Technical Assessment of a Hybrid Solar-geothermal System Including Adsorption Refrigerator for Energy Supply to Restaurants in Smart City

Ruixi ZHAO, Masakuni WATAKI, Daiki YOSHITOME, Andante Hadi PANDYASWARGO, Hao HU, Hiroshi ONODA*

Graduate School of Environment and Energy Engineering, Waseda University, Japan
*Corresponding author: onoda@waseda.jp

Abstract CO_2 emissions from restaurants have increased over the past five years in Japan. As a result, countermeasures such as hybrid heat source systems that use renewable energy have gained increasing attention. In this paper, we assessed the efficiency of a hybrid solar-geothermal heat system including an adsorption refrigerator during its use in providing energy for air conditioning and hot water. We presented an energy prediction formula based on measured data on solar heat collection, cooling, and heating load. We also documented our evaluation of the performance of each component of the solar-geothermal heat system, i.e. the solar collector, adsorption refrigerator, and geothermal heat pump. And finally, we presented a case study on the use of this system in restaurants in a smart energy town in Japan. On solar collector, this study found that the heat collection efficiency during sunny and mostly sunny conditions were 28%. This percentage dropped to 23% for cloudy conditions and 11% for rainy conditions. On adsorption refrigerator, the Coefficient of Performance (COP) in summer was found to be lower than in autumn. On geothermal heat pump, the COP was found to be 4.5 during the cooling period and 4.3 during the heating period. Overall, the highest values for both energy consumption and energy utilization occurred in August, and the utilization efficiency was lower in winter than in summer. Moreover, the average annual energy utilization efficiency of the total system was 59.02%, while the Annual Performance Factor (APF) was 2.082. This study contributes to decision making and academic researches regarding the planning and implementation of energy-efficient cooling and heating system.

Keywords: *solar, geothermal, adsorption refrigerator, CO_2 reduction, APF, COP*

Cite This Article: Ruixi ZHAO, Masakuni WATAKI, Daiki YOSHITOME, Andante Hadi PANDYASWARGO, Hao HU, and Hiroshi ONODA, "Technical Assessment of a Hybrid Solar-geothermal System Including Adsorption Refrigerator for Energy Supply to Restaurants in Smart City." *American Journal of Civil Engineering and Architecture*, vol. 6, no. 5 (2018): 199-205. doi: 10.12691/ajcea-6-5-5.

1. Introduction

As of 2015, renewable sources (excluding hydroelectric power) constituted 14.6% of Japan's total generated energy, and this figure is predicted to rise to 22-24% by 2030. Since 2012 (the year of Feed in Tariff (FIT) introduction in Japan) until 2016, the residential, non-residential, and geothermal energy sources have contributed 4.5 billion kW, 27.5 billion kW, and 10 thousand kW respectively. [1]

In recent years, the Japanese government has actively been implementing CO_2 emission mitigation strategies, with the aim to reduce 26% emissions of 2013 by 2030. [2] And according to the latest report from the Japanese Ministry of the Environment, CO_2 emissions totaled 1.3 billion tons in 2016, which is a 4.6% decrease from 2005. However, the civilian sector accounted for 19% of emissions in 2016, which constitutes a 0.8% increase from 2005. [3] This increase in CO_2 emissions in the civilian sector was mainly generated by facilities such as office

buildings, retail businesses, restaurants, hotels, schools, and hospitals.

Hybrid heat source systems is one example of the countermeasures designed to combat this increase in CO_2 emissions from civilian sector facilities. Solar-based renewable energy systems are reported to be able to convey electricity, heat water, and provide space heating and cooling and they are suitable on-site generation of renewable energy. [4-15] In the civilian sector, these systems are highly suitable options for restaurants, as that can partially cover restaurants' energy needs.

Herein, we evaluate the energy saving capabilities of an efficient hybrid heat source system that uses a combination of solar and geothermal energy. Furthermore, the adsorption refrigerator is included for cooling. We study the use of this system in restaurants in Honjo smart energy town, Saitama prefecture, Japan. And we developed an energy prediction formula by analyzing data on the solar heat collection, cooling, and heating load capabilities of the hybrid heat source system. The system we feature here has three key components: the solar

collector, the adsorption refrigerator, and the geothermal heat pump, and we evaluated the performance of each of these components.

