Potential of Residential Combined Heat and Power Systems in Korea

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***Abstract*—We describe how 1-kWe combined heat and power (CHP) systems in the Korean residential sector affect the electrical grid. The maximum diffusible capacity of the CHP systems was determined based on user benefit, and these results were used to assess the domestic effect of CHP system diffusion. The maximum diffusible capacity was 840,000 kW, which should yield an annual reduction in fuel costs of 381 million USD, a 2.5-million-ton reduction in equivalent CO2 emissions, and a reduction in the peak demand for electricity of 0.84 GW. The Korean government has recently announced its intention to increase the use of distributed power sources; on-site 1-kWe CHP systems are expected to be an important aspect of this.**

***Index Terms*—cogeneration, national benefit, distributed power source**

I. Introduction

The electrical power reserve rate in Korea has been falling recently: from 14% in 2002, to 11% in 2006, to 6% in 2010 [1]. Nation-wide rolling blackouts occurred during September 2011, which led to the resignation of Knowledge and Economy Minister Choi. Since then, the Korean government has controlled the demand for electricity, but the reserve rate remains 6% or less. The Korean electricity supply is heavily dependent on nuclear power. The Korean government has classified nuclear energy as a clean energy source, and had planned to expand nuclear power capacity from 20 GW (as of 2012) to 36 GW (by 2027) [2]. However, this plan lost much support following the Fukushima Daiichi nuclear power accident, and for this reason the government has suggested that use of distributed power sources [3].

In Korea, 44% of the population [4] and 32% of the demand [5] for electricity is concentrated in and around the capital, Seoul. The population density in Seoul is 16,189 people per kilometer squared, making it one of the top cities in the Organization for Economic Cooperation and Development (OECD) ranking. According to this index, Korea has limited options to expand its distributed power resources. Therefore, distributed power sources require a high generation capacity per unit area, which is not a straightforward process to implement. Combined heat and power (CHP) systems yield benefits in terms of generation capacity per unit area, but to date wide-scale uptake of CHP systems have not been common in Korea. This is related to poorly designed policy, which focused only on supporting the initial costs of the CHP systems, and led to a large number of oversized installations. These oversized CHP systems caused economic losses because of the relatively low load factor and corresponding low electric al efficiency during short operating hours.

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Here we describe how more widespread use of CHP systems could improve the Korean energy portfolio by analyzing the use of 1-kWe CHP systems in the Korean residential sector. The residential sector has significant potential for CHP systems due to the energy pricing structure, and a 1-kWe CHP system has recently been introduced into the market.

II. Residential CHP Systems

Here, we consider a 1-kWe CHP system powered using natural gas. The system consists of an engine/generator unit, an auxiliary boiler, and a thermal storage system, as shown in Fig. 1. In this analysis, we neglect the transient response characteristics that occur during start-up and shut-down, so we do not specify the type of prime mover, and only consider an overall electrical efficiency of 0.20 and a thermal efficiency of 0.75.

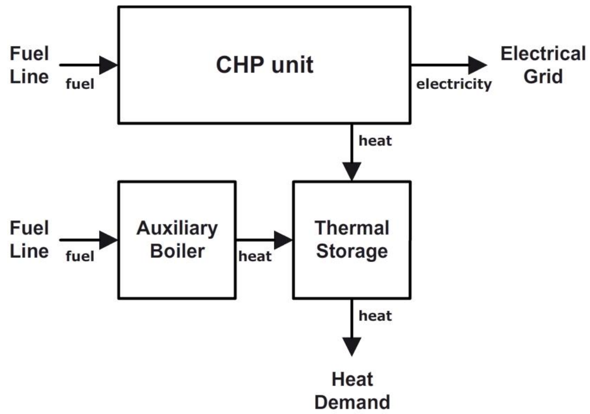

Figure 1. Diagram of the residential CHP system

The design of the operating strategy includes scheduled operations. The CHP system operates when the price of electricity is high, while also being constrained to prevent over-production of heat. Fig. 2 presents an example operating strategy. The average Korean household consumes 6.8 kWh per day during the warm season, and the required thermal storage capacity is 230 liters

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(assuming a storage temperature of 60℃ and a supply temperature of 35℃). Thus, if there are 230 liters or more of thermal storage, the CHP system may operate at any time without dumping excess heat. For comparison, the average volume of a refrigerator in Korea is 600 liters.

