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Analysis of Experimental Test Data on the Use of Regional Renewable Energy for Achieving Low-Carbon Campus – Challenging at Kyoto University –

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Greenhouse gas (GHG) reduction from the campus is of considerable concern for every university across the world. In response to this concern, Kyoto University commenced an experimental project involving the use of regional renewable energy including wood pellets made of forest thinning for an air conditioning (AC) system in 2011. The aim of this study was to clarify the effects of the energy savings, GHG reduction, and energy cost of this regional renewable energy. Uji-North Bldg. No. 4, one of the buildings in the Uji campus in Kyoto University, was selected as the object building. Wood pellets and solar heat were used as the regional renewable energy sources. A pellet fired absorption heater chiller (PF-AHC), and a solar heating absorption heater chiller (SH-AHC) using urban gas as supplemental fuel, were introduced in conjunction with an air-cooled heat pump chiller (AC-HPC). This configuration, referred to as ‘the renewable AC system’, was compared to ‘the previous AC system’ using only a direct-fired absorption heater chiller between FY2005 and FY2009.

Our results show that the renewable AC system reduced 50.8% of fossil energy consumption, 52.8% of CO_2 emission, and 36.9% of energy cost compared to the previous AC system. The AC system operations in summer had more impact on these results than winter operation, because the cooling load accounted for 72.9% of the annual load. PF-AHC and SH-AHC (SH), which used renewable energy sources, contributed to only 7.4% of annual CO_2 emission while they supplied 16.9% of the annual cooling and heating load. However, our analysis also implies that PF-AHC must be managed carefully because the cost of wood pellets created a trade-off relationship between environmental and economical aspects. Going forward, optimal planning of summer operations of the renewable AC system will be considered.

Keywords: Sustainable campus, Greenhouse gas, Renewable energy, Energy cost, Wood pellet, Air conditioning system, Case study

1. Introduction

Achieving sustainable campus has been proposed across the world, and many universities have laid out ambitious targets including greenhouse gas (GHG) reduction. For instance, Yale University set a target in 2005 to reduce campus GHG emission to 10% below 1990 level by the year 2020, a 43% reduction from 2005 level[1)]. Yale University actually achieved 7% reduction in FY (fiscal year) 2008 from FY2005 despite a 3.2% increase in its campus size. It was reported that reduction in power plant emissions was the main driver of the GHG decrease, as the University increased the efficiency of on-campus energy production and distribution, with the largest reduction in GHG emission attributed to a switch to natural gas[1)]. In Japan, national universities have been obliged to publish and open their environmental reports since FY2005, after the establishment of the Environmental Consideration Law. The total amount of GHG emission from universities in Japan was estimated to be 1.69–1.86 million t-CO_2/y between FY2005 and FY2007[2)]. Greenhouse gas (GHG) reduction at the campus is of considerable concern for every university.

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Air conditioning (AC) systems in campus buildings are often the focus of efforts to save energy and reduce environmental impacts. Oda et al.[3)] estimated power consumption for AC at a building in the University of Tokyo Institute of Technology by developing a discontinuity and nonlinear programming model, which used the change of ambient temperature and could divide the total power consumption between the AC and other uses. They concluded the model could describe estimated consumption for the AC system with reasonable accuracy by using ambient temperature. In other words, ambient temperature is implied to be an important parameter. Yanagihara et al.[4)] reported the actual data with regards to AC system operation, such as running load, at a building of the University of Tokyo in the summer season. Then, Kindaichi et al.[5)] simulated energy consumption using LCEM (Life Cycle Energy Management) and concluded that a reduction of 70 t-CO_2/y would be achieved in the building in summer by reducing the number of operating AC equipment and the operating pattern of secondary pump. The University of Tokyo launched TSCP project (Todai Sustainable Campus Project) with a target to reduce 15% of CO_2 emission from non-laboratory sector in FY2012 compared to that in FY2006[6)].

Kyoto University established a target in 2007 of continuously reducing CO_2 emissions and energy consumption by 2% (per floor area) every year[7)]. 1% of the reduction is achieved by installing more efficient equipment or managing facilities efficiently, and another 1% is achieved by increasing awareness of constituent members. However, GHG emission in Kyoto University was approximately 90 kt-CO_2/y in 2010, which equalled an increase of 7.9% in total (3.5% per floor area) compared to the previous year[8)]. Further efforts were necessary to achieve the target.

