Economic Analysis of Microgrids

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Abstract-- **In Japan, three national field tests of microgrid were started in 2005. These projects are trying to demonstrate technical feasibility of microgrids with renewable energy, but economic and environmental benefits have not been shown yet. The economic evaluation of the microgrids is still challenging. This paper presents a methodology for economic design and optimal operation of microgrids with renewable energy sources. Numerical examples are illustrated to show the optimal configuration of a microgrid.**

Index Terms-- **cogeneration system, economic analysis, microgrid, optimization**

I. INTRODUCTION

The concept of microgrid involves interconnection of small distributed generation (DG)DGs and loads through a local grid. These systems can be connected to the main power network or be operated autonomously in an islanded mode, when the main power network is disturbed with severe faults.

Traditionally, customers operates DGs with fuel such as gas engine CHP mostly at rated power or use intermittent renewable energy such as photovoltaic generation(PV) and wind power. In this case, a customer adjusts balance of supply and demand through purchased power from the main grid. On the other hand, a microgrid can contribute load following to a utility grid by adjusting output of DGs.

The New Energy and Industrial Technology Development Organization(NEDO) started three demonstrations "the Regional Power Grid with Renewable Energy Resources Project". These projects are qualified for the national program because they have a significant share of renewable energy in a microgrid. The sites are in Hachinohe, Aichi and Kyoto[1]. These projects are trying to demonstrate technical feasibility of microgrids with renewable energy, but economic and environmental benefits have not been shown yet. The economic evaluation of the microgrids is still challenging. This paper presents a methodology for economic design and optimal operation of microgrids with renewable energy sources.

II. ECONOMICS OF THE MICROGRIDS

If technology and regulatory challenges are overcome, the microgrid market opportunity is attractive. Microgrids can deliver several value propositions including reduced cost, increased reliability and security, green power, service differentiation, and power system optimization [6].

Cost drivers of microgrid include capital costs of equipment, fuel cost of DGs, purchased cost and selling price of electricity from the main grid, construction costs of distribution lines (and thermal grid costs). The operational cost of the microgrid depends on high availability of DGs. One of dominant factors of the economics is load shapes of the customers.

There are three basic questions on the economics of the microgrids;

Q1) How much size of the microgrid does become economically?

Q2) How much percent of capacity of PV or wind power do contribute to a microgrid with constraints of power quality?

Q3 How much do customers pay extra money for premium power and/or green power?

Microgrids could capture 4.5 GW of the US market according to the market assessment report by Navigant[6]. Half of this market could likely be under 2 MW in size. It is applicable to Japanese market. However, smaller size of microgrid faces the expensive personnel cost of operation and maintenance, in particular, in the initial stage of the market.

Relative to question 2, Japan and dozens of states in the US have RPSs. Intermittency of wind power and PV is a problem, and microgrids are used to manage intermittency with controllable DGs such as gas engines and battery storage. An environmental push scenario will expand the microgrid market significantly in 2020-2030. For reliability-oriented microgrid (Q3), outage cost of customers and willingness to pay to green power should be included.

III. DESIGN OF OPTIMAL CAPACITY OF EQUIPMENT

The first question is how much size of microgrid is economically feasible and how much size of equipment should be installed in a microgrid. To increase renewable energy near the demand side, one of main equipment is a gas engine cogeneration(CHP) system. Because gas engine CHP can be used to adjust the output of the intermittent renewable energy sources such as PV. The generating efficiency of gas engine generation exceeds 40%(LHV) due to remarkable technological progress in class of 350kW. It is economically effective to aggregate the demand into the scale on which two or

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more DG of this class is set up in. Therefore, a problem is how to determine the numbers and capacity of main machine for a microgrid. This is an optimal capacity problem including the number of equipment and contract demand of the purchased power and selling power.

The objective function of the long-run optimization problem is annual total cost.

A. A Illustrative Microgrid

To illustrate an optimization method of capacity sizing, a microgrid system for a building complex is taken as a case study. Figure 1 shows the structure of the system investigated here. The system is composed of the following equipment; gas-engine(GE), battery(BAT), heat exchangers(HE), thermal storage tanks(TS), a steam-absorption refrigerator(RS), a gas-absorption chiller(RG), and a gas-boiler(GB). Electricity was supplied to the building complex by the parallel operation of gas-engine-driven generators, battery, and by power purchased from the utility grid. The surplus electricity is sold to satisfy the lowest load factor constraint of the engine because of off-peak demand, and to improve the power generation efficiency, and the revenue from the utility may improve the economy of the system. Here, the selling price from the microgrid to the utility is set, referring to the surplus electricity unit price of Tokyo Electric Power Company.

