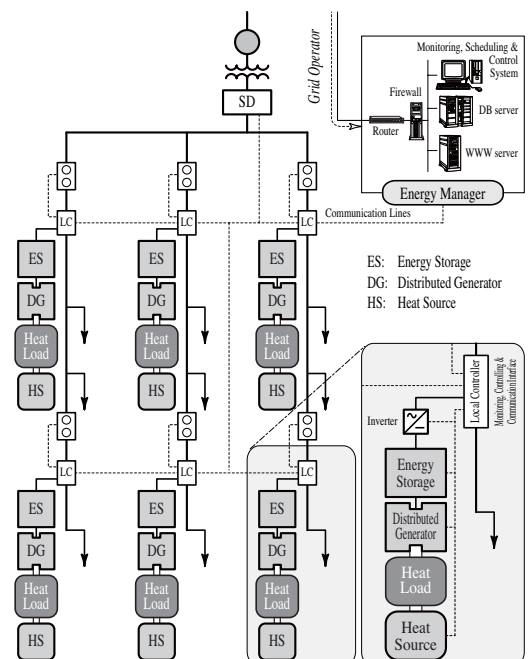


Fig. 2. A test system of the Microgrid.

2 shows the test system used in the numerical simulations.

4.2 Parameter settings

In this paper it is assumed that the load data of the consumers is given. In the practical operation of a Microgrid, however, the demand in the near future would be forecast and the actual optimal operation plan would be made by using this forecast load data; the forecast data may be based on fundamental information such as weather, temperature, day of the week or past load profiles.

Energy Manager plays an important role in storing and managing a variety of necessary information and data in a Data Base; this information may relate to the upper system operation or the Microgrid condition. The Energy Manager is also responsible for the decision-making of the minute-by-minute operation according to an economic dispatching method: decisions are broken down into several instructions and sent to local controllers through communication lines.

Table 2 shows the costs of all components to build a Microgrid. There is no complete Energy Manager developed at present, and the corresponding figure in Table 2 does not express the exact cost but that is considered a reasonable estimate [9, 10]. The same estimation was made for Separation Device, which is responsible for fast islanding. Other parameters related to DERs are summarized in Table 3.

Figures 3 and 4 illustrate an example of electrical and thermal load curves of the six types of consumers in summer. The Office has a large difference in electrical load between the day and night. In contrast, the Hospital does not show a significant change in electrical load throughout the day but at night the load is comparably large. The electrical load of the Sports Center during the day is large and almost constant. The daily variations of the other electrical loads are relatively small, and the loads at night are generally smaller than that of the Hospital. The total

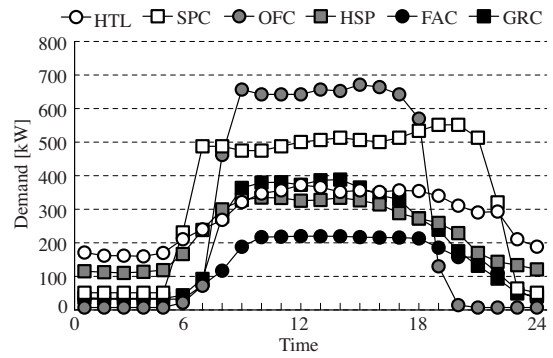


Fig. 3. Electric demand curves in summer.

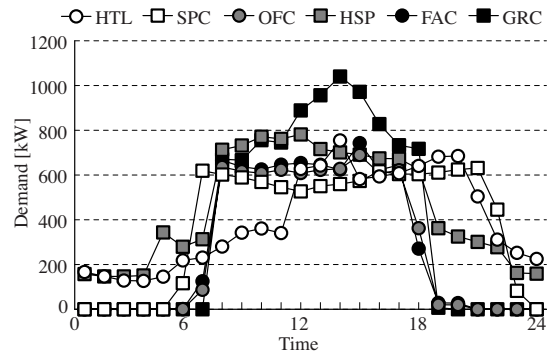


Fig. 4. Thermal demand curves in summer.

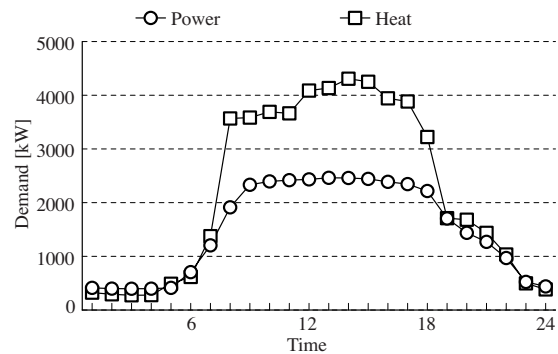


Fig. 5. Electric and thermal demand curves of the Microgrid in summer.