Therefore, Kyoto University commenced an experimental project involving the use of regional renewable energy including wood pellets made of forest thinning for an AC system in FY2011. This regional renewable energy project is one of the case studies for environmental management in Kyoto University. We focused on wood resources because three quarters of Kyoto City is forest area, and it was estimated that 48 million ton of forest thinning is generated annually[9)]. Although most of them are currently unused, regional renewable resources such as forest thinning are effective in achieving GHG reduction and fossil energy savings in the medium and the long term. The aim of this study was to clarify the energy savings and GHG reduction achieved in this project.

2. Materials and Methods

2.1 Buildings and air conditioning system

Uji-North Bldg. No. 4, one of the buildings in the Uji campus, was selected as the object building in this project. Uji campus is one of the campuses in Kyoto University located in the Uji City, approximately 15 km south of Kyoto city, Kyoto Prefecture. Table 1 shows relevant information for Uji-North Bldg. No. 4.

Table 2 shows the actual specifications of the AC equipment that is or was used in the building, all of which cools or heats the building through cyclic water. The fuel used to cool or heat is different among the various pieces of AC equipment. Before FY2009, only a direct-fired absorption heater chiller (DF-AHC), which used urban gas (UG) as the fuel, was run as the AC system in Uji-North Bldg. No.4; we call this AC system ‘the previous AC system’ in this study. An air-cooled heat pump chiller (AC-HPC) was added to the system in FY2010. Then, after this experimental project was launched in June 2011, wood pellets and solar heat were used as the renewable energy sources for the AC system. Therefore, the pellet fired absorption heater chiller (PF-AHC) and the solar heating absorption heater chiller (SH-AHC) were operated in conjunction with AC-HPC. The use of DF-AHC was discontinued after FY2011. In this study, we refer to this renewed AC system as ‘the renewable AC system’ and compare it with the previous AC system.

Wood pellet used in this project was produced within Kyoto City. This local production drives the environmental load lower than the imported wood pellet because of reduced transportation distance. Reduced transportation costs and CO_2 emissions are benefits of regional renewable energy resources.

The installation area of the solar panel was 54 m^2, and SH-AHC consumed urban gas as supplemental fuel if it was not sunny or the cooling/heating load was larger than the solar heating capacity. SH-AHC was analysed separately according to fuel source and described as either SH-AHC (SH) or SH-AHC (UG) in this study.

Table 1 Information of Uji-North Bldg. No. 4

Structure	Reinforced Concrete
Scale	4 Floors (above ground)
Completion Year	1979
Ground Floor Area	4,757 m^2
Gross Floor Area	8,617 m^2
Departments	Institute of Advanced Energy, Graduate School of Energy Science
Number of Users	Approximately 70

Table 2 Specification of Air Conditioning Equipment

Equipment		Energy Consumption			Cooling and Heating Power	COP*[8]
		Urban Gas	Electricity	Wood Pellet		
		(Nm^3/h)	(kW)	(kg/h)	(kW)	(-)
DF-AHC*[1]	C*[5]	47.2	6.85	-	426	0.80
	H*[6]	50.7	6.85	-	423	0.74
AC-HPC*[2]	C	-	49.2	-	211	4.29
	H	-	61.2	-	185	3.03
SH-AHC*[3] (Solar heat)	C	-	2.25	-	50	0.80
	H	-	2.25	-	59	0.95
SH-AHC (Urban gas)	C	11.8 / 17.3*[7]	2.25	-	256	1.31
	H	11.8 / 17.3	2.25	-	168	0.86
PF-AHC*[4]	C	-	1.27	22.2	117	1.05
	H	-	1.27	22.2	92	0.83

*1 Direct fired absorption heater chiller, *2 Air-cooled heat pump chiller, *3 Solar heating absorption heater chiller, *4 Pellet fired absorption heater chiller, *5 Cooling, *6 Heating, *7 11.8: Both urban gas and solar heat consumed case, 17.3: Only urban gas consumed case, *8 Coefficient of performance.

2.2 *Operation control and monitoring*

In order to use as much renewable energy as possible, the operation order in the renewable AC system was set as follows: 1) SH-AHC (SH), 2) PF-AHC, 3) AC-HPC, and 4) SH-AHC (UG). First, the maximum number of working AC units was determined according to required cooling and heating load in the building. Then, the actual number of working AC units was decided based on the outlet temperature of cyclic water in each unit.