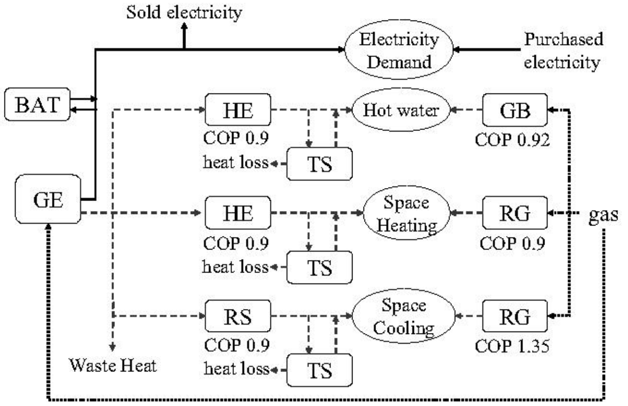

Figure 1. System configuration

B. Data

Energy demand is estimated at each of 24 hours on six representative days in a year(three seasons (summer, winter, and spring & fall) and weekdays and holidays). Its maximum demand is circa 1000 kW. Representative values of equipment performance, initial cost of equipment, and utility prices are summarized in Table I.

C. Optimal design of a microgrid

Table II shows the results of the optimal capacities of equipment and cost components. The optimal capacity of gas engine is 672kW. Neither the battery, nor the heat storage tank have been introduced because of expensive initial costs of these equipment in this case.

Table I Equipment characteristics and utility prices

GE	Scale constraint		90 - 1500	kW
	Load factor constraint		0.5 -1.0	
	Unit price of maintenance		2.5	JPY/kWh
	Unit price of start-up/shutdown		0.286	JPY/kW
	Initial cost		130,000 (JPY/kW)× GE rated power (kW)	
BAT	Charging efficiency		0.8	
	Discharging efficiency		0.9	
	Initial cost		50,186 (JPY/kWh) × BAT capacity (kWh) + 410,570 (JPY)	
RS	Initial cost		51,136 (JPY/kW) × RS rated power (kW)	
GB	Initial cost		28,409 (JPY/kW) × GB rated power (kW)	
RG	Initial cost		56,818 (JPY/kW) × RG rated power (kW)	
Hot-Water Tank	Capacity constraint		6	m^3
	Temperature constraint		70-80	℃
	Heat loss		10	% / h
	Initial cost		100,000 (JPY/m^3) × tank capacity (m^3)	
Thermal Storage Tank	Temperature constraint	Water for air heating	50-55	℃
		Water for air cooling	7-12	℃
	Heat loss	Water for air heating	7.0	% / h
		Water for air cooling	2.0	% / h
	Initial cost		100,000 (JPY/m^3) × tank capacity (m^3)	
City Gas	Energy charge		35.1	JPY/m^3
	Demand charge		7.85	JPY/m^3
	Heating value of city-gas		11.56	kWh/m^3
Electric Price	Demand charge		1560	JPY / (kW·month)
	Energy charge rate	Peak period (13:00-16:00 in summer)	13.9	JPY / kWh
		Shoulder period (summer)	13.25	
		Shoulder period (other seasons)	12.3	
		Off peak period (22:00-8:00, Sunday, holiday)	6.15	
	Selling unit price	Peak period (13:00 - 16:00 in summer)	5.5	JPY/ kWh
		Shoulder period	4.95	
		Off peak period (22:00 - 8:00, Sunday, holiday)	2.45	
Interest Rate			0.03	

