Analysis of Distributed Energy Supplying Technologies From the Viewpoint of Waste Heat

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ABSTRACT

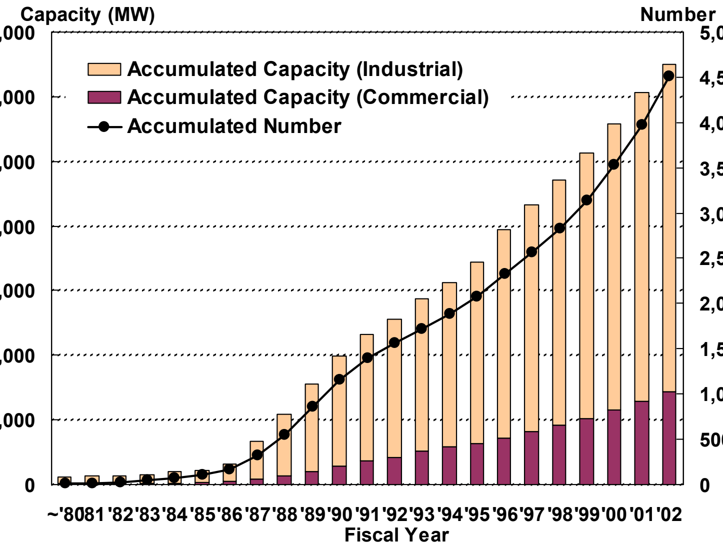
In Japan and other countries cogeneration systems have attracted attention because of their dramatically increased efficiency. However, these systems consume fossil fuels and there is the fear of worsening the heat island phenomenon, if they are installed in city areas. On the other hand, heat pump technology has been applied to various energy services. Because heat pump technology is quite efficient and if its energy is delivered from the outside of city area, the waste heat in city area is expected to be much less than cogeneration systems even though the loss of generation and transmission is taken into account. This study examined the characteristics of waste heat from various urban energy supplying systems by the reference survey; also, energy consumption and the amount of waste heat from a model house in summer season were estimated. The result shows: 1. The forms of waste heat differ greatly according to the cooling methods of energy supplying systems in commercial use, 2. There are various theories about the influence of latent heat on the heat island phenomenon, 3. Energy consumption is the lowest with the fuel cell cogeneration system (high waste heat recovery), but, the smallest amount of waste heat is exhausted in the city area with a combination of grid electricity and a heat pump water heater. The amount of waste heat from a gas engine cogeneration system and a fuel cell cogeneration system are even larger than that from the combination of grid electricity and an efficient gas water heater.

Introduction

The penetration of small-sized cogeneration systems (CGSs) has increased in Japan in recent years. According to the statistics of the Japan Cogeneration Center, the number of cogeneration sites in Japan has grown steadily (Figure 1). This is particularly true, in the commercial sector where average size of CGSs is relatively small (less than 500 kW/site, except for district heating and cooling). The prime mover of CGSs for the commercial sector is a gas engine. In addition, sales of a gas engine CGS for the residential sector began in 2003. It is the smallest gas engine CGS, called "ECOWILL," with only 1 kW of electrical output (Osaka Gas 2003a). It is expected the penetration of these small-sized CGSs will continue in the residential and commercial sectors in future and they will become a new source of waste heat in city areas.

Concentrated consumption of energy in metropolitan areas is considered to be one of the root causes of the heat island phenomenon. According to the Ministry of Environment, the total number of the hours when the atmospheric temperature exceeded 30˚C in Tokyo area doubled from 168 to 357 over the past twenty years (Ministry of Environment 2001). At present the increase in artificial sensible heat from the natural condition in central 3 wards of Tokyo is $61.9 W/m^2$, which is considerably larger than other areas in Japan (Center for Environmental Information Science 2002).