An operating period between April 2011 and the next March was regarded as one year's data (as FY2011). The AC system was used for cooling from June through October, and used for heating from November through May. The monitoring data on monthly, daily, and hourly fuel consumption of each AC unit was obtained in the renewable AC system. We could divide the monitoring period into four periods as shown in Table 3 according to the operating mode of the PF-AHC when seasonal variation was considered. However, the detailed result of the cooling with preference mode was excluded since monitoring started after September. The timing for PF-AHC to start to run can be controlled using the outlet temperature of cyclic water. In the preference mode, its temperature at which PF-AHC start to run was set by 5 degrees higher than that in the saved mode in order to promote pellet consumption. With regard to the previous AC system, only monthly data could be obtained and the average between FY2005 and FY2009 was used as the system input.

It was assumed that the compositions of the monthly load of each AC unit in April (heating) and from May to June (cooling) 2011 equalled those in November (heating) and September (cooling) 2011 respectively. The loads supplied by each unit were estimated by allocating in proportion to the compositions in every month, because the renewable AC system started to operate in June 2011 and therefore there were no actual monthly data from April to June 2011.

Table 3 Operating mode of the PF-AHC

Cooling / Heating	Cooling		Heating	
Operating mode	Preference	Saved	Saved	Preference
Period	Jun. 16 to Aug. 9 2011 (46 days)	Aug. 10 to Nov. 30 2011 (113 days)	Jan. 1 to Jan. 31 2012 (31 days)	Feb. 10 to Mar. 31 2012 (51 days)

* December was excluded from this table since operating mode was irregular because of the exhaust gas sampling.

2.3 *System boundary*

Figure 1 describes the system flow of the PF-AHC cooling and heating system. The wood pellet was made of forest thinning from the forest area within Kyoto City. Thinning, transportation, and pellet production processes were included in considering the case of PF-AHC. The transportation and landfill of the ash residue after the combustion use of wood pellets were also considered. The round-trip distances from forest to the wood pellet production facility and from the facility to Uji-North Bldg. No. 4 were assumed to be 100 km and 60 km respectively. However, the production processes of every AC unit were not included in this study.

With respect to the fossil fuel consumption, the system boundary from the raw material extraction to fuel production to the combustion use was considered.

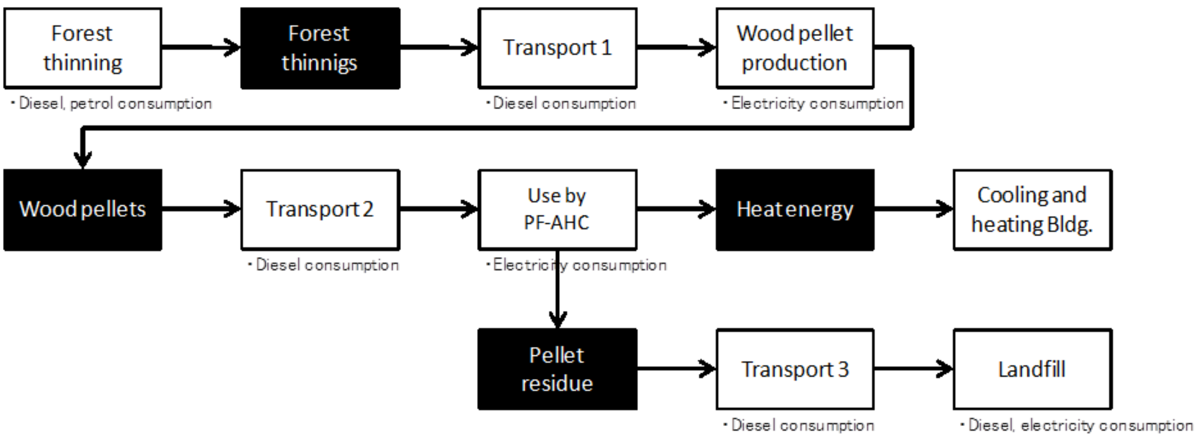

Fig. 1 System Flow of PF-AHC Cooling and Heating (Black coloured boxes: Product and energy, White coloured boxes: Process.)

2.4 *Indicators and their estimated methods*

The important parameters and units of each piece of AC equipment are shown in Tables 4 and 5 respectively. The definitions of indicators and their estimated methods are explained below.

2.4.1 *Cooling and heating load*

Cooling and heating load means supplied or removed amount of energy for cooling and heating by the AC equipment. At first, the monthly cooling and heating loads were estimated (Eq. (1)) because they were different between the AC systems and would have an effect on the energy consumption, CO_2 emission and energy cost.