Several studies have analyzed the performance capabilities of heat source systems [16,17,18,19], but we believe that our study is original in several aspects. Firstly, while other studies have considered large-scale retail stores [20], here we explored the possibility of using renewable energy in medium and small sized restaurants. Secondly, previous studies on renewable energy in Japan have focused on ground source heat pump (GSHP) systems (e.g. heat router and geo-heat pump systems) or solar energy systems. In this study however, we considered a hybrid solar-geothermal system. Furthermore, our system includes an adsorption refrigerator. Finally, previous studies have not attempted to predict energy demand and the duration of any assessment has been short. [21] In this paper, however, we developed a prediction formula that supports our system evaluation.

To the best of our knowledge, this study documents the first Japanese-based, renewable energy-sourced heat supply system for multiple medium and small sized restaurants. In addition, the system presented here contributes energy towards to air conditioners Fan Coil Unit (via its adsorption refrigerator and heat pump), and provides hot water by using solar heat, which is more efficient than solar electricity. Additionally, a thermal heat pump system was provided as a backup to provide heat supply.

The paper is structured as follows. The hybrid solar and thermal heat system was described in Section 2. Section 3 presented the formula prediction of energy needed through multiple regression analysis. Section 4 provided discussions and evaluations of the system. Finally, conclusions were drawn in Section 5.

2. Hybrid Solar-geothermal Heat System

The hybrid solar-geothermal system featured in our study includes an adsorption refrigerator. It employs solar heat, which is abundantly available, and geothermal heat, which has a more stable temperature than above-ground sources. Together, these components improve both the energy supply and the efficiency of the system. In addition, the adsorption refrigerator helps to cool the underground temperature by cooling water in summer, which enhances the system's efficiency.

The system is designed with a centrally configured solar collector with an attached adsorption refrigerator, and the boreholes for geothermal heat collection are located underground. Details are illustrated in Figure 1. And this system is applied for 3 shops that are medium and small sized restaurants.

All of the machines in each shop are connected to the heat conduit, and the air conditioners are supplied by energy from the geothermal heat pump (Figure 2). The adsorption refrigerator, which uses water warmed by solar heat as a heat source, cools the heat gathering and radiating pipe. And the adsorption refrigerator is set to stop functioning when the temperature of the input warm water falls below 55°C in winter. Geothermal heated warm water is used as a backup source to the conventional hot water supplied by the solar collector.

The primary monitoring data is obtained from an energy service company that remotely manages the system. Variables such as external air temperature, pipe temperature, pipe pressure, and input heat are measured every minute by thermometers, calorimeters and pressure gauges. The facility has been checked annually, and the details are illustrated in Table 1. For this study, we have mainly analyzed data collected during 2015 and 2016.