120 JPY=one USD

Table II Optimal capacity of equipment

		sm-w	sm-h	wt-w	wt-h	other-w	other-h	
spec	GE rated power	672.2	672.2	672.2	672.2	672.2	672.2	kW
	BAT rated power							kWh
	Hot-Water Tank capacity							m3
	thermal storage tank capacity							m3
	RS rated power	559.6	559.6	559.6	559.6	559.6	559.6	kW
	RG rated power(warm air)	708.3	708.3	708.3	708.3	708.3	708.3	kW
	RG rated power(cool air)	2181.9	2181.9	2181.9	2181.9	2181.9	2181.9	kW
	GB rated power	245.6	245.6	245.6	245.6	245.6	245.6	kW
	contract demand	336.1	336.1	336.1	336.1	336.1	336.1	kWh
	waste heat	611.0	2004.4	434.2	391.9	1392.0	1783.0	kWh
running sost	electric power selling							yen/day
	purchased electricity	72710	42973	31473	25634	27789	19368	yen/day
	gas charge of GE	126470	37205	124800	82169	122797	82169	yen/day
	gas charge of GB	211		10381	9309	1334	1786	yen/day
	gas charge of RG(warm air)			22232	8127	2268		yen/day
	gas charge of RG(cool air)	64810	4362	2238	71	3475	814	yen/day
	demand charge	17477	17477	17477	17477	17477	17477	yen/day
	GE maintenance cost	33203	21562	32770	20166	32153	20166	yen/day
	start-up and stop cost							yen/day
	total	314882	173580	241370	162953	207293	141781	yen/day
initial cost	GE	20055	20055	20055	20055	20055	20055	yen/day
	BAT							yen/day
	Hot-Water Tank							yen/day
	thermal storage tank							yen/day
	RS	6567	6567	6567	6567	6567	6567	yen/day
	RG(warm air)	9206	9206	9206	9206	9206	9206	yen/day
	RG(cool air)	28451	28451	28451	28451	28451	28451	yen/day
	GB	1601	1601	1601	1601	1601	1601	yen/day
	toal	65911	35911	65911	65911	65911	65911	yen/day
total cost		380792	239490	307281	228864	273203	207691	yen/day
property	average of GE generating efficiency	0.390	0.367	0.390	0.364	0.389	0.364	%
	average of GE exhaust heat recovery efficiency	0.380	0.413	0.380	0.417	0.382	0.417	%
	average of GE total efficiency	0.770	0.780	0.770	0.781	0.771	0.781	%
	average electricity price generated from GE	12.02	12.61	12.02	12.69	12.05	12.69	yen/kWh
	average electricity price generated from GE	7.68	8.11	7.65	7.63	7.84	8.06	yen/kWh

IV. A. ECONOMIC OPERATION OF A MICROGRID

The second problem is how to operate each equipment under operational constraints.

A. Mathematical Formulation of Economic Operation of a Microgrid

The operation plan of the system that consists of PV and gas-engine CHP is illustrated here for a building complex consisting of an office building of (25000 m2 total floor space) and apartment buildings (600 households) as a case study. PV is added and the number and the capacity of gas engine is fixed here. Electricity demand and thermal demand are assumed based on combined measured data of the office building and apartment building. Figure 2 illustrates the structure of the hybrid system investigated here; three or two gas-engines (350kW per unit), PV (100kW), one steam-absorption refrigerator, one gas-absorption chiller, and one gas-boiler. Electricity is supplied to the building complex by the parallel operation of multiple gas engine-driven generators, PV, battery and by power purchased from the utility grid.

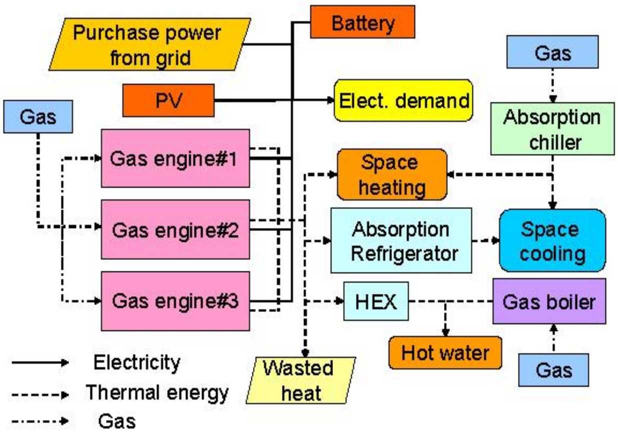

Figure 2. System configuration of hybrid system of PV and CHP

We formulate a problem to minimize a cost to supply electricity to load in a microgrid. Here, we model the optimal operation planning of a system for the day ahead.

Partial load efficiency (LHV), $\eta_{e\,i,j}$, of three gas-engine generators is as follows;

$$\eta_{e\,i,j} = -0.216 x_{i,j}{}^{2} + 0.434 x_{i,j} + 0.187 \text{ ....} (1)$$

$$0.5 \cdot \delta_{i,j} \leq x_{i,j} \leq 1.0 \cdot \delta_{i,j}$$

where, $x_{i,j}$, $\delta_{i,j}$ represent partial load and on-off binary variable of engine operation, respectively.