2.4.2 Running load rate

Amount of cooling and heating load supplied by each piece of AC equipment depends on the power of each unit. For instance, AC-HPC can supply 4.2 times as large cooling load as SH-AHC (SH) (See the COP value in Table 2). Therefore running load rate was defined as Eq. (2) in this study and estimated in order to figure out the performance against their specification.

2.4.3 Fossil fuel consumption

The use of renewable energy would contribute to the saving of fossil energy and CO_2 reduction. Therefore, the amount of fossil energy consumption was considered as the evaluation indicator. The unit of $U_{i,fe}$ calculated similarly as to the previous study[10)] was used for the estimation (Eq. (3)). As mentioned earlier, not only the use (combustion) but also other processes such as the production processes were considered within the system boundary.

2.4.4 CO_2 emission

Amount of CO_2 emission was also estimated by the following Eq. (4). The unit of U_{i,CO_2} calculated similarly as to the previous study[10)] was used for the estimation. Note that CO_2 emissions derived from biomass combustion (waste forest thinning and wood pellets) were ignored because biomass is considered to be a carbon-neutral energy source.

2.4.5 Energy cost

Both the environmental and economical aspects of the AC operation were important to the project. The type of fuel used was different between AC units, and the cost of used fuels was considered and estimated by Eq. (5) as energy cost although it was desired to quantify the total cost. That was because initial cost had some uncertainty due to the lack of actual introduced examples and the maintenance cost for the previous and renewable AC systems was considered to be equal.

$$L_i^t = F_i^t \times CF_i \times COP_i / E \qquad (1)$$

$$Rr_i^t = (L_i^t / Rt_i^t) / Pch_i \times 100 \qquad (2)$$

$$Cons_{i,fe}^t = L_i^t \times U_{i,fe} \qquad (3)$$

$$Emis_{i,CO_2}^t = L_i^t \times U_{i,CO_2} \qquad (4)$$

$$Cost_{i,energy}^t = L_i^t \times U_{i,cost} \qquad (5)$$

i	: Type of AC equipment (DF-AHC, AC-HPC, SH-AHC, or PF-AHC)	-
L_i^t	: Cooling and heating load of AC equipment *i* at term *t*	[kWh]
F_i^t	: Amount of fuel consumption for AC equipment *i* running at term *t*	[kg], [Nm^3], [kWh]
CF_i	: Heat conversion factor of the fuel for AC equipment *i* running	[MJ/kg], [MJ/Nm^3], [MJ/kWh]
COP_i	: Coefficient of performance of AC equipment *i*	[kW/kW]
E	: Secondary energy conversion factor	[MJ/kWh]
Rr_i^t	: Running load rate of AC equipment *i* at term *t*	[%]
Rt_i^t	: Running time of AC equipment *i* at term *t*	[h]
Pch_i	: Cooling and heating power of AC equipment *i*	[kW]
$Cons_{i,fe}^t$	: Amount of fossil fuel consumption of AC equipment *i* at term *t*	[MJ]
$Emis_{i,CO_2}^t$	: Amount of CO_2 emission of AC equipment *i* at term *t*	[t-CO_2]
$Cost_{i,energy}^t$	: Amount of energy cost of AC equipment *i* at term *t*	[yen]
$U_{i,fe}$	: fossil energy consumption unit of AC equipment *i*	[MJ/ kWh]
U_{i,CO_2}	: CO_2 emission unit of AC equipment *i*	[t-CO_2/kWh]
$U_{i,cost}$	: Energy cost unit of AC equipment *i*	[yen/kWh]

Table 4 Important parameters used in this study

Category		Value	Unit	Reference
Energy	Primary energy conversion factor	9.76	MJ/kWh	11)
	Secondary energy conversion factor	3.60	MJ/kWh	12)
Heat conversion factor	Urban gas	45.0	MJ/Nm^3	13)
	Wood pellet	18.0	MJ/kg	14)
CO_2 emission factor	Electricity	0.555	kg-CO_2/kWh	15)
	Urban gas	0.067	kg-CO_2/MJ	15), 16)
Fuel price	Wood pellet	41.0	[yen/kg]*1	*2
	Urban gas	74.7	[yen/Nm^3]	*2
	Electricity	13.0	[yen/kWh]	*2

*1 yen = 77.5 $ = 100.3 € (September 28, 2012), *2 Hearing.