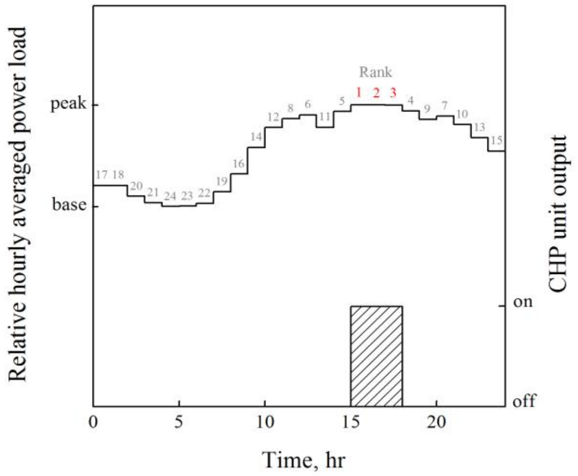


Figure 2. Example of scheduled operation

III. ENERGY STATISTICS IN KOREA

The Korean Energy Consumption Survey [5] is published every four years, and describes the national demand and supply of electricity and heat. Here we refer to the most current survey, which was published in 2011 and contains data for 2010.

Total electricity demand in Korea was 390 TWh, of which demand from the residential sector was 62 TWh (15.9%). Fig. 3 presents the monthly demand for electricity and heat in the residential sector. The heat-to-power ratio in the residential sector ranged from 0.3 in summer to 2.2 in winter. Fig. 4 shows an example of hourly electricity load and dispatch stack. Table I lists the electrical efficiency, generation cost, CO_2 emissions, and construction cost of the electricity plants in the dispatch stack.

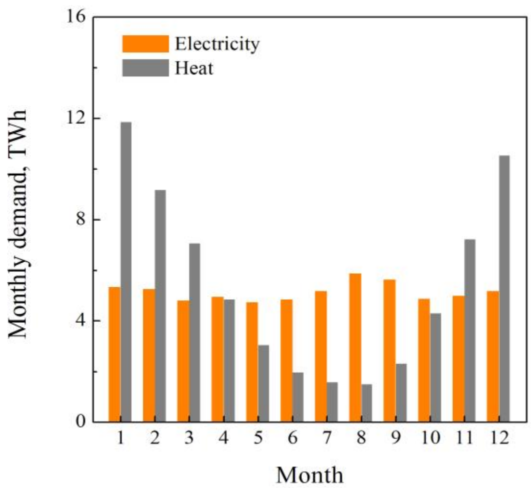


Figure 3. Monthly demand for Korean residential sector

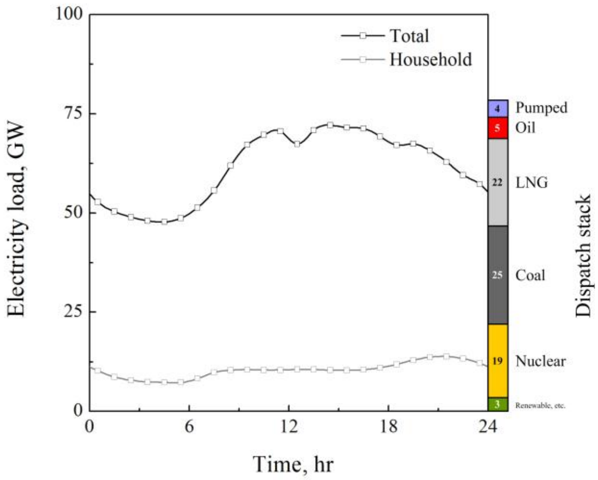


Figure 4. Example of hourly electrical load and dispatch stack

IV. MAXUMYM DIFFUSIBLE CAPACITY

The Korean government does not currently provide subsidies for residential CHP systems. Here, we consider the maximum number of residential customers who could obtain economic benefit from the use of the CHP systems without subsidies to be the maximum diffusible capacity for CHP systems in the residential sector. Table II lists the data we used to estimate this maximum diffusible capacity. We selected a 10-year payback period to assess whether economic benefit is obtained, together with an initial cost of 5,000 USD, which is the market price of such systems in Korea. We assumed an energy price for heat of 0.08 USD per kWh, based on a 90%-efficiency natural gas boiler. No pricing rules have been set for energy generated from residential CHP systems in Korea. Thus, we assumed a power purchase agreement (PPA) rule, which has recently been applied in some on-site power sources in Korea. An electricity selling price of 0.15 USD per kWh was the average PPA price in 2012. The electricity buying price for customers, however, is meaningless when applying PPA rules to electricity from the CHP system.