In this study, we applied this heat source system to the restaurants of Honjo smart energy town, which is located in Honjo Waseda area, Saitama prefecture, Japan. This town has been designed as a smart community that makes full use of natural resources such as solar energy, thermal energy, and biomass. The urban planning follows collaboration between industry, academia, and the government, and includes Waseda University (Honjo campus), Honjo city, and its associated enterprises. The smart energy town is centered around Honjo Waseda station (on the Joestu-Shinkansen Line), which is surrounded by residential areas and commercial facilities, including restaurants. These restaurants are the target for our heat source system experiment. Shop A (Conveyor belt Sushi restaurant), located east of the solar collector is only provided with hot water supply, whereas shops B (Chinese food restaurant) and Shop C (Italian food restaurant) also have access to the geothermal heat pump and located north (see Figure 3).
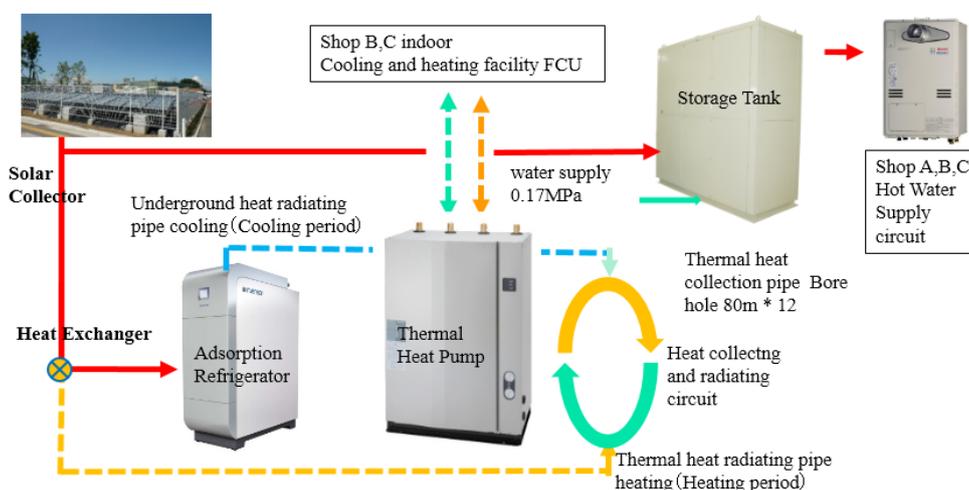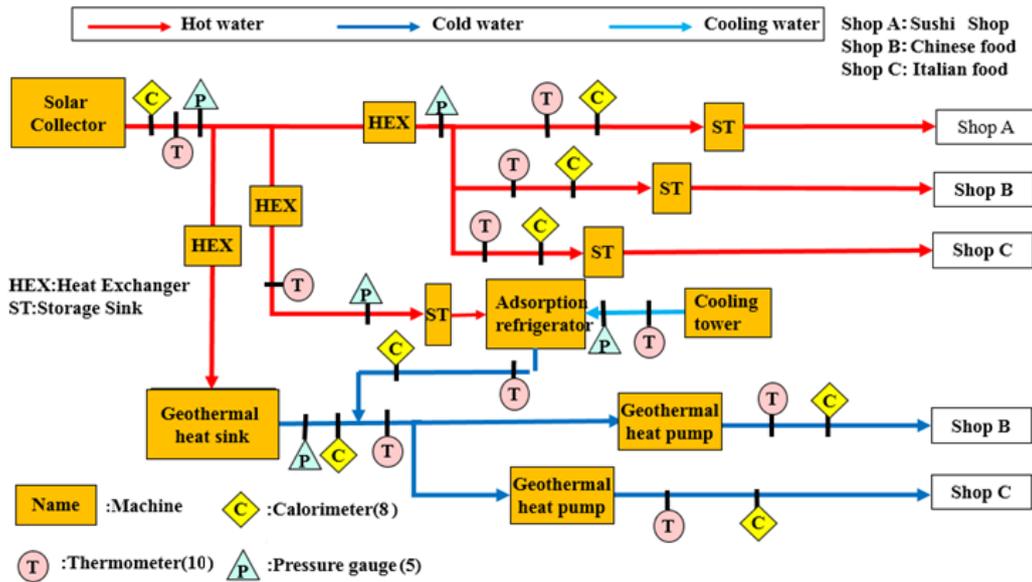

Figure 1. System outline

Figure 2. System flow

Table 1. Description of devices.

