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# Application of a heat source system using solar energy with hot water storage

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**Abstract**. To increase the adoption and value of solar heat energy, a heat source system was designed and constructed that consists of a large-capacity water thermal storage tank, water source heat pump unit, and waste heat recovery chiller. This heat source system contributes to energy savings and to maintaining the function of a building when infrastructure is unavailable at the time of a disaster. This system was installed in a high school in Tokyo, Japan, and its effectiveness was verified. Actual results indicated that it operates at high efficiency with an average COP of 6.8 and full utilization of solar heat throughout the year. The actual annual usage of solar heat was about 103% that of the simulation at design time. The annual primary energy consumption was reduced by approximately 45% compared to that of an ordinary high school in Japan.

## 1. Introduction

In Japan, a country that is short on natural resources, the utilization of renewable energy is one of the most important issues. Increasing the rate of renewable energy use, including solar energy, is part of the government of Japan's Strategic Energy Plan for 2030. Studies of using solar energy for air conditioning in Japan have been conducted since the 1970s. However, until now, a heat source system using solar energy has not become widespread owing to the initial cost and energy instability. Today, there are still problems such as how to eliminate the unstable energy supply, which is easily influenced by the weather. To increase the use of such a solar energy system, it is necessary to apply and demonstrate its functionality with the goals of increasing stability and the amount of utilization in an actual building.

The purpose of this research is to increase the value of solar heat energy by constructing a heat source system using solar energy with hot water storage. A demonstration and evaluation were conducted using an actual building. While solar heat is clean energy, fossil fuel energy is often used as well in order to ensure stability. Since Japan has four seasons, the demand for heating and hot water in offices and schools is low in spring, summer, and autumn, and their value tends to be lower during these seasons. Therefore, this research focused on a heat source system that consists of a large-capacity thermal water storage tank, a water source heat pump unit, and a waste heat recovery chiller to solve the abovementioned challenges. This heat source system can be used throughout the year, increasing the utilization of solar heat. The system effectiveness was confirmed from actual measured values.

## 2. Architectural outline

Figure 1 and Table 1 show an outline of the school buildings to which the heat source system was applied. These high school buildings were introduced to an advanced environmental technology in a classroom, auditorium, and gymnasium.

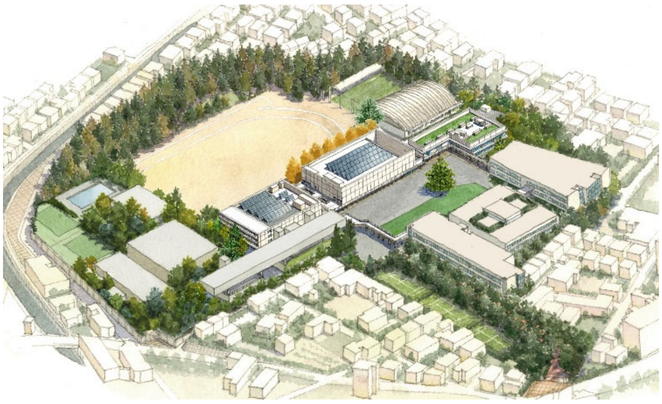

**Figure 1.** Aerial view of school buildings.

**Table 1.** Architectural outline.

| | |
|---|---|
| Building area | Approx. 56,000 $ft^2$ (5,200 $m^2$) |
| Total floor area | Approx. 93,600 $ft^2$ (8,700 $m^2$) |
| Structure | Reinforced concrete/steel |

The building is constructed of exposed reinforced concrete, arranged as seen in Figure 2. Figure 3 shows a sectional view of the auditorium, where a double wall structure is used to create an optimal acoustic environment. Acoustic insulation is installed on the inside of the external slab. As shown in Figure 4, the interior walls of the auditorium are made of exposed concrete covered with an acoustic material, and many inclined panels have been carefully placed so that sound reverberates for about 1.2 s.

Figure 5 shows flat-plate-type solar heat collectors installed on the rooftop of the auditorium. A 150-kW solar heat collector and 40-kW solar photovoltaic system are installed on the rooftop of the auditorium and gymnasium, respectively. The total roof area is approximately 6,500 $ft^2$ (600 $m^2$). This system can provide energy savings in normal times, while providing resiliency in times of disaster.