Table 5 Units of each AC equipment

		Energy consumption	CO_2 emission	Energy cost
		$U_{i,fe}$	U_{i,CO_2}	$U_{i,cost}$
		[MJ/kWh]	[kg-CO_2/kWh]	[yen/kWh]
DF-AHC*1	C*5	4.66	0.31	7.5
	H*6	5.03	0.33	8.1
AC-HPC*2	C	2.10	0.13	3.0
	H	2.97	0.18	4.3
SH-AHC*3 (Solar heat)	C	0.41	0.025	0.0
	H	0.34	0.021	0.0
SH-AHC*4 (Urban gas)	C	2.83	0.19	4.6
	H	4.32	0.29	6.9
PF-AHC*5	C	0.90	0.058	7.8
	H	1.04	0.068	9.9

*1 Direct fired absorption heater chiller, *2 Air-cooled heat pump chiller, *3 Solar heating absorption heater chiller, *4 Pellet fired absorption heater chiller, *5 Cooling, *6 Heating.

3. Results and Discussion

3.1 Cooling and heating load

Estimated results of the cooling and heating loads are shown in Fig. 2(a). The total amount of load and seasonal tendency were not so different between the previous and the renewable AC systems. The annual total loads in the previous and renewable AC system were estimated to be 824.0 and 859.3 MWh, respectively. From the viewpoint of seasonal tendency, the result indicated that operating in summer was more important since the cooling load was considerably higher than the heating load. The cooling load accounted for 72.9% of the total load in the renewable AC system.

The load composition of the AC equipment shown in Fig. 2(b) revealed that AC-HPC annually accounted for 53.7% of the total load. That was because the power and COP of AC-HPC were the highest of the AC equipment. PF-AHC and SH-AHC (SH), which used the renewable energy source, could supply 15.9% and 1.0% of the annual load respectively. 30 t/y of wood pellet was used for annual PF-AHC running as listed in Table 6. The load compositions of PF-AHC in winter months were higher than those in other months. This result implies that the heating load can be provided by only the PF-AHC and AC-HPC, without the SH-AHC (UG). Wood pellet consumption with saved mode in months such as September and January could be actually saved as intended. The use of SH-AHC (UG) should be saved from the viewpoint of environment because the unit $U_{i,fe}$

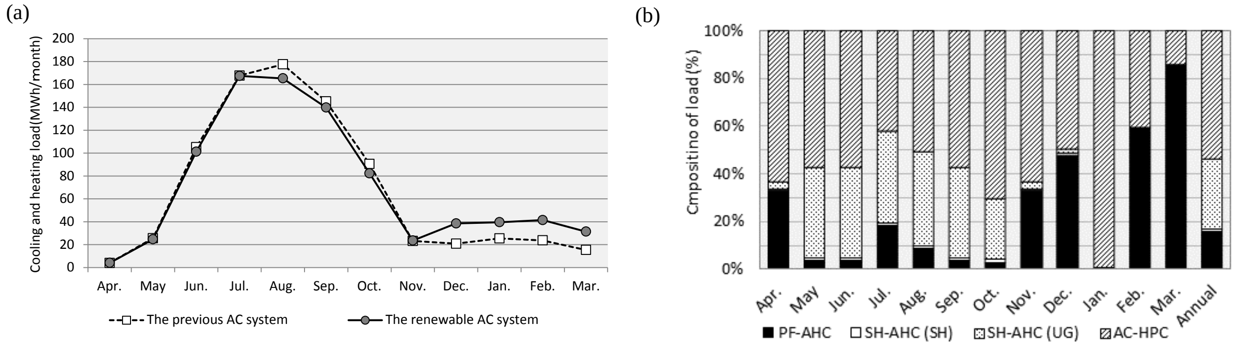

Fig. 2 Estimated result of (a) cooling and heating load, (b) its composition of each equipment in the renewable AC system

Table 6 Amount of monthly wood pellet consumption [t/month]

Apr.*	May*	Jun.*	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Annual
0.3	0.2	0.7	5.8	2.8	1.0	0.5	1.9	4.4	0.0	5.9	6.5	30.0

* estimated value.

and U_{i,CO_2} were the highest of the equipment in the renewable AC system and SH-AHC (UG) still consisted of 29.4% of the total load.

3.2 Running load rate

The running load rates according to the different PF-AHC operating modes were shown in Figs. 3(a), (b) and (c). In the cooling with saved mode, PF-AHC still showed high running load rate on the day when it operated (Fig. 3(a)). From this, we deduced that the required cooling load could only be supplied by operating all of the AC equipment, though the heating load could be supplied by PF-AHC and AC-HPC. In the heating with saved mode, PF-AHC could be saved as intended (Fig. 3(b)). The running load rate showed high performance in the heating with preference mode (Fig. 3(c)).