Place	Wasedanomori, Honjo, (Saitama)	Hot-water supply facility	Solar heat, Gas water heater (LPG)
Use	3 shops, hot-water supply and air conditioning	Air conditioning equipment	Geothermal HP , Adsorption type refrigerator (by Solar heating)
Store Area	□ 300 m²	Geothermal HP	30 kW × 4
Borehole	80m × 12	Heat storage tank	1500 L × 3
Solar panel	190.4m² × 16	1 Adsorption type refrigerator	10(4-14) kW
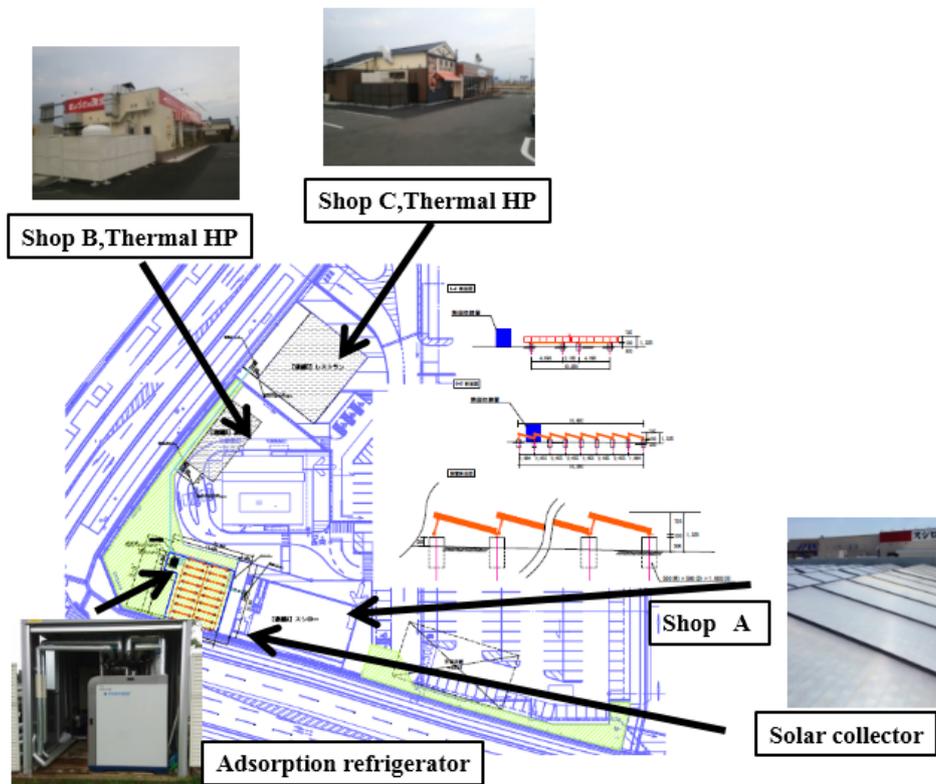
Figure 3. Arrangement drawing of restaurant district in Honjo smart energy town

3. Prediction Formula of Energy Demand

We developed our formula for predicting energy demand by conducting multiple regression analysis on measured data. Specifically, we treated the quantity of heat collection by the solar collector as an objective variable, while the weather was treated as an explanatory variable. As a result, a regression formula was created for each weather variable due to unsatisfied conditions according to a stepwise method.
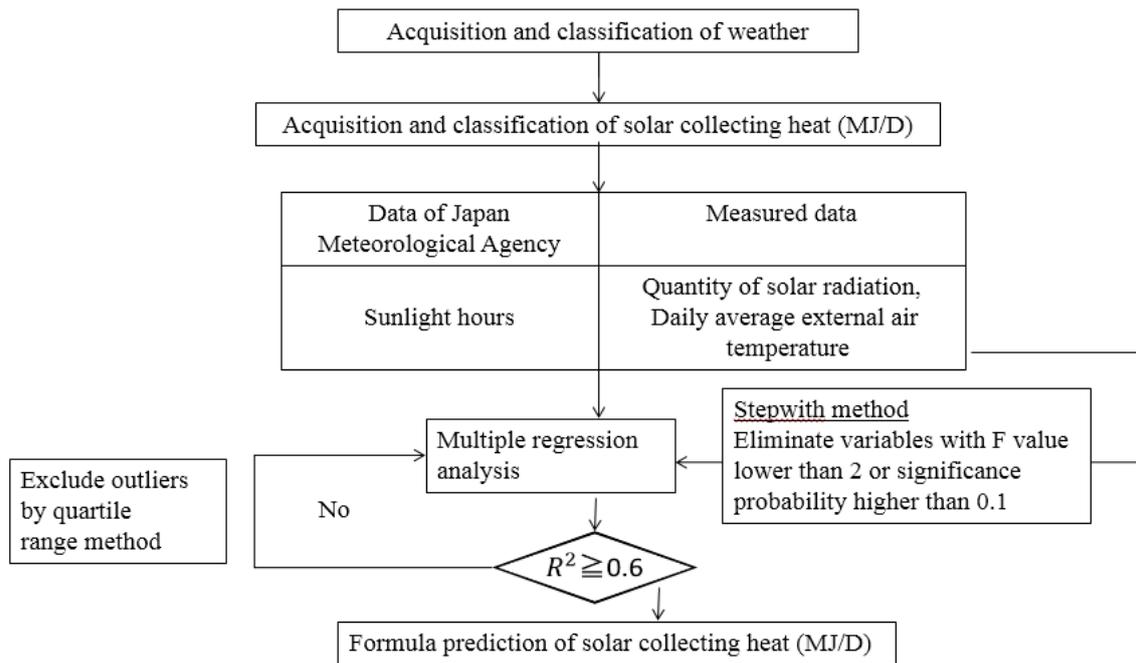
Figure 4. Deriving flow of prediction formula of solar heat collection