Table 2

A breakdown of construction cost of a Microgrid.

	EM*	SD*	LC*	DL*	CL*
Equipment/ Interface	System		CPU		
	Server	High-Speed CB	Ethernet	300 [m]	600 [m]
	Modem/Router		Serial		
		Firewall			
Cost [JPY]	3,500,000	15,000,000	300,000	3,000,000	3,000,000
Lifetime [yr.]	6	20	6	30	20

*(EM: Energy Manager, SD: Separation Device, LC: Local Controller, DL: Distribution Line, CL: Communication Line)

Table 3

Parameters related to DERs.

DG*1	Operation cost	10 [JPY/kWh]
	Production ratio	50 : 50
	Heat recovery rate	50 [%]
	Initial cost	200,000 [JPY/kWh]
	Lifetime	6 [yr]
ESS	Operation cost	1 [JPY/kWh]
	Charging time	8 [hr]
	Charge/discharge rate	90 [%]
	Initial Cost	200,000 [JPY/kWh]
	Lifetime	15 [yr]
ASH*2	Operation cost	6 [JPY/kWh]
	Initial cost	20,000 [JPY/kWh]
	Lifetime	30 [yr]

*1: fuel cell (FC), *2: boiler

load curve of the Microgrid formed by these six consumers is depicted in Fig. 5: this figure shows only the summer season, but all four seasons (spring, summer, fall and winter) are considered in the numerical simulations to evaluate an annual cost.

4.3 Simulation cases

The following four cases have been prepared to evaluate the economic feasibility of the test system of Microgrid.

- Case 1: No consumers install DERs and each of them makes a contract with the utility, as is current practice.
- Case 2: Each consumer optimally installs DERs and makes a contract with the utility.
- Case 3: The Microgrid is formed by the six consumers and all loads within the Microgrid are supplied by the DERs only.
- Case 4: The Microgrid is formed by the six consumers and all loads are optimally supplied by both the DERs and the utility.

Table 4
Contract tariff (Constant rate).

Type	Base charge [JPY/kW]	Electricity rate [JPY/kWh]	
		Summer	Others
CP* ¹	1,575	12.17	11.06
HVPS-A* ²	1,130	11.22	10.20

*1: Commercial Power, *2: High-Voltage Power Service A

Table 5
Contract tariff (Time of use rate).

Type	Base charge [JPY/kW]	Electricity rate [JPY/kWh]			
		Peak	Daytime		Midnight
			Summer	Others	
CP* ¹	1,575	17.55	14.35	13.88	6.27
HVPS-A* ²	1,130	16.83	13.76	12.97	6.27

*1: Commercial Power, *2: High-Voltage Power Service A

Tables 4 and 5 show example contract tariffs applied to each consumer in Cases 1 and 2; the tariffs are those practically applied by a particular utility in Japan [11]. There are two types of tariff: constant rate, as shown in Table 4, and time-of-use rate, as shown in Table 5. Each consumer selects the most economical tariff in Case 1 and 2 and does not form the Microgrid, which means $z_2 = 0$. Case 1 does not include the optimal operation of DERs ($gs(l)$, $bs(l)$, $ss(l) = 0$) but Case 2 does. In Case 3 the Microgrid is formed and the optimal operation of DERs is considered but no electricity is supplied from the utility ($es = 0$). Case 4 is the same as Case 3, except that purchasing inexpensive electricity from the utility is also taken into account; for this, the Microgrid is regarded as a single large consumer and it can make an economic contract with the utility accordingly.

5. Simulation results

In all cases the total annual costs to be paid by consumers were evaluated through numerical simulations. The obtained results are shown in Tables 6, 7 and 8.

5.1 Case 1

This is the base case, in which no consumers installed DERs and each of them made a separate contract with the utility. As you can see in Table 6, PIC of the Sports Center and the Hotel are large compared to the other consumers. The total annual cost of all consumers is 268,981,000 JPY (approximately 2,561,700 USD).

5.2 Case 2

In this case, each consumer optimally installs DERs and makes its own contract with the utility: the Sports Center has a commercial power (constant) contract; the Office, Hospital and Grocery Store have commercial power (time-of-use) contracts; and the Factory has a HVPS-A (constant) contract. All consumers installed DERs and operated them according to the optimal operation plans.