TABLE I. EFFICIENCY, GENERATION COST, CONSTRUCTION COST, AND CO_2 EMISSIONS FOR ELECTRICAL PLANTS

	Nuclear	Coal	LNG	Oil	Pumped Storage*
Efficiency	N/A	0.37	0.4	0.39	0.769
Generation cost, USD/kWh	N/A	0.075	0.141	0.248	N/A
Construction cost,** USD/kW	1,884	906	759	2,242	829
CO_2 emission, g $CO_{2\text{-eq}}$/kWh	10	1250	575	800	N/A

TABLE II. DATA FOR THE MAXIMUM DIFFUSIBLE CAPACITY ESTIMATION

Payback period	10 years	for CHP unit
Initial cost	5,000 USD	
PPA price	0.16 USD/kWh	
Fuel price	0.07 USD/kWh	
Heating price	0.08 USD/kWh	for current heat source

Annual electricity and heat consumption are linearly interrelated, as shown in Fig. 5, so we can use electricity consumption alone to determine an index of customer energy consumption. Table III lists the payback period for various monthly average energy consumption levels. Based on these data, households that used at least 480 kWh per month would obtain an economic benefit from the CHP system. Fig. 6 shows the frequency density function for monthly averaged electricity consumption. Approximately 840,000 households used at least 480 kWh per month, so an additional 840,000 kW (i.e., 840,000 1-kWe CHP units) is the maximum diffusible capacity.

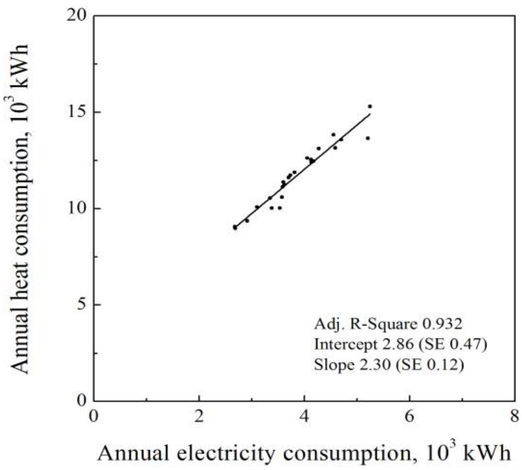


Figure 5. Relationship between electricity and heat consumption

V. METHODOLOGY

We simulated the operating output of the 840,000 CHP systems based on the 2010 data about demand and supply in the electrical power supply system. Fig. 7(a) presents the frequency density function and the expected operating hours for each energy consumption level in December 2010. In this example, a household that consumed 480 kWh of electricity per month consumed 70 kWh heat per day, and this 70 kWh of heat corresponds to 19 hours of CHP system operation. The CHP system selects the 19 hours with the highest electrical prices (in this case 0:00 to 02:00 and 07:00 to 24:00) and operates during the selected hours. If we apply this process to all energy consumption levels within the maximum diffusible capacity, we can obtain the total electricity production from all the diffused CHP systems during this time interval, as shown in Fig. 7 (b). Here, the region with diagonal lines indicates the amount of electricity from the diffused CHP systems, and the orange region indicates electricity supplied from the grid.

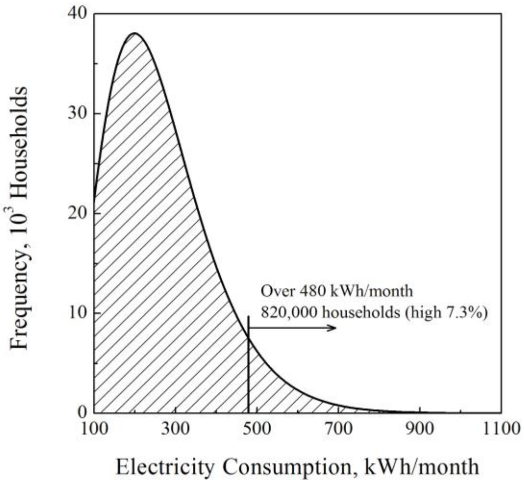


Figure 6. Frequency density function for monthly averaged electricity consumption