As illustrated in Figure 4, we firstly divided the weather into four categories: sunny, mostly sunny, cloudy, and rainy, solar radiation are recorded from 06:00 to 18:00 each day. We also utilized data on the calorie capacity of the solar collector, the quantity of solar radiation, daily average external air temperature, and number of sunlight hours per day (recorded by the Japan Meteorological Agency). We then established a formula for estimating calorie capacity of solar collector by eliminating variables that did not meet conditions according to the stepwise method, and then judging the coefficient of determination through regression analysis. Filtering out outliers using an inter-quartile range method made it possible to calculate the annual quantity of heat collection (the solar collector) through a number of days of each weather type, and we estimated their quantity of heat collection per day based on our regression formula. We conducted multiple regression analysis on data from the year 2016. In equation (1), y is the quantity of heat collection by the solar collector (MJ/d), x1 is the solar radiation (MJ/d), x2 is the average daytime external air temperature (°C), a1 and a2 are coefficients, and a0 is the segment. The calculated coefficients of determination (R^2) are around 0.9 of the measured and estimated data, which is relatively accurate (see Table 2).

$$y = a_1 x_1 + a_2 x_2 + a_0. \qquad (1)$$

Table 2. Result of Regression Analysis

Weather	a1	a2	a0	R^2	t	
					a1	a2
Sunny	0.348	0	-148.9	0.895	20.48	0
Mostly Sunny	0.388	-8.894	-101.3	0.879	22.34	-4.349
Cloudiness	0.38	-6.241	-104.2	0.941	40.85	-5.238
Rain	0.391	-5.826	-90.2	0.925	19.83	-3.568

We found the correlation between the power capacities of the adsorption refrigerator and two other variables (the quantity of heat collection by the solar collector and the daytime average external air temperature). We defined the cooling period, intermediary period, and heating period according to average daytime external air temperature (i.e. from 06:00-18:00), and deduced the prediction formula of cooling and heating loads through multiple regression analysis. The coefficient of determination (measured and estimated data) is 0.744, which again is relatively accurate.

4. Evaluation of the System

4.1. Evaluation of Each Machine

We analyzed the heat collection efficiency of solar heat collector, the Coefficient of Performance (COP) of adsorption refrigerator and geothermal heat pump. The heat collection efficiency of the solar heat collector is calculated through the equation (2). As shown in Figure 5, regarding its relation to weather, we found out that during both sunny and mostly sunny conditions the efficiency is 28%, and the percentage dropped to 23% in cloudy conditions and 11% in rainy conditions. Meanwhile, as illustrated in Figure 6, heat collection was at its most efficient in February (32.4%), and was the least efficient in November (16.7%), whereas the quantity of heat collection by solar collector was the highest in May (32,670 MJ) and the lowest in November (7,260 MJ). In details, shown in Figure 7, January had the highest proportion of sunny and mostly sunny weather conditions (July had the lowest), so, the high heat collection efficiency in February was likely a result of the large heat quantity collected by the solar collector and the clear weather. Meanwhile, the low efficiency in November was the lowest due to the small quantity of heat collection by the solar collector and the

inclement weather. In addition, the annual average of daily heat collection efficiency was 26.85%.

$$\eta h = \frac{Qh}{Qs}. \qquad (2)$$

Regarding the adsorption refrigerator, we assessed the COP by using equation (3). Here Pc (MJ) is electricity consumption multiplied by 3.6, Qh (MJ) is input power from hot water, Qc (MJ) is input power from cold water, and Qp (MJ) is output power. The calculation of Q is shown in equation (4), where ρ is water density (1000 kg/m^3), C is the specific heat capacity of water (4.187 kJ/kg°C),is quantity of flow (m3/h), and is the temperature variation of water flow across the whole refrigeration component (°C). Equation (5) shows the calculation of (m^3/h), in which Ac is pipe's cross-sectional area, and P is its internal stress (Pa). In April, May, and June, the COP is lower than the rated value, while in August, September, and October it is higher (Figure 8). The average COP over the whole duration of the experiment was 0.3350.