It is assumed that the microgrid acquires the residual electricity that it needs beyond its self-generation from the utility. The optimization problem is formulated as follows.

Objective function:

$$Z_{cost} - \gamma \cdot \sum_{i,j} Fa_{i,j} + \sum_j \theta_j \cdot B_j + \varepsilon \cdot \sum_{i,j} D_{i,j} \text{ ....} (2)$$

Constraints:

$$E_d(i) = E_{PV}(i) + \sum_j E_{i,j} + E_{bat}^{in}(i) + E_{bat}^{out}(i) + E_{buy}(i) \quad (3)$$

$$E_{bat}(i) = E_{bat}(i-1) + \frac{1}{2}\tau \cdot E_{bat}^{in}(i) + \frac{1}{2} E_{bat}^{out}(i) / \varsigma \quad (4)$$

$$Q_{cool} = COP_{AR} * Q_{GE1} + Q_{RGC} = Q_{RW} + Q_{RGC} \quad (5)$$

$$Q_{hotair} = COP_{AR} * Q_{GE2} + Q_{RGH} \quad (6)$$

$$Q_{hotwater} = Q_{GE3} + Q_{GB} \quad (7)$$

$$Q_{RD} = Q_{GE4} \quad (8)$$

$$Q_{GE} = \sum_{n\ 1}^{3} Q_{GEn} \quad (9)$$

Z_{cost} [JPY]: operation cost per day, γ [JPY/m^3]: energy charge of city-gas, Fa [m^3]: gas consumption, ε [JPY/time]: cost of start and stop of a gas engine, D: number of starts and stops of gas engines, θ [JPY/kWh]: the electricity price, B [kWh]: purchased electric energy, E_d [kW]: electric power demand, E_{PV} [kW]: output power from PV, E_{buy} [kW]: purchased electric power. E^{in}_{bat} [kW]: battery charge, τ: efficiency of charging, E^{out}_{bat} [kW]: battery discharge. ζ: efficiency of discharging, E_{bat}[kWh]: electricity stored in battery, Q_{cool} [kW]: space-cooling demand, Q_{hotair} [kW]: space-heating demand, $Q_{hotwater}$ [kW]: hot-water demand, Q_{GE} [kW]: heat recovered from gas engines, Q_{GE1} [kW]: heat recovered from gas engines for space cooling, Q_{GE2} [kW]: heat recovered from gas engines for space heating, Q_{GE3} [kW]: heat recovered from gas engines for hot water, Q_{GE4} [kW]: heat recovered from gas engines, Q_{RGC} [kW]: output from a gas-absorption chiller, Q_{RGH} [kW]: output from a gas-absorption water heater, Q_{RW} [kW]: output from an absorption refrigerator, Q_{GB} [kW]: output from a gas boiler, Q_{RD} [kW]: waste heat. i: unit number of gas engines, j: time

(2) is the objective function that states the microgrid will minimize running energy cost (operation cost only, not including fixed costs). The constraints to this problem enforce the energy balance and are expressed above in (3) to (9). The capacities of an absorption refrigerator , a

gas-absorption chiller, and a gas boiler are determined to satisfy the supply/demand constraints (3) to (9) In addition to the above operation cost, we consider annual cost of utility demand charges and initial costs of major equipment as follows,

$$Cost = Z_{\cos t} + 12A_E \cdot Max(E_{buy}) + A_G \sum_{i,j} Fa_{i,j} + C_m \cdot P_{GE} + C_{GE}\frac{l(1+l)^{\kappa}}{(1+l)^{\kappa}-1} + C_{BT}\frac{l(1+l)^{\nu}}{(1+l)^{\nu}-1} \quad (10)$$

where ν, κ, l, A_E [JPY/kW], A_G [JPY/m^3], C_m [JPY/kWh], P_{GE} [kWh], C_{GE} [JPY], and C_{BT} [JPY] represent life time of gas engine (15 years), that of battery (10 years) and an interest rate, demand charge of utility grid, demand charge of city gas, maintenance cost of gas engine, total electricity generated from gas engines, initial cost of gas engine, and initial cost of battery, respectively.

B. *DATA AND RESULTS*

In this study, we use the average electricity and heat demand data of week day, Saturday and holiday in each season(three seasons: summer, winter, spring & fall), calculated from the measured load data of the office building and the apartment in Tokyo. The initial cost of gas engine CHP is 130000 JPY/kW (1100US$/kW). The initial cost of battery is 40000 JPY/kWh.