Figure 1. The Cumulative Number and Capacity of Cogeneration Sites Each Year



Source: Japan Cogeneration Center. 2004

CGSs are energy-efficient if their waste heat is utilized effectively, but the rate of waste heat recovery declines in summer months because of limited demand for hot water and heat. On the other hand, generating efficiency of large-scale LNG combined cycle power plants exceeds 50%[1] at full-load operation and some percentage of capacity located outside of the city area. Moreover, a hot water heater called "Eco Cute," which uses heat pump technology, was developed in 2001 and its annual average COP is 3.0 or more (Tokyo Electric Power Company 2003)[2]. This combination of grid electricity from the outside of the city area and an efficient water heater offers the possibility of reducing waste heat discharge in the city area much more than CGSs, even though the loss of generation and transmission of electricity is taken into account. Through literature review of waste heat discharge from distributed energy supplying systems and its relationship to the heat island phenomenon, we've estimated the amount of waste heat from various energy supplying systems. The targeted technologies were cogeneration systems (both gas engine and fuel cell), heat pump water heaters, and efficient gas water heaters.

Relationship between Energy Utilization and Heat Island Phenomenon: A Survey

As shown in Figure 2, several stages exist between energy utilization and the heat island phenomenon. In the first stage, the demands for energy services are determined by climatic conditions, load pattern of users, and percentage by user type (residential, commercial, industrial). In the second stage, the demands for commercialized energy are determined mainly by type of device, device efficiency, and operating mode. In the next stage, the amount of waste heat can be estimated. The forms of waste heat (sensible or latent) have a different impact on the heat island phenomenon as described later. The cooling methods of the various devices (cooling tower, outside unit, or heat recovery as hot water) determine the form of this waste heat. The resulting changes to local climate will, in turn, impact demand for energy services. Many uncertainties exist in each stage and they are investigated in this section by the reference survey.

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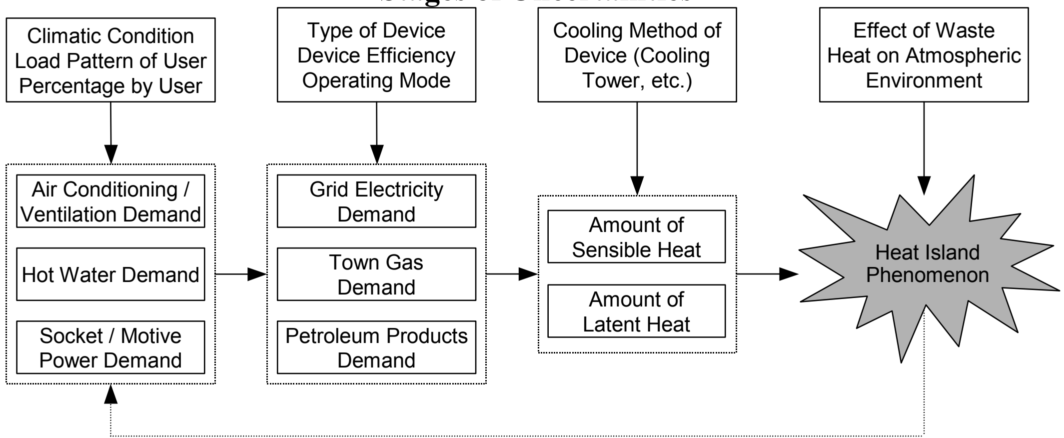
[1] Thermal efficiency is expressed by the high heat value (HHV) base in this paper.

[2] The unit for household use was commercialized first. Then the sales of commercial unit started in 2002.