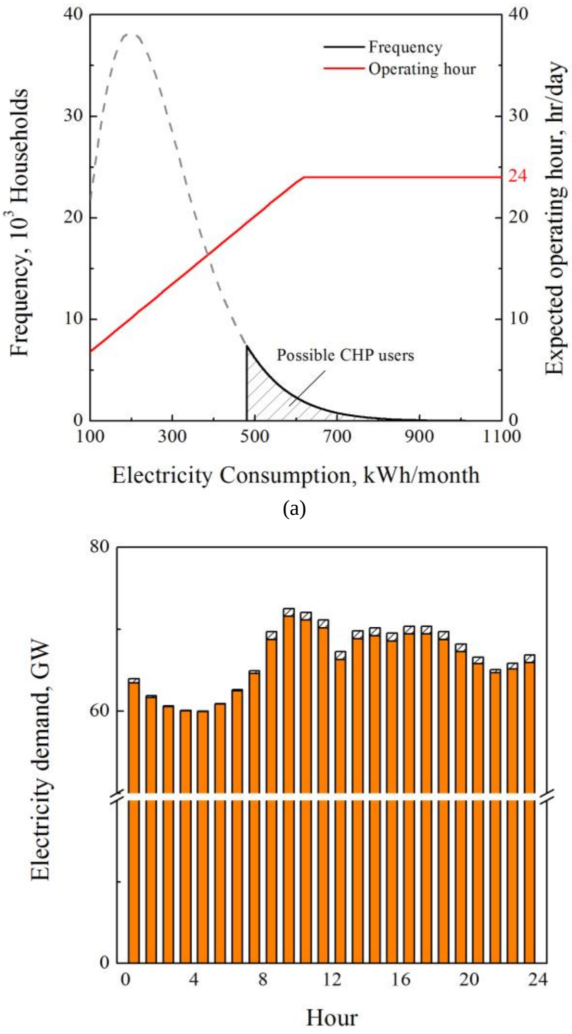


Figure 7. (a) Estimating operating hour and (b) Estimating hourly grid demand after CHP systems diffusion

TABLE III. PAYBACK PERIOD FOR VARIOUS MONTHLY AVERAGE ENERGY CONSUMPTION LEVELS

Avg. elec. consumption (kWh/month)	Avg. heat consumption (kWh/month)	**Jan.** Avg. operating hr. (hour/day)	**Aug.** Avg. operating hr. (hour/day)	Elec. production, (kWh/year)	Heat production, (kWh/year)	CHP Fuel consumption (kWh/year)	Energy saving cost, (USD/year)	**Payback period, (year)**
300	296	17	1.8	2,966	11,123	14,830	349	**14.3**
400	315	21	2.3	3,701	13,877	18,503	438	**11.4**
460	326	24	2.5	4,141	15,529	20,706	492	**10.1**
480	**330**	**24**	**2.6**	**4,268**	**16,004**	**21,339**	**508**	**9.8**
500	334	24	2.7	4,389	16,460	21,947	525	**9.5**
600	353	24	3.1	4,899	18,370	24,494	602	**8.3**
700	372	24	3.6	5,276	19,784	26,379	670	**7.4**

We can calculate change in demand for the electricity plant based on the data plotted in Fig. 7. We can do this monthly to obtain annual figures. If we apply generation costs and the CO_2 emissions shown in Table II to these data, we can obtain the total energy saving and the total change in CO_2 emissions.

VI. RESULTS AND DISCUSSION

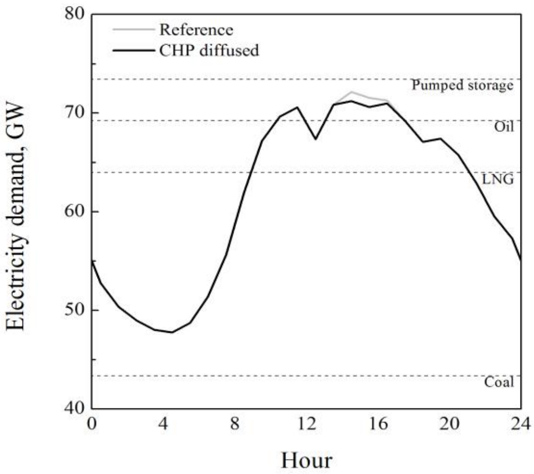
Table IV illustrates the potential effects of installing 840,000 1-kWe CHP units, based on 2010 data: annual reductions of 838 GWh in electricity generated from pumped storage plants, 1,160 GWh in electricity from oil-powered plants, 1,282 GWh in electricity from liquefied natural gas (LNG) plants, and 12,303 GWh in electricity from conventional sources. The CHP systems, however, consumed 16,404 GWh of fuel. These data can be used to calculate an annual energy saving, which was 381 million USD. In terms of CO2 emissions, we calculated a reduction of 2.5 million tons of equivalent CO2, which corresponds to 39 million USD (assuming 16 USD per ton of equivalent CO2, which was the ICE ECX emissions trading price as of December 2010).