SH-AHC (SH) barely operated after November, although the running load rate showed 10–30% between September and October. Insufficient solar radiation after November appeared to be the cause, and the monitoring data implied that SH-AHC (SH) could not provide useful performance in winter.

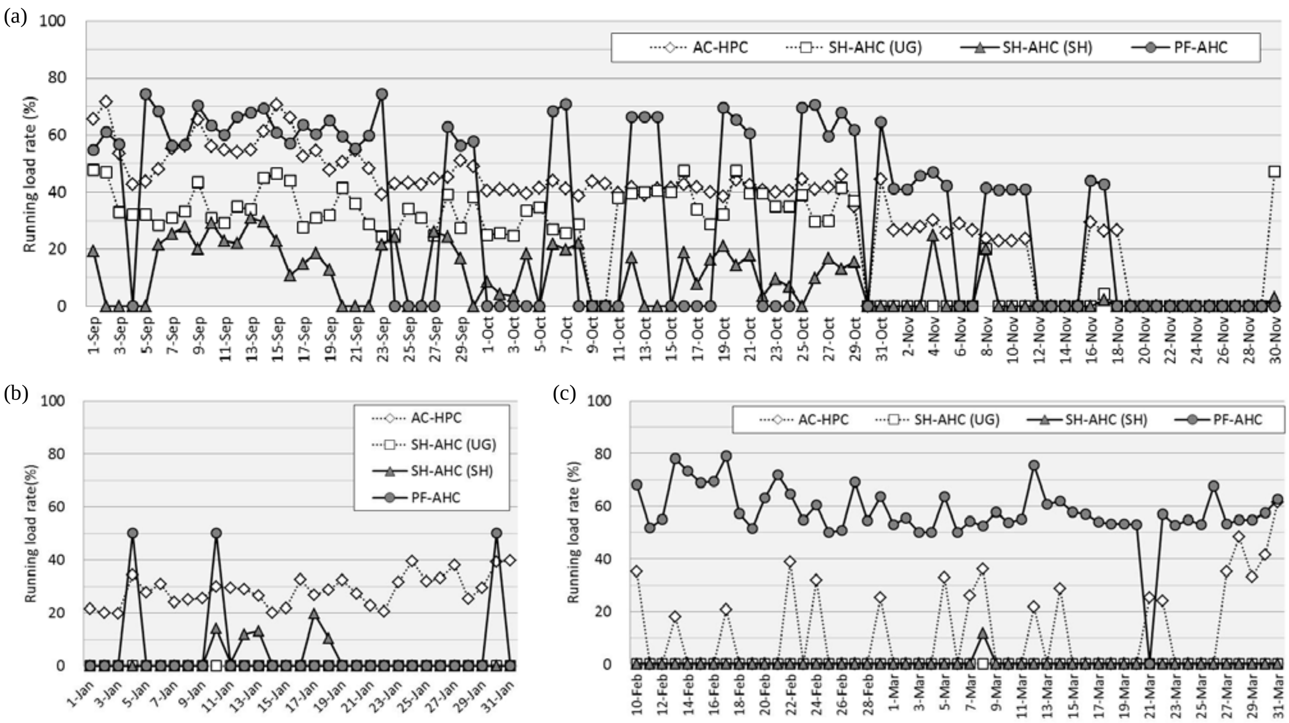

Fig. 3 The results of running load rate with the each PF-AHC operating mode
(a) Cooling with save mode of PF-AHC : Sep. 1 to Nov. 30, (b) Heating with save mode of PF-AHC: 1 to 31 Jan., (c) Heating with preference mode of PF-AHC: 10 Feb. to 31 Mar.

3.3 *Fossil energy and CO_2 emission*

The amounts of fossil energy consumption and CO_2 emission in the renewable AC system were estimated to be 1,909 GJ/y and 121.5 t-CO_2/y respectively (Figs. 4(a) and 5(a)). The renewable AC system appears to be especially successful in reducing both fossil energy consumption and CO_2 emission in summer months. Compared to the previous AC system, a reduction of 1,972 GJ/y and 135.7 t-CO_2/y could be realised; in other words, a reduction of 50.8% of fossil fuel consumption and 52.8% of CO_2 emission could be achieved.