Figure 2. Relationship between Energy Utilization and Heat Island Phenomenon: Many Stages of Uncertainties



The first uncertainty is the consumption of commercialized energy in the city area. Fortunately, energy consumption statistics by prefecture for grid electricity and city gas exist in Japan. However, for petroleum products, only sales statistics are available and, because large portions of them are consumed in the transportation sector, it is difficult to precisely estimate the consumption of petroleum products by prefecture. The situation gets worse to estimate the energy consumption by the type of device. For example, the statistics of consumed energy by CGS are not available separately; they are included in total consumption along with other devices. A typical manner to estimate it is bottom-up calculation. Ashie et al. estimated waste heat of air conditioning systems from five kinds of buildings in August in Tokyo area (Ashie et al. 2002). The floor space is 10,000 m^2 for each building type. The declines in efficiency by partial-load are taken into account for the calculation of energy consumption. The standard values of demands for energy services estimated by the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan (excepting schools) and by Waseda University's Ojima laboratory (for schools) are used in this estimation. This means variation in demand for energy services is neglected, thus there is no guarantee the result of the estimation expresses the actual conditions.

The estimated results show that the forms of waste heat are closely correlated to the cooling method (Table 1), in that the form of waste heat from air-cooled systems will be mostly sensible heat while that from water-cooled systems will be mostly latent heat. Shimoda et al. estimated waste heat from other air conditioning systems of office buildings in Osaka area (Shimoda et al. 2003) with a floor space of 30,000 m^2. The result is almost the same as the Ashie's study: the waste heat from the electric systems is mostly sensible heat and that from gas systems is mostly latent heat (Table 2). However, the form of waste heat from a gas engine CGS changes according to its actual operating mode. Kikegawa et al. estimated the changes in average atmospheric temperature in summer that would be derived by replacing air conditioning systems in the central area of Osaka City using their original MM-CM-BEM model (Kikegawa et al. 2003). They assumed the waste heat from a gas engine CGS is discharged as both 100% sensible heat and 100% latent heat respectively, considering the variations in the control method of heat radiation (Figure 3). That assumption means the waste heat of CGSs is not always recovered and CGSs are sometimes operated in the "mono-generation" (no heat recovery) mode. Their findings are very interesting: if all of the waste heat from gas engine CGSs is discharged as sensible heat, atmospheric temperature will rise by 0.3˚C; conversely, atmospheric temperature will fall by 0.1˚C if the waste heat is discharged as latent heat.

Table 1. Amount of Waste Heat from Air Conditioning Systems and Related Devices (August, Tokyo Area)

Building Type	Type of Air Conditioning System	Sensible Heat	Latent Heat
Office	Air-Cooled Electric Chiller	1,100.5	- 60.5
	Air-Cooled Electric Heat Pump	833.3	- 60.5
	Direct-Fired Absorption Chiller/Heater (Water-Cooled)	426.7	979.4
Wholesale / Retail	Air Cooled Electric Heat Pump	1,383.1	- 120.1
	Direct-Fired Absorption Chiller/Heater (Water-Cooled)	607.4	1,473.1
	Steam-Fired Absorption Chiller (Water-Cooled)	625.1	1,542.8
Hotel	Air-Cooled Electric Heat Pump	1,402.7	- 52.1
	Direct-Fired Absorption Chiller/Heater (Water-Cooled)	884.1	1,802.7
	Steam-Fired Absorption Chiller (Water-Cooled)	825.3	1,941.8
House	Room Air Conditioner (Air-Cooled)	188.6	- 28.4
School	No Systems	78.3	0.0

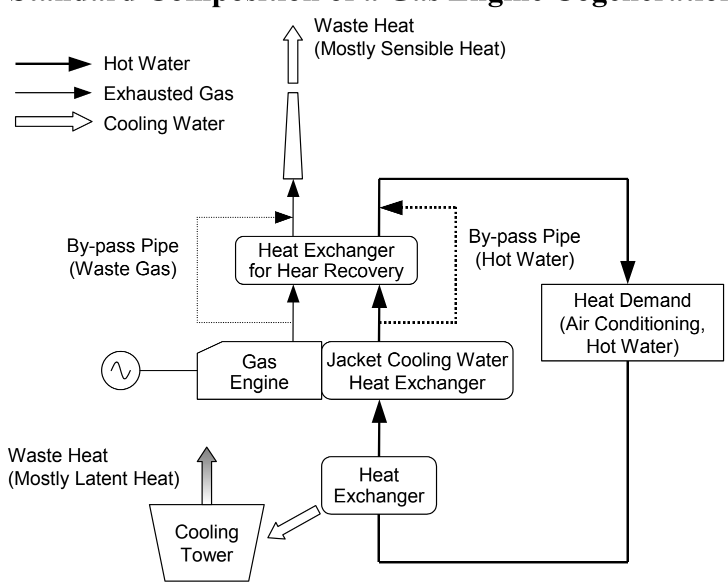
Unit: (W•h) / (m^2•day)
Source: Ashie et al. 2002 (translated).