Fig. 8 presents hourly electricity demand during summer and winter peak demand days in 2010. Summer peak demand decreased from 72.14 GW to 71.21 GW, and winter peak demand decreased from 72.51 GW to 71.67 GW, i.e., both decreased by 0.84 GW. If we apply the unit construction cost of the plants used during peak and intermediate load (i.e., the LNG- and oil-powered plants), we obtain an annual construction cost of 36 million USD, which can be avoided by using CHP systems (assuming a 30-year lifetime for all plants). Taking into account the above economic considerations, the reductions in energy costs and CO2 emissions, together with the avoidance of construction costs, provide a total annual economic benefit of 456 million USD, which is equivalent to 543 USD per 1-kWe CHP system.

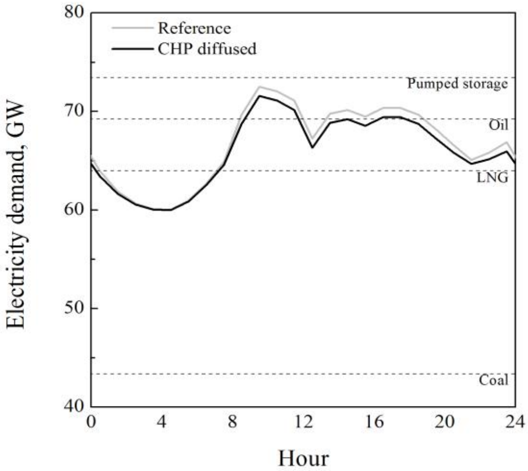
Diffusion of on-site CHP systems (such as the 1-kWe residential CHP system described here) also provides additional benefits. Electrical grids in Korea are currently approaching capacity (in both transmission and distribution). Peak demand increased by a factor of 1.6 from 2001 to 2010; but the capacity of the transmission and distribution system only increased by a factor of 1.2 during the same period. This is related to recent increases in social resistance and compensation costs. On-site CHP systems can be installed at the site of demand, reducing the requirements for transmission and distribution systems. Combined with increased use of smart grid technologies, on-site CHP systems can improve the long-term stability of electrical supply and demand. These systems are the most feasible distributed power sources currently available, and smart grid infrastructure, such as two-way metering systems, can enable energy pricing rules for distributed power sources.

TABLE IV. POTENTIAL EFFECTS OF 840,000 1-KWE CHP SYSTEMS

		Electricity grid (Amount of product)				Residential sector only (Amount of primary energy)	
		Nuclear & Fuel	LNG	Oil	Pumped storage	Heat (LNG)	CHP fuel (LNG)
Annual consumption	Reference, A (TWh)	351	136	12	2	191	0
	CHP diffused, B	351	134	10	1	179	16
Annual reduction	Consumption, A-B (TWh)	0	1,282	1,160	838	12,303	-16,404
	Fuel cost (10^6 USD)	0	181	288	82	844	-1,013
	CO_2 emmision (10^3 ton CO_2-eq)	0	737	928	1,362	2,751	-3,301



(a)



(b)

Figure 8. Hourly electricity demand during (a) summer and (b) winter peak demand days in 2010

VII. CONCLUSIONS

We investigated the maximum diffusible capacity of 1-kWe CHP systems in the Korean residential sector, and assessed the impact on national energy costs. The estimated maximum diffusible capacity for customers to see an economic benefit was 840,000 kWe. Installing 840,000 kWe of residential CHP systems should save 381 million USD in energy generation costs, reduce equivalent CO2 emissions by 2.5 million tons, and reduce peak demand for electricity by 0.84 GW. These effects can be aggregated into an annual reduction in energy costs of 541 USD per 1-kWe CHP system.

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