Figures 4(b) and 5(b) show the composition of fuel consumption for each piece of AC equipment in the renewable AC system. Notably, PF-AHC and SH-AHC (SH), which used renewable energy sources, contributed only 7.4% of annual CO_2 emission while they supplied 16.9% of the annual cooling and heating load. The fossil fuel composition in summer was more significant than that in winter because of the greater overall AC requirements in summer. Therefore, the impact of PF-AHC in winter was small although PF-AHC appeared to have higher proportion of fossil energy consumption and CO_2 emission in winter months than in other months. Most amounts of fossil-derived energy consumption and CO_2 emission attributed to PF-AHC were derived from the wood pellet production process.

The AC-HPC had good COP performance and high power rating. Therefore, it was expected to be difficult to shift the entire supply source from AC-HPC to the renewable AC equipment when the capacity of equipment and energy costs were considered. On the other hand, the COP of SH-AHC (UG), which accounted for 29.4% of the annual cooling and heating load, was comparable with the renewable AC equipment. In addition, the unit $U_{i,fe}$ and U_{i,CO_2} of SH-AHC (UG) were largest of the AC equipment. Therefore, fossil energy consumption and CO_2 emission might be reduced if the use of SH-AHC (UG) could be saved by using PF-AHC.

3.4 *Energy cost*

Figure 6(a) shows the estimated result of energy cost. Annual energy cost was estimated to be approximately 3.9 million yen and equalled a decrease by 36.9% (2.3 million yen) compared to the previous AC system. Only the unit $U_{i,cost}$ of PF-AHC was larger than that of DF-AHC in the previous AC system, and the annual load composition of PF-AHC accounted for 31.4%. Energy cost in winter in the renewable AC system was expected to be more expensive than that in the previous AC system because most of energy cost in these months was derived from wood pellet consumption as shown in Fig. 6(b).

Only energy cost was included in this study. Initial and maintenance costs are also important expenses for AC systems and need to be considered in further study.

3.5 *Trade-off relationship between environmental and economical aspects*

The price of wood pellet was more expensive than the other fuels, although PF-AHC contributed to the reduction in fossil energy consumption and CO_2 emission. PF-AHC would still have some potential to reduce CO_2 emission if it had no saved mode operating, however, full time operations would also increase energy costs.

The energy cost was actually increased by 0.9% if the

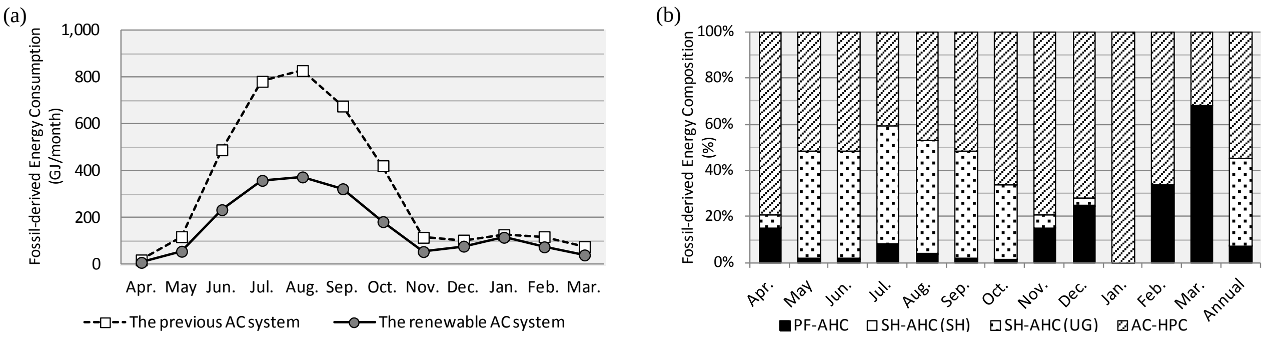

Fig. 4 Estimated result of (a) fossil energy consumption, (b) its composition of each equipment in the renewable AC system