Table 2. Amount of Waste Heat from Air Conditioning Systems (Office Building, August, Osaka Area)

Type of Air Conditioning System	Daytime (7am - 6pm)		Nighttime (7pm - 6am)	
	Sensible Heat	Latent Heat	Sensible Heat	Latent Heat
Gas Engine CGS	- 48.2	161.7	0.0	1.1
Gas Absorption Chiller/Heater	- 53.9	163.5	- 0.3	1.2
Air-Cooled Electric Heat Pump	69.2	- 32.7	0.6	- 0.3
Air-Cooled Electric Heat Pump + Ice Thermal Storage	20.2	-32.7	61.0	- 0.3

Unit: GJ / day
Source: Shimoda et al. 2003 (translated).

Figure 3. Standard Composition of a Gas Engine Cogeneration System



Source: Kikegawa et al. 2003 (translated).

It's clear that sensible heat raises the ambient atmospheric temperature and is directly related to the heat island phenomenon. On the other hand, there are different opinions about the impact of latent heat on the heat island trend; making this another point of uncertainty. If the impact of latent heat is much smaller than that of sensible heat, a water-cooled absorption chiller/heater and a gas engine CGS are very effective means of mitigating heat accumulation. But various secondary effects of latent heat's relationship to the heat island phenomenon can be imagined. One is condensation of vapor that is discharged from a water-cooling tower. During this process, the latent heat of the vapor is transformed to sensible heat. Another effect is the increase in humidity and a resulting increase in energy demand for dehumidification. Shimoda et al. assessed the effects of artificial waste heat on the atmospheric environment by the Effective Temperature (ET). ET is a function of temperature, airflow, clothing, and/or metabolism. They calculated the relative magnitude of latent heat to be 0.8 times the daytime sensible heat of Osaka area in August. That means latent heat has an impact comparable to sensible heat.

Another possibility exists in sensible heat of waste hot water. If it is drained to the sea, whose heat capacity is enormous, its impact on atmospheric temperature can be negligible. The Japan District Heating & Cooling Association studied the effects of collecting and disposing of the waste heat from air conditioners in about 2 km^2 area around Tokyo Station by building a duct to Tokyo Bay. This study indicated the maximum temperature would be lowered by 0.4˚C on average (Japan District Heating & Cooling Association 2003). They also examined the impact of waste hot water to the sea on atmospheric temperature and concluded it is negligible compared with the cooling effect. However, it is expected some portion of sensible heat of waste hot water is lost as sensible heat before reaching sewage plants and/or during the processing of the sewage.

Looking within the context of these possibilities, only sensible heat discharged from air-cooled air conditioning systems shows a clear relationship to the heat island phenomenon. The impact of other forms of heat on the heat island phenomenon varies according to the method of assessment.