From Table 7, it can be seen that the Factory did not install DGs and energy storage systems as it has a contract through the HVPS-A class, which has an inexpensive base charge. Other consumers installed DERs, and the average capacities of them are 280 kW for DGs and 90 kW for energy storage systems. The total cost for Case 2 is 254,394,000 JPY (approximately 2,422,800 USD). This

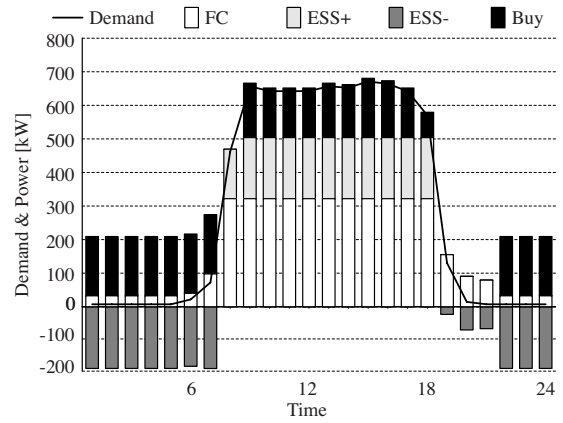


Fig. 6. Optimal operation pattern for the Office (summer).

means that it is more economical for the consumers to install DERs when compared to Case 1. As an example, the optimal operation pattern of DERs at the Office in summer is depicted in Fig. 6, in which the charged power by energy storage systems appears as a negative value.

5.3 Cases 3 and 4

In Cases 3 and 4, the consumers install DERs and form a Microgrid; the total cost is evaluated by calculating z in equation (13). Table 8 shows the simulation results obtained. In Case 3, the installed capacity of DGs is 1,877 kW and that of energy storage systems is 651 kW: this can meet the entire demand of the Microgrid. In addition, Case 4 shows that the amount of purchased electricity is only 67 kW, as most of the load is supplied by the DGs and energy storage systems.

Fig. 7 illustrates the optimal operation pattern of the Microgrid for Case 3. Energy storage systems are charged during the night and discharged in the peak time, in a similar way to Case 1. The installed capacity of the DGs and energy storage systems is large enough to cover all loads even when a fault occurs in the upper grid: PICs of Cases 3 and 4 are almost zero.

Table 6
Simulation results of Case 1.

	HTL*	SPC*	OFC*	HOS*	FAC*	GRS*
Contracted capacity [kW]	372	552	671	335	290	388
ASH capacity [kW]	755	632	816	781	743	1040
FC capacity [kW]	0	0	0	0	0	0
ESS capacity [kW]	0	0	0	0	0	0
PIC [10^3 JPY]	413	566	76	57	160	304
Total cost [10^3 JPY]	48,314	59,305	51,960	42,390	27,915	37,521

* (HTL: Hotel, SPC: Sports Center, OFC: Office, HOS: Hospital, FAC: Factory, GRS: Grocery Store)

Table 7
Simulation results of Case 2.

	HTL*	SPC*	OFC*	HOS*	FAC*	GRS*
Contracted capacity [kW]	59	126	177	24	290	105
ASH capacity [kW]	628	426	655	663	743	939
FC capacity [kW]	253	412	322	236	0	203
ESS capacity [kW]	412	15	192	83	0	88
PIC [10^3 JPY]	0	38	67	0	160	16
Total cost [10^3 JPY]	44,506	55,631	52,266	39,582	25,214	36,914

* (HTL: Hotel, SPC: Sports Center, OFC: Office, HOS: Hospital, FAC: Factory, GRS: Grocery Store)

5.4 Comparison of all cases

The total costs evaluated through the numerical simulations are summarized in Fig. 8. This figure shows that a Microgrid can create an energy cost reduction even though additional investments are needed to build a Microgrid. A comparison between Cases 3 and 4 shows that Case 4 is slightly more economical than Case 3. One feature of a Microgrid, however, is that all loads in the Microgrid should be met by the installed DERs when a fault occurs in the upper grid; Case 4 is not able to achieve this function.

6. Conclusions

This paper proposes a method for economic evaluation of Microgrids from the consumer's point of view. The obtained simulation results show that building a Microgrid with an optimal operation of DERs is more economical than having each consumer operate DERs independently. In this simulation, no sale of electricity was observed due to the chosen parameter settings. However, when the initial and operation costs of DERs become lower due to mass-production or technological innovation, the sale of electricity would become a viable option and would contribute to the reduction of total energy costs. This means that Microgrids have great technical and economic potential to become a new energy supply system.

The proposed method is based on a linear programming method and comparatively easy to implement. All cost functions are expressed by simple linear functions and many commercial packages are available for solving linear programming problems. When consumers intend to use the proposed framework, what they need to do is just setting the parameters and forming the related functions.

The evaluation in this paper is just one example, and it is

Table 8
Simulation results of Cases 3 and 4.