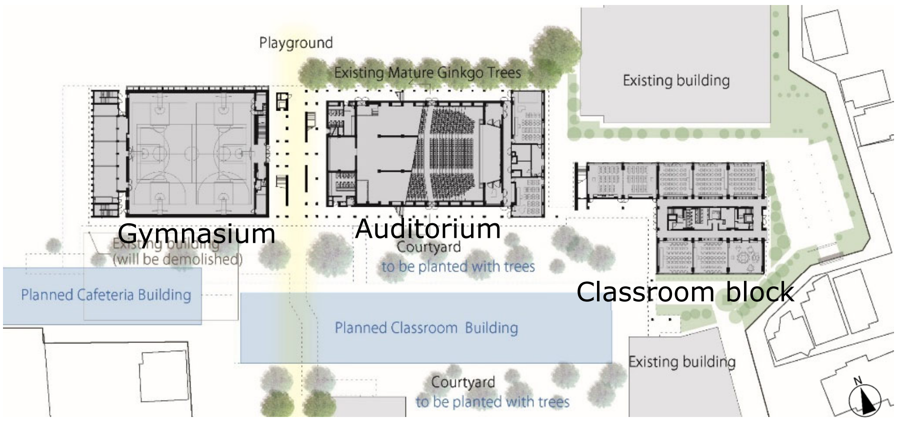


**Figure 2.** Plan.

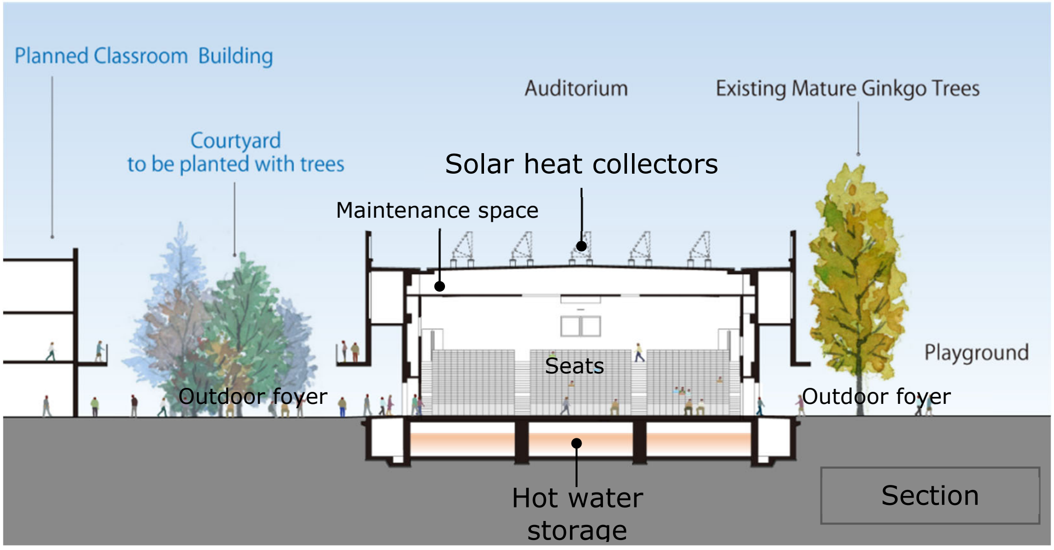


**Figure 3.** Section of auditorium.

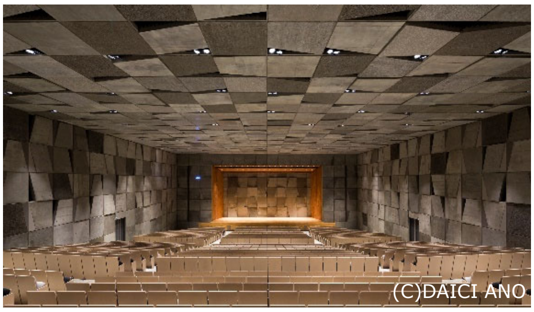


**Figure 4.** Auditorium interior.

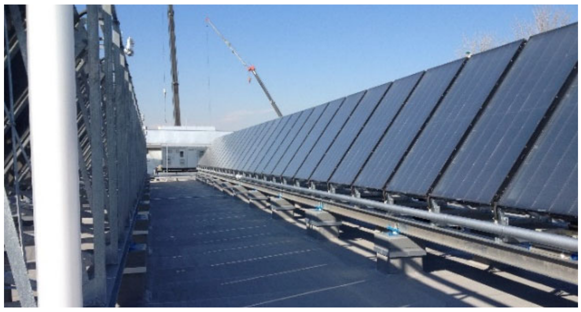

**Figure 5.** Solar heat collectors.

## 3. Outline of heat source system

The heat source system consists of solar heat collectors and high-capacity thermal storage tanks with low-to-moderate- and high-temperature capability. By installing these appliances, solar energy can be stored for a long time and utilized stably in large quantities. The central heat source system is applied to the air conditioners in the auditorium and gymnasium. Figure 6 shows a diagram of the system. During the summer, hot water at 194°F (90℃) is utilized by the waste heat recovery chiller to produce cooling water. In the winter, solar heat [approximately 62.5ºF (17℃)] is stored in a thermal storage tank [26,500 $ft^3$ (750 $m^3$)] installed in an underground pit, and is used by the water heat source pumps as heat source water. The efficiency of the heat pump system was expected to increase by about 20% when utilizing solar energy. [1]