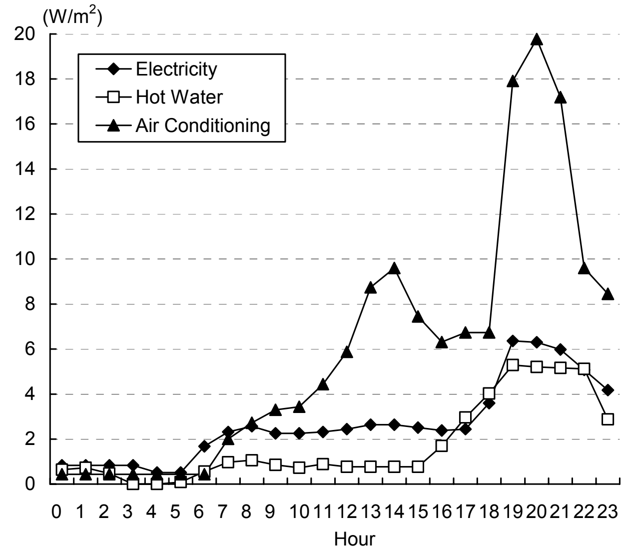
Estimating the Amounts of Waste Heat Discharge from a Model House in Summer

As described earlier, the relationship between energy utilization and the heat island phenomenon is very complicated. In particular, in the commercial sector the ratio of sensible and latent heat changes greatly according to the cooling method employed by heat source devices. In this section, the amount of waste heat discharge from a model house in August is estimated because all of the residential devices are air-cooled and waste heat is discharged as sensible heat. Like in other study, the standard values of demands for energy services as estimated by the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan are used. Unit demand per floor space is shown in Figure 4. Floor space is assumed to be 120 m^2 based on recent averages.

Figure 5 shows the selected energy supplying systems. All of these devices are expected to penetrate in the near future[3]. The efficiencies of the gas water heater, the gas engine CGS, and the heat pump water heater are catalogue values at full-load operation (heat loss from water tank is included in the efficiency of heat pump water heater). The efficiency of the Proton Exchange Membrane (PEM) fuel cell CGS is the target value of technical development by manufacturers and city gas suppliers. Both of the CGSs have 1 kW electric output. Because demand for hot water is smaller in the summer, it is assumed a back-up boiler for hot water supply is not needed.

[3] Gas water heater supposed in this study is an efficient, latent heat recovery-type for a house developed in 2002 Osaka Gas 2003a). COP of a peat pump water heater is annual average and it is more efficient in summer.

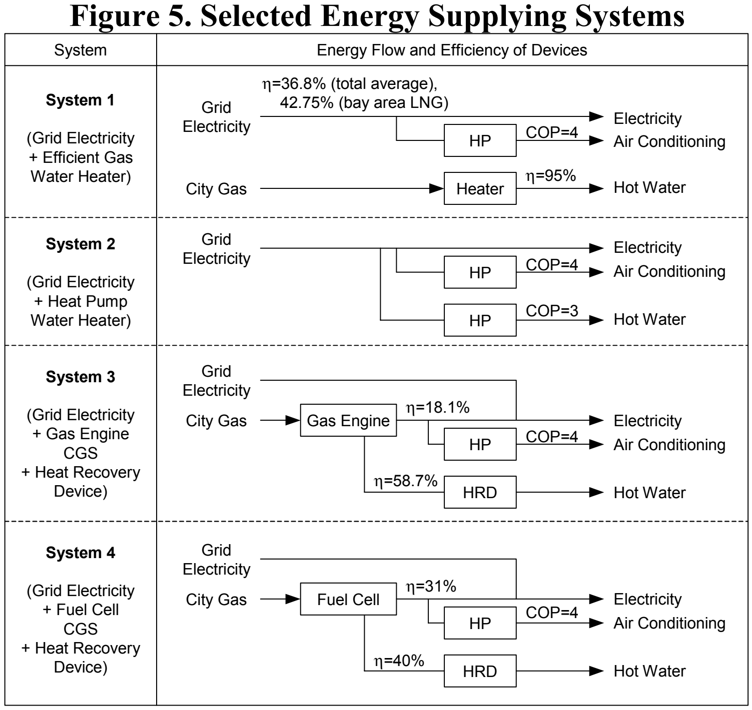
Figure 4. Demand for Energy Services of a Model House (in August, Tokyo Area)