Gas price is based on the special discount tariff for CHP in the service area of Tokyo Gas Company. Electricity price is based on the tariff schedule of Tokyo Electric Power Company. In addition to energy charge of electricity and city gas, we consider utility demand charges. The cost of starting and stopping of a gas engine is assumed 100 JPY per start based on fuel consumption of start-up. In addition to the constraint functions, we assumed the running time and the stop period exceed three hours and the number of gas engine start-up is twice a day because of maintenance of engines. The starting time of daily optimal operation planning is changed in order to use battery charging most efficiently. Thirteen cases based on combinations among the contract demand of purchased power, battery capacity and the number of gas engine unit is considered.

Table III shows the result of the sensitivity of contract demand and battery capacity. The case "CE=50kW, BT=100kWh" shows the most reasonable annual cost, and basically it is effective to make the contract demand as small as possible. In night time operation pattern, electricity from the utility grid is bought as much as possible for reducing the exhausted heat. However, in the cases CE=50kW, 100kW, 200kW, it is necessary to operate more than one gas engine in night time in order to supply electricity to the customers, and it generates a lot of exhausted heat. But the benefit of the reduction of the demand charge to utility grid is larger than unused energy of the exhausted heat.

TABLE III

ANNUAL COST IN EACH CASE

Annual cost (10^3 JPY)		Contracted demand of purchased electricity (kW)				
		50 (3 GE units)	100 (3 GE units)	200 (3 GE units)	500 (3 GE units)	500 (2 GE units)
Backup contract		○	○	○	×	○
Battery Capacity (kWh)	0	-	-	-	91,162	-
	100	90,558	90,595	90,784	91,560	90,532
	200	90,868	90,903	91,176	91,905	90,765
	500	92,194	92,120	-	-	92,109
	1000	-	-	-	-	94,207

The larger capacity a battery has, the more expensive the annual cost in every case under the same contract demand of purchased power. And the larger contract demand becomes, the more expensive the annual cost in the case that the battery capacity is 100kWh and 200kWh. Although in the case that the battery capacity is 500kWh, the larger contract demand becomes, the smaller the annual cost becomes. This is because the reduction of cost of gas engine is effective shown in Table 1.

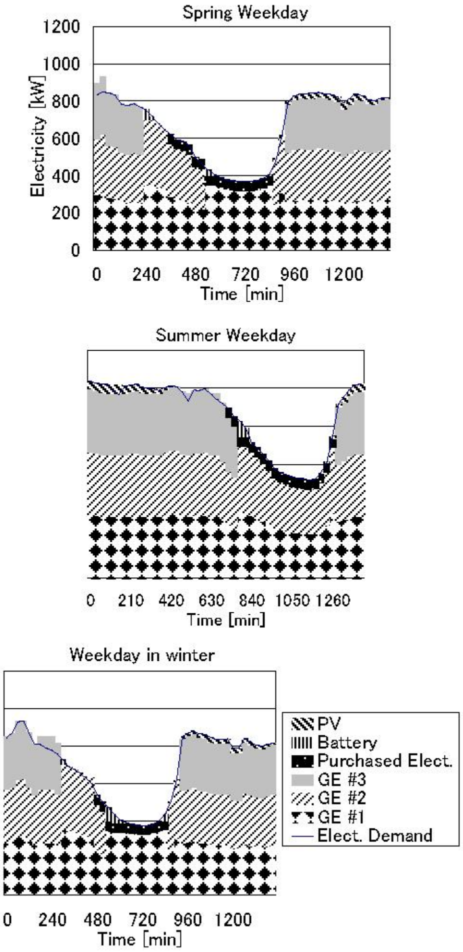

Figure 3. Optimal operation pattern of PV/CHP hybrid system.

Figure 3 shows gas engine operation patterns on the week day in each season when PV capacity, the contracted demand, and battery capacity are 100kW, 50kW, and 100kWh, respectively. The first unit of gas engine is operated all the time. In summer, the second unit of gas engine is also operated all day due to larger energy demand.

V. CONCLUSIONS

Development of design technique to determine a system configuration and operational strategy is important and challenging subject in the microgrid study. Because microgrid should be economically practical, attaining maximum introduction of renewable energy sources and maintaining power quality simultaneously. We propose a methodology for economic design and optimal operation of microgrids with renewable energy sources. Microgrids can foster the services of smaller loads with cleaner, more efficient, more reliable technologies.

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