	Case 3	Case 4
Contracted capacity [kW]	0	67
ASH capacity [kW]	3,369	3,372
FC capacity [kW]	1,877	1,871
ESS capacity [kW]	651	583
PIC [10^3 JPY]	0	0.3
Total cost [10^3 JPY]	251,414	251,249

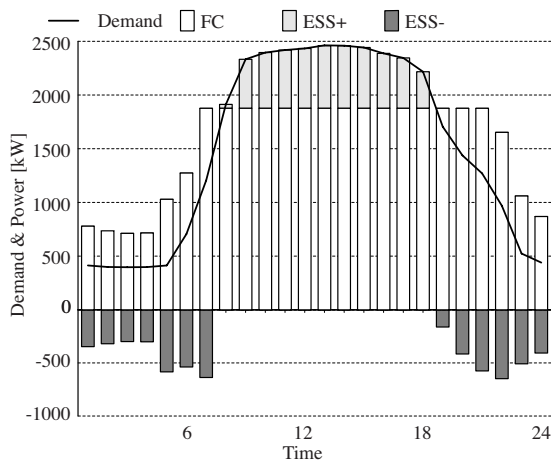


Fig. 7. Optimal operation pattern for the Microgrid (Case 3, summer)

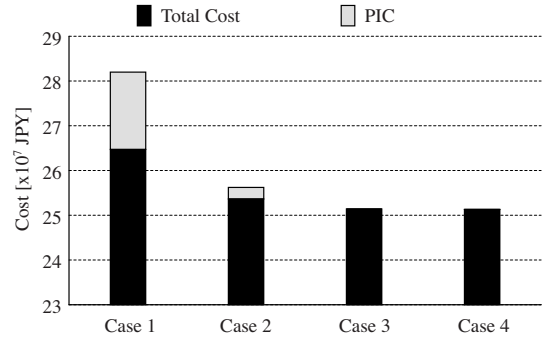


Fig. 8. Total costs of all cases (Case 1, 2, 3 and 4).

sensitive to the type of consumer profiles and other chosen parameters. Other types of loads, therefore, should be considered to enhance the accuracy of this optimal operation planning. In addition, Microgrids have the potential to provide ancillary services, and the benefits of these should be considered in the economic evaluations of future studies.

List of symbols

The following is the list of symbols used in this paper.

- j season index,
- i time index,
- m the number of seasons,
- t the number of time periods,
- S_j the number of days per season j ,
- f_{dg} fuel cost of DGs [JPY/kWh],
- m_{dg} maintenance cost of DGs [JPY/kWh],
- l consumer index,
- n the number of consumers,
- $p_{dg}()$ output of DGs [kW],
- f_{bl} fuel cost of heat sources [JPY/kWh],
- m_{bl} maintenance cost of heat sources [JPY/kWh],
- $p_{bl}()$ output of heat sources [kW],
- $e_e()$ electricity rate in purchase [JPY/kWh],
- $p_e()$ purchased electric power [kW],
- m_{st} maintenance cost of energy storage systems [JPY/kWh],
- $pr_{st}()$ discharged electric power [kW],
- $e_s()$ electricity rate in selling [JPY/kWh],
- $p_s()$ sold electric power [kW],
- α, β, γ depreciation rate of DGs, energy storage systems and heat sources,
- c_{gs} initial cost of DGs [JPY/kW],
- $gs()$ installed capacity of DGs,
- c_{st} initial cost of energy storage systems [JPY/kW],
- $ss()$ installed capacity of energy storage systems [kW],
- c_{bl} initial cost of heat sources [JPY/kW],
- $bs()$ installed capacity of heat sources [kW],
- e_b base charge of power contract [JPY/kW],
- es contracted capacity [kW],
- $n_\alpha, n_\beta, n_\gamma$ lifetime of DGs, energy storage systems and heat sources [yr],
- u interest rate,
- $pc_{st}()$ charged power [kW],

$L_e()$	electric demand [kW],
hr	heat/electricity rate of DGs (CHP),
$L_h()$	thermal demand [kW],
h	charge/discharge time limit,
lv	lower limit coefficient of DGs,
C_{SD}	installation cost of SD [JPY],
C_{EM}	installation cost of EM [JPY],
$C_{DL}()$	distribution line construction cost [JPY],
$C_{CL}()$	communication line construction cost [JPY],
dl_{total}	total length of the distribution lines [m],
cl_{total}	total length of the communication lines [m],
$\delta, \eta, \lambda, \sigma$	depreciation rate for SD, EM, distribution line and communication line, respectively,
$n_\delta, n_\eta, n_\lambda, n_\sigma$	lifetime of DGs, energy storage systems and heat sources [yr],
$IC()$	power interruption cost (PIC) [JPY],
d	outage duration time [min],
a_l, b_l	constants depending on the type of consumers,
$prob()$	probability of power interruption.

Reference

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