Hour	Electricity	Hot Water	Air Con-ditioning
0	0.84	0.63	0.43
1	0.84	0.72	0.43
2	0.84	0.47	0.43
3	0.84	0.00	0.43
4	0.51	0.00	0.43
5	0.51	0.08	0.43
6	1.67	0.55	0.43
7	2.31	0.97	2.01
8	2.57	1.06	2.72
9	2.25	0.85	3.30
10	2.25	0.72	3.44
11	2.31	0.89	4.44
12	2.44	0.76	5.88
13	2.64	0.76	8.74
14	2.64	0.76	9.60
15	2.51	0.76	7.45
16	2.38	1.69	6.31
17	2.44	2.96	6.74
18	3.60	4.02	6.74
19	6.36	5.29	17.91
20	6.30	5.20	19.78
21	5.98	5.16	17.20
22	5.08	5.12	9.60
23	4.18	2.88	8.46
Total	64.29	42.31	143.32

Unit: W/m^2

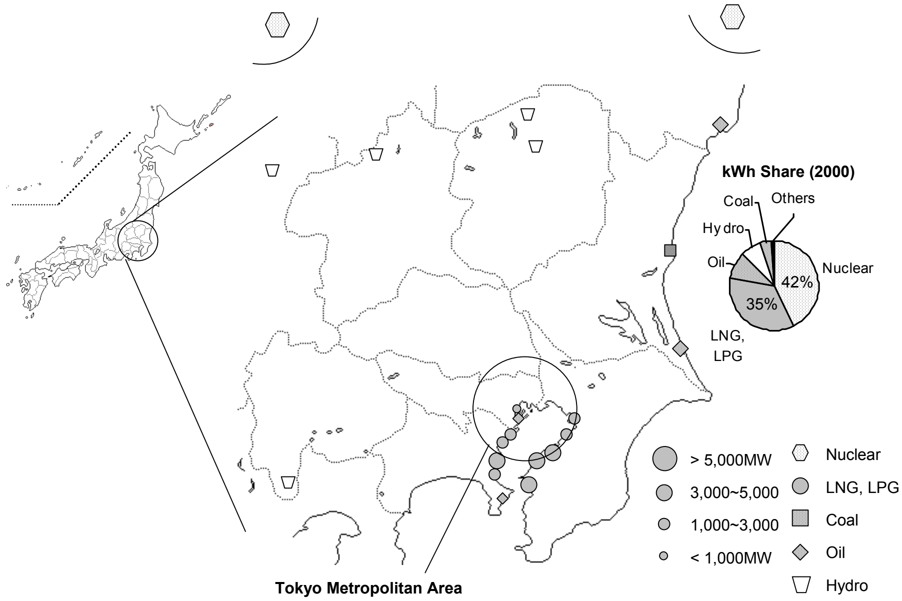
Figure 5. Selected Energy Supplying Systems



Two ways of considering the efficiency of grid electricity are used: one is the average of all power plants and the other is the efficiency of LNG power plants located in Tokyo bay area (Figure 6)[4]. This difference is important in that it allows us to account for the location of waste heat discharge from power plants and the loss of transmission. Overall efficiency of grid electricity is assumed to be 36.8% (=40% for generating and 8% loss for transmitting) for the former case and 42.75% (=45% for generating and 5% loss for transmitting) for the latter case.