$$COP = \frac{Qp}{Pc + Qh + Qc} \qquad (3)$$

$$Q = pc\,\dot{m}\,\Delta t \qquad (4)$$

$$\dot{M} = 0.6Ac\sqrt{\frac{2 \times P}{\rho}} \qquad (5)$$

The geothermal heat pump system was employed in both a cooling and a heating capacity. The geothermal heat pump system's COP in summer was lower than that in winter because the temperature at the entrance to the heat-collecting component was higher than the daily average external air temperature in summer (see Figure 9). The measured COP was 2.943 (estimated value: 4.5) during the cooling period, while the measured data was 4.6 (estimated value: 4.3) during the heating period. Meanwhile, the Annual Performance Factor (APF) of this system in 2016 was 2.836 by following the equation (6), in which P is annual output (MJ), and Pc (MJ) is annual electricity consumption.

$$APF = \frac{P\ annual}{Pc\ annual}. \qquad (6)$$

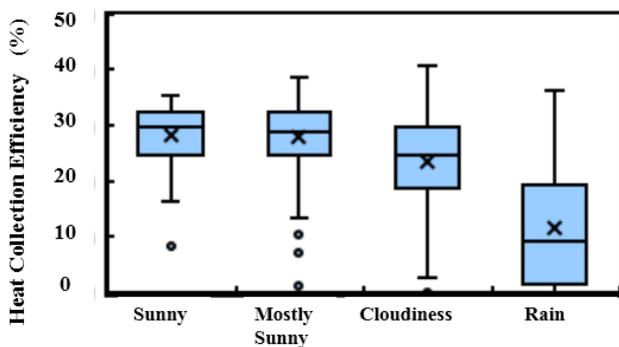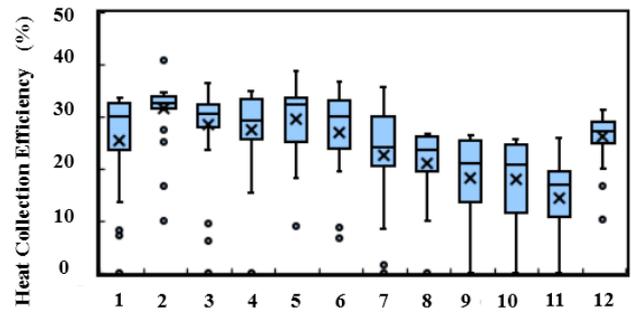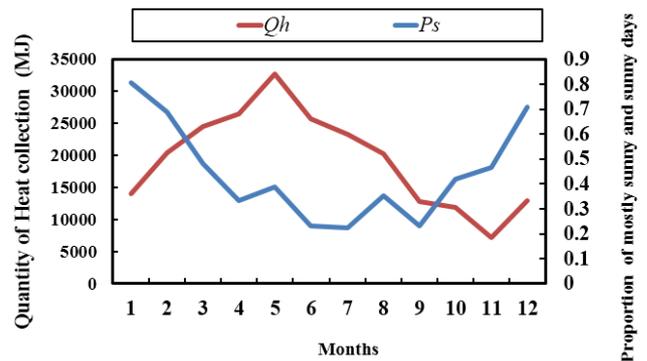**Figure 6.** Heat collection efficiency of solar collector

Figure 7. Quantity of solar heat collection (Qh) and Proportion of sunny and mostly sunny days by months
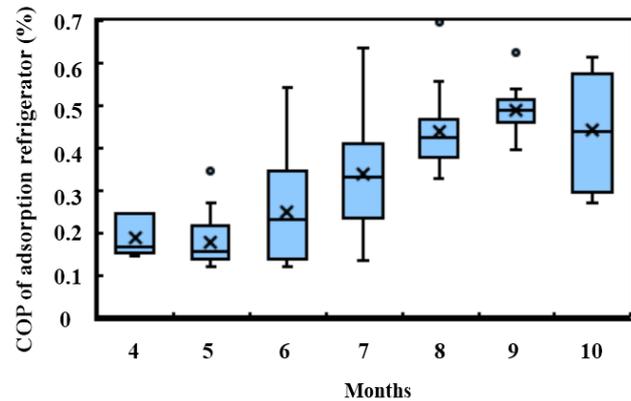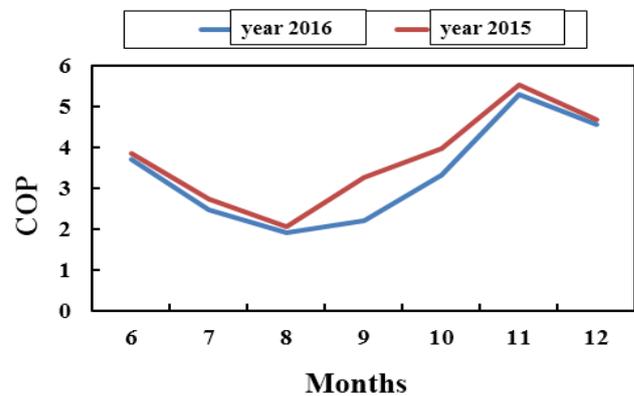