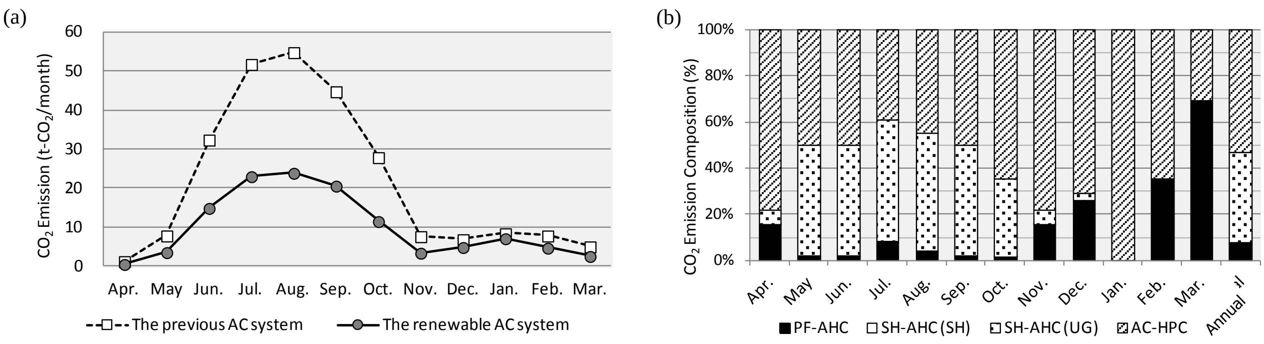

Fig. 5 Estimated result of (a) CO_2 emission, (b) its composition of each equipment in the renewable AC system

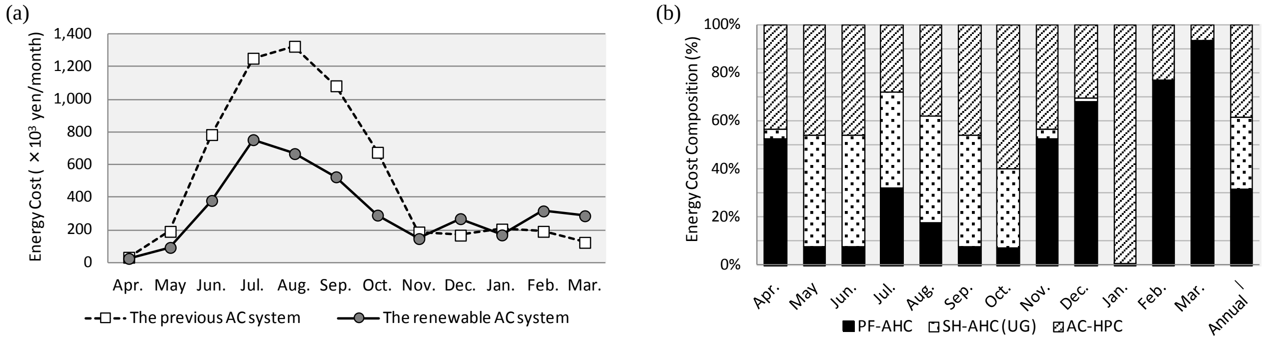

Fig. 6 Estimated result of (a) energy cost, (b) its composition of each equipment in the renewable AC system

renewable AC system was compared to the AC system using DF-AHC and AC-HPC in the immediately previous year, 2010. This was one of the reasons that saved mode operations were used for the PF-AHC for several intervals. Although our results seem to show that the renewable AC system has both environmental and economical benefits, the use of wood pellet for PF-AHC has a potential economical trade-off for the reduced CO_2 emission, and this trade-off should be considered carefully.

4. Conclusions

Kyoto University commenced an experimental project involving the use of regional renewable energy including forest thinning for an air conditioning (AC) system in FY2011. The aim of this study was to clarify the energy savings and greenhouse gas reduction achieved in this project.

Our conclusions at this study are:

・The renewable AC system can reduce 50.8% of fossil energy consumption, 52.8% of CO_2 emission and 36.9% of energy cost compared to the previous AC system.

・The AC system operations in summer were more important than those in winter, because the cooling load accounted for 72.9% of the annual load.

・PF-AHC and SH-AHC (SH), which were used for renewable energy sources, contributed to only 7.4% of annual CO_2 emission and supplied 16.9% of the annual cooling and heating load.

・However, our results also imply that PF-AHC must be managed carefully because the high price of wood pellets creates a trade-off relationship between environmental and economical aspects.

Going forward with the first year of data, optimal planning of renewable AC system operations in summer will be considered. Some external factors have to be considered, because the cooling and heating load is influenced by conditions such as temperature, humidity, and solar radiation. The potential of solar heating will also need to be clarified, as in this case, solar heating failed to be useful in winter owing to insufficient solar radiation. Scale of the building and AC equipment are significant factors. Cooling and heating demands and its daily trends have to be described in advance when the renewable AC system is put to practical use. Cooling and heating power of renewable AC equipment will have effect on environmental and economical aspects.

A life cycle cost perspective will be important when the total economical effects of the AC system are evaluated. A way to consider not only energy cost but also initial cost needs to be developed. In addition, other environmental aspects not addressed in this study, such as NO_x, SO_x, and PAHs emissions, should be also considered when the use of wood pellet is promoted.

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