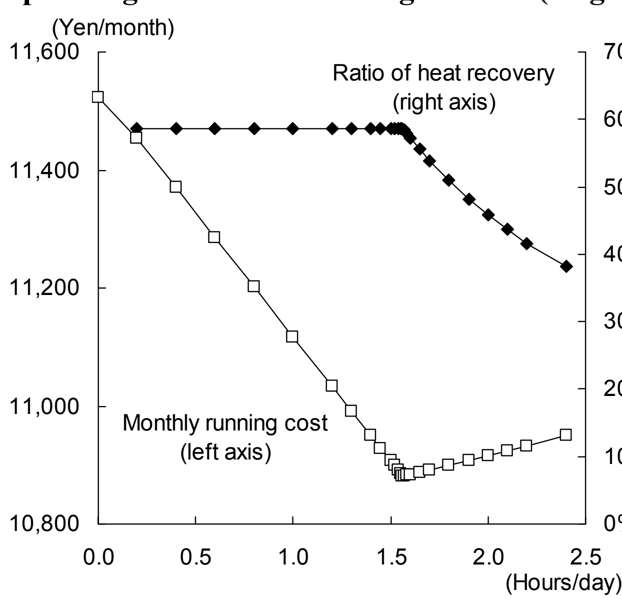
[4] This consideration relates to the discussion of "marginal" power plants. It means the type of power plants whose new construction is postponed will change if CGSs will be installed and demand for grid electricity will decrease.

Figure 6. Locations and Capacities of Large-Scale Power Plants Surrounding Tokyo Metropolitan Area



Operating patterns of CGSs are assumed as follows: for a gas engine CGS, the operating hours are determined so as to minimize total running cost of grid electricity and city gas based on the current rates of Kansai Electric Power Company and Osaka Gas. Total running cost is minimized just before the ratio of waste heat recovery begins to fall (Figure 7). According to the trial calculations by Osaka Gas, the annual average of operating hours is 4.34 hours/day (Osaka Gas 2003b). These estimated operating hours seem appropriate because the demand for hot water in summer is less than the half of annual average and there also is no heating demand.

Figure 7. Total Running Cost and Ratio of Heat Recovery as a Function of Operating Hours of a Gas Engine CGS (August)



Two types of operating patterns are assumed for fuel cell CGS. Because a fuel cell CGS is much more efficient at power generation than a gas engine CGS, the "mono-generation" operation is still economic if the discounted rate of city gas for a gas engine CGS is applied[5]. Therefore, "electricity demand following" and "high heat recovery" operating patterns are assumed. A fuel cell CGS is operated during the hours when the demand for electricity exceeds the technically minimum load (25% of full-load electric output) in the former pattern. In the latter pattern, the operation of a fuel cell CGS is limited from 6 p.m. to 11 p.m. in order to achieve the high rate of waste heat recovery.

Table 3 shows the estimated energy consumption and efficiency of the energy supplying systems. As for energy consumption, a fuel cell CGS in the "high heat recovery" operating pattern (System 4-2) is the smallest on the primary base. This is because both high generating efficiency and waste heat recovery are achieved at the same time. A gas engine CGS (System 3) has comparable CGS efficiency to that of System 4-2; however, it consumes primary energy the most because of low generating efficiency. Overall efficiency has the same tendency: System 2 and System 4-2 have very high efficiency and System 1 follows. This result shows that generating efficiency for a gas engine CGS and the ratio of heat recovery for a fuel cell CGS need to be improved to achieve overall efficiency comparable to those of other energy supplying systems.

Table 4 shows the waste heat discharge from these systems. To calculate the waste heat in the city area, half of all large-scale power plants and total from bay area LNG power plants are counted respectively, considering the kWh share by power plants (see pie graph in Figure 6) and seasonal differences[6].

Table 3. Energy Consumption and Efficiency of a Model House (August)

	System 1	System 2	System 3	System 4-1 (Elec. Follow)	System 4-2 (Heat Recovery)
Secondary Base Total	17.36	13.71	21.09	34.97	22.10
Grid Electricity	12.01	13.71	10.01	1.70	7.48
City Gas	5.34	-	11.08	33.27	14.62
Primary Base Total*1	37.99	37.25	38.29	37.89	34.95
Grid Electricity	32.65	37.25	27.21	4.62	20.33
City Gas	5.34	-	11.08	33.27	14.62
Efficiency of CGS	-	-	63.9%	46.3%	65.7%
Generation	-	-	18.1%	31.0%	31.0%
Heat Recovery	-	-	45.8%	15.3%	34.7%
Overall Efficiency					
All power plant*1	78.9%	80.5%	67.1%	79.1%	85.8%
Bay area LNG*2	89.7%	93.5%	74.5%	80.5%	93.4%

Unit: kWh / day

*1 Based on the average of all power plants (generating efficiency: 40%, loss for transmitting: 8%).

*2 Based on the LNG power plants located on Tokyo bay area (generating efficiency: 45%, loss for transmitting: 5%).

[5] Marginal gas price in summer is 63.46 yen/m^3 for a gas engine-CGS at present, and so the "mono-generation" production cost of electricity is calculated to be 16 yen/kWh. It is cheaper than the normal rates of grid electricity.

[6] The ratio of thermal power plants becomes large in summer and winter when the demand for electricity is large in Japan because nuclear and hydro power plants supply base-load electricity and thermal power plants supply middle and peak-load electricity.

Table 4. Waste Heat Discharge from a Model House (August)

	System 1	System 2	System 3	System 4-1 (Elec. Follow)	System 4-2 (Heat Recovery)
Total (all power plant)*1	37.99	37.25	38.29	37.89	34.95
In city area	21.67	18.62	24.69	35.58	24.78
Outside of city	16.32	18.62	13.61	2.31	10.17
Total (bay area LNG)*2	33.45	32.06	34.50	37.25	32.12
In city area	33.45	32.06	34.50	37.25	32.12
Total (without waste water)*3	14.82	11.17	17.84	28.32	19.18

Unit: kWh / day

*1, *2 Same as *1 and *2 notes of Table 3.

*3 Without total waste heat from large-scale power plants and a half of on-site waste hot water.

The result shows the system using a heat pump water heater (System 2) discharges the least waste heat in the city area, even if bay area LNG power plants are chosen and all of the waste heat from power plants is assumed to be discharged into the city area. If it is supposed that the effect of waste hot water on the heat island phenomenon is extremely small, the superiority of System 2 to other systems increases. On the other hand, the amount of waste heat from a gas engine cogeneration system and a fuel cell cogeneration system are larger than that from the combination of grid electricity and an efficient gas water heater. It seems CGS systems have high potential for increasing waste heat in city areas as compared with other systems. If a subsidy is applied to fuel cell CGSs and gas companies set discounted gas rates for them, then System 4-1 could exist in the near future; however, from the viewpoint of waste heat discharge this outcome is not desirable.

Conclusions

This study examined the characteristics of waste heat from various urban energy supplying systems by the reference survey and energy consumption, also the amount of waste heat from a model house in the summer season was estimated. The results are summarized as follows:

1. The forms of waste heat differ greatly according to the cooling methods of the energy supplying systems in commercial use.
2. There are various theories about the influence of latent heat on the heat island phenomenon.
3. Among the various energy supplying systems for a model house, energy consumption by the fuel cell cogeneration system (high waste heat recovery) is the lowest. On the other hand, the amount of waste heat in discharged into the urban environment by a combination of grid electricity and a heat pump water heater is the lowest.

The results show that heat pump technology can reduce the waste heat considerably and that CGSs can increase the waste heat in the city area in the summer. The main reason is that heat pump water heaters collect atmospheric heat effectively to produces hot water. Therefore, it is desirable to promote the introduction of heat pump water heaters in the buildings sector. Another important point addressed in this paper was the assessment of the distributed energy supplying systems from the viewpoint not only of energy consumption and CO_2 emissions, but also by the form of waste heat and the location where that heat is discharged. I believe the content of this paper will provide valuable information for both policy makers who must tackle the heat island problem, and for city planners who are seeking energy-efficient and environmental-friendly energy supplying systems for their urban areas.

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