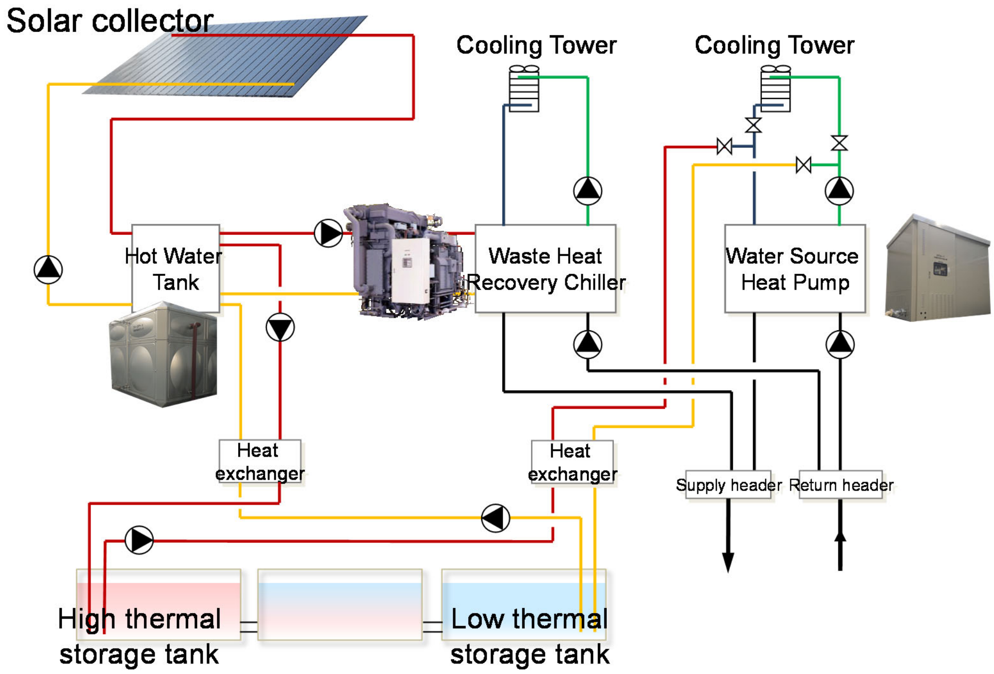


**Figure 6.** Diagram of the air-conditioning system.

## 4. Selection of solar collectors

When the solar collector system was designed, a higher priority was given to efficiency in the winter rather than in the summer. In the summer, water source heat pumps can be used as an alternative heat source for the waste heat recovery chiller, and the primary energy COP is over 1.8. On the other hand, in the winter, a gas-absorption heater is the alternative heat source of the water source heat pumps for heating, and the primary COP is, at most, 0.8. Therefore, if adequate solar heat is not collected, the efficiency in the heat source will be lower in winter than in summer, which means that as much heat as possible needs to be collected in the winter. Because of this, the solar collectors were installed at an angle of 55°, which enables more heat to be collected in the winter, corresponding to the low solar altitude. In addition, it was determined that these solar collectors should be of the flat-plate type, which works more efficiently than evacuated tube solar collectors at low temperatures.