Figure 8. COP of adsorption refrigerator

Figure 9. COP of geothermal heat pump

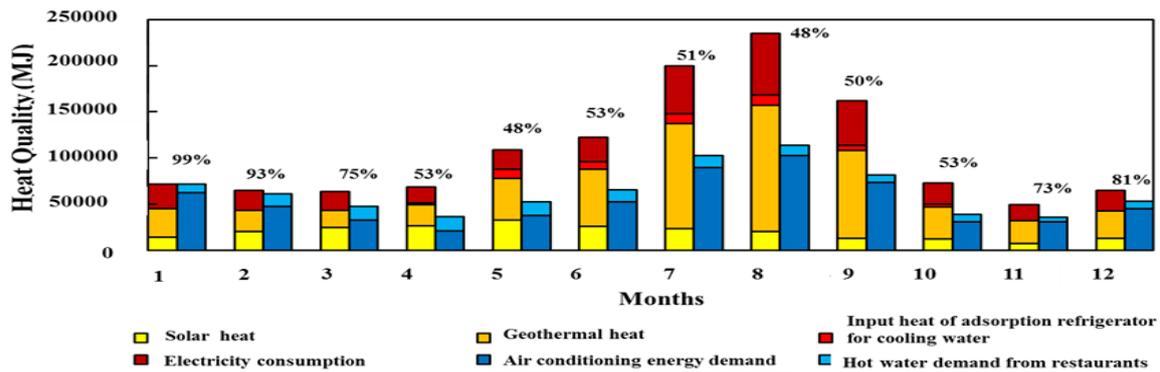**Figure 5.** Relationship between weather and main heat efficiency

Figure 10. Total system energy consumption

4.2. Overall Evaluation of This System

The energy consumption and energy utilization efficiency of the whole system in year 2016 were calculated and shown by months in Figure 10. The left bar graphs illustrate the energy supply (including renewable energy), and the right bar graphs indicate the energy demand. And the percentages show the energy utilization efficiency.

Analyzing the performance of the system as a whole, the highest values for both energy supply (235,226 MJ) and demand (113,461 MJ) occurred in August, with the energy utilization efficiency at 48.24%. And, looking at the overall, energy utilization efficiency was lower in summer than that in winter. The average annual energy utilization efficiency of the total system was 59.02%, while the APF was 2.082.

5. Conclusion

In this study we developed prediction formulas and estimated the energy demand of a hybrid solar-geothermal system (including adsorption refrigerator) by using measured data. In addition, we also conducted system performance analysis of each of the system's components. We found that the quantity of heat collection by the solar collector, the cooling and heat load, and the power capacity of its adsorption refrigerator are influenced by the average external air temperature. Furthermore, we showed that the quantity of heat collection by the solar collector affects the cooling and heating load, and the hot water supply load. Based on these findings, we were able to evaluate measured solar, adsorption refrigerator and geothermal heat data, which enabled us to define parameters such as COP and APF. On solar collector, this study found that the heat collection efficiency during sunny and mostly sunny conditions were 28%, which dropped to 23% for cloudy conditions and 11% for rainy conditions. On geothermal heat pump, the Coefficient of Performance (COP) was found to be 4.5 during the cooling period and 4.3 during the heating period. And on adsorption refrigerator, the COP in autumn was found to be higher than in summer. Furthermore, the average annual energy utilization efficiency of the total system was 59.02%. And the Annual Performance Factor (APF) was 2.082. This study contributes to decision makers and academic researchers understanding, planning, and implementing such systems to other smart communities.

References

[1]   Ministry of Economy, Trade and Industry, Japan, "Topics towards introducing renewable energy in Japan Report", 2018.