## 5. Direct and indirect use of solar energy

In this system, solar heat is collected at a low or moderate temperature and indirectly used for heat source water. However, it is possible for solar heat to be maintained at a high temperature and directly used in another way. Diagrams of direct and indirect use of solar energy are shown in Figure 7. There is usually a time gap between when solar heat can be collected and when the heating load occurs. Figure 8 shows a distribution map of the relationship between the heating load and heat collection, based on a schedule planned during the design phase for use of the gymnasium. This implies that a heating system is not required for several time slots, even though solar heat can be collected at that time.

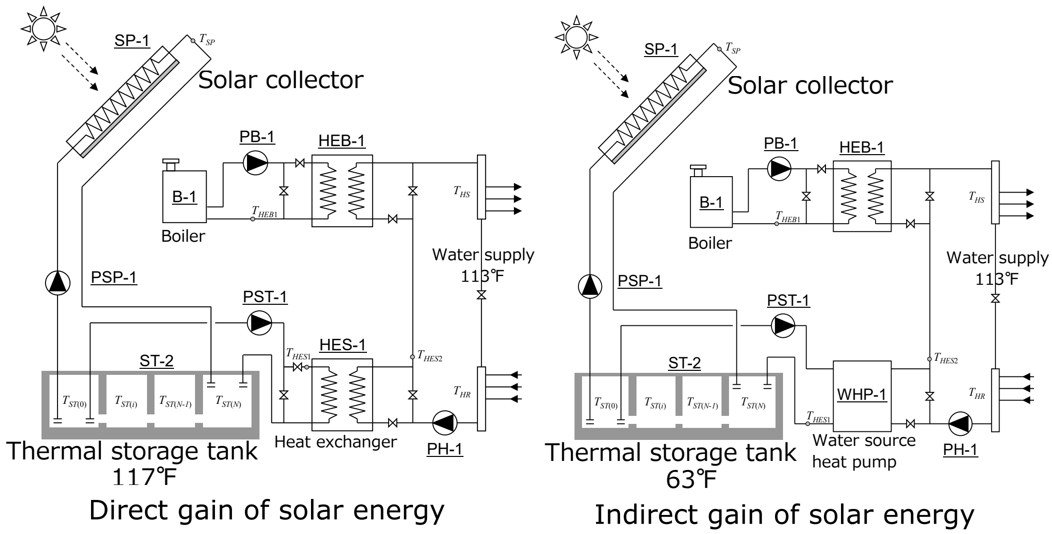


**Figure 7.** Diagrams of direct and indirect use of solar energy.

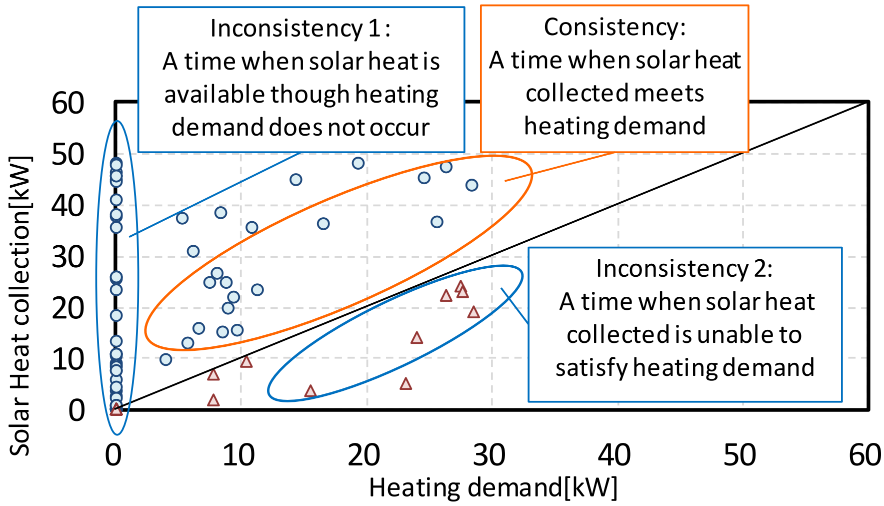


**Figure 8.** Difference in efficiency among temperatures of heat collected.

Figure 9 shows the results of the ratios of heat collected when heating demand actually occurred. The results were confirmed based on the actual measured values. More than half of the heat was collected when a heating demand did not occur. To utilize as much solar heat as possible, regardless of whether its use was direct or indirect, a thermal storage tank needed to be installed to eliminate the gap. If both the direct and indirect systems have the same capacity for solar heat, the efficiency in direct use is higher than in indirect use because additional power energy is not required. However, the reasons why indirect use is applied to this project are as follows:

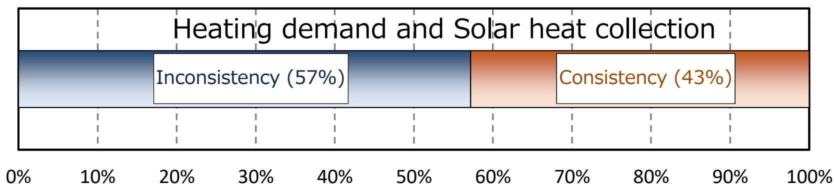


**Figure 9.** Percentage of heat collection according to actual demand.

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1）Improvement of efficiency in heat collection at a lower temperature

If 113ºF (45℃) water is assumed to be used, approximately 117ºF (47℃) water needs to be collected for direct use. On the other hand, in indirect use, approximately 63ºF (17℃) water can be available. The lower the temperature of the heating water collected by the solar collectors, the more efficiently the solar collectors work to collect heat. As Figure 10 shows, when 63ºF (17℃) heat is collected, the solar collectors work 17% more efficiently than when 117ºF (47℃) heat is collected. [2]

2）Increase in frequency to utilize as much solar heat as possible

If the difference between the temperature of the supply water and that of the return water is ΔT = 50ºF (10℃), the supply water needs to be over 99ºF (37℃) for direct use. Furthermore, if the capacity of the water tank is too large, the heat loss will increase. Conversely, if the capacity of the water tank is too small, the water will be heated too quickly. However, the heat-resistant temperature of ordinary tank insulation is approximately 122ºF (50℃). If the temperature of water exceeds this value, then the heating system needs to be stopped, for example, by means of water removal.

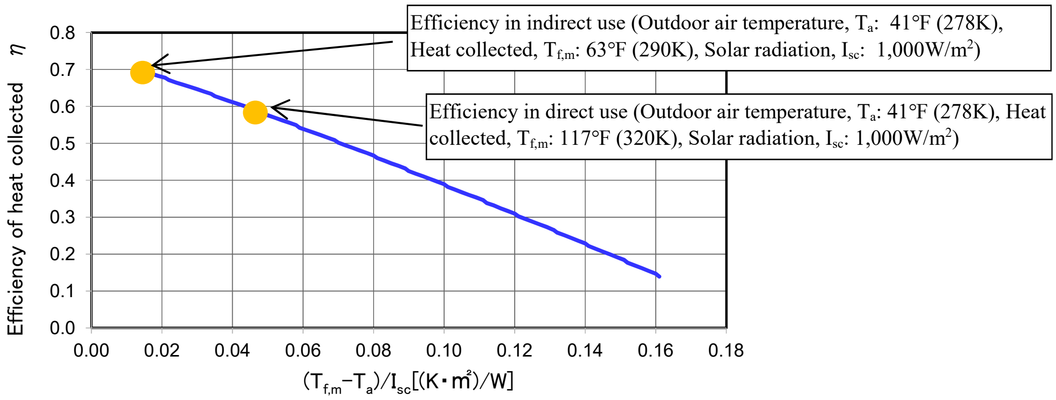


**Figure 10.** Difference in efficiency between temperatures of heat collected.

On the other hand, if the heat is indirectly collected, at a temperature variation between 41 and 86ºF (5 and 30℃), it has no impact on the water source heat pump operation. Hence, it is assumed that the amount of collected heat can be increased if heat is collected more frequently. In particular, if the heat is used for air conditioners in the gymnasium and the auditorium, indirect use of solar energy is considered more effective because the air conditioners can make good use of the solar heat collected after school hours and during the weekends and holidays.

## 6. Effects of thermal storage in winter

Figure 11 shows the changes in the actual accumulated heating loads, amount of collected heat, and mean temperature in the storage tank on a daily basis, when the heating system was in operation. As assumed in the planning phase, the auditorium had irregular heating loads and the gymnasium had intermittent loads, which makes it difficult to predict these changes. The amount of collected heat was quite consistent throughout the time period, regardless of the heating demand. Consequently, the