[2]   Ministry of the Environment, Japan, "GHG mitigation goal of Japan Report", 2018.

[3]   Japanese Ministry of the Environment, "GHG emission report in year 2016 (preliminary value)", 2018.

[4]   D.S.G., M. Maria, A.F.C. Fortes, R.P.G. deSouza, J.A.M. Silva, M. Carvalho, et al., "Carbon footprints for the supply of electricity to a heat pump: Solar energy vs. electric grid", *Journal of Renewable and Sustainable Energy*, 10 (2), 2018.

[5]   Sujala Bhattaraia, Jae-Heun Ohb, Seung-Hee Euha, Gopi Krishna Kaflea, DaeHyun Kim, "Simulation and model validation of sheet and tube type photovoltaic thermal solar system and conventional solar collecting system in transient states", *Solar Energy Materials and Solar Cells*, 103, 184-193, 2012

[6]   H. Getu, H. Philip, and M. Mark, "Seasonal sand-bed solar thermal energy storage in a region with extended freezing periods: Experimentally verified numerical simulation", *Journal of Renewable and Sustainable Energy*, 9(6), 2017.

[7]   International Energy Agency, "Technology roadmap, Solar photovoltaic energy", 2010. https://webstore.iea.org/technology-roadmap-solar-photovoltaic-energy-2014.

[8]   María Herrando, Christos N Markides, Klaus Hellgardt, "A UK-based assessment of hybrid PV and solar-thermal systems for domestic heating and power: System performance", *Applied Energy Journal*, 161, 512, 2016.

[9]   Chow TT. "A review on photovoltaic/thermal hybrid solar technology". *Applie Energy,* 87. 365, 2010.

[10] SA Kalogirou and Y. Tripanagnostopoulos. "Hybrid PV/T solar systems for domestic hot water and electricity production Energy Convers Manage", 47(18-19). 3368-3382, 2006.

[11] C. Cristofari, J. Canaletti, G. Notton, C.Darras, "Innovative patented PV/TH Solar Collector: optimization and performance evaluation", *Energy Procedia*, 14. 235-240, 2012.

[12] E. Halawaa K. C. Changb M. Yoshinagac, "Thermal performance evaluation of solar water heating systems in Australia, Taiwan and Japan – A comparative review", *Renewable Energy*, 83, 1279-1286, 2015.

[13] SA.Kalogirou, "Solar thermal collectors and applications", *Renewable Energy,* 30(3), 231-295, 2004.

[14] S. Tselepis and Y. Tripanagnostopoulos, Design aspects of hybrid Pvt/Water solar systems, 19th European Solar Energy Conference and Exhibition 7-11 June 2004, Paris, France

[15] J. Freemana I., Guarracinoa, S. A. Kalogiroub, C. N. Markidesa, "A small-scale solar organic Rankine cycle combined heat and power system with integrated thermal energy storage", *Applied Thermal Engineering*, 127. 1543-1554, 2007.

[16] Alba Ramosab Maria Anna Chatzopouloua James Freemana Christos N. Markidesa, "Optimisation of a high-efficiency solar-driven organic Rankine cycle for applications in the built environment", *Applied Energy*, 228. 755-765, 2018.

[17] María Herrandoab Christos N. Markidesa, "Hybrid PV and solar-thermal systems for domestic heat and power provision in the UK: Techno-economic considerations", *Applied Energy,* 161, 512-532, 2016.

[18] M. Beccali, P. Finocchiaro, and Nocke B., "Energy and economic assessment of desiccant cooling systems coupled with single glazed air and hybrid PV/thermal solar collectors for applications in hot and humid climate", *Solar Energy*, 83(10),1828-1846, 2009.

[19] M Herrando and C.N. Markides, "Hybrid PV and solar-thermal systems for domestic heat and power provision in the UK: Techno-economic considerations", *Applied Energy,* 161, 512-532, 2016.

[20] H. Shun and K.Nagano, Design and evaluation of one of the largest ground source heat pump systems in a large scale retail store. *Journal of Environmental Engineering*, 80 (709). 249-258, 2015.

[21] Mikako Maeta, Akihito Ozaki, "Study on Central Space Conditioning System of Residential Buildings with Air Circulation Utilizing Solar Heat", *The society of heating, air-conditioning and sanitary engineers of Japan,* A-10, 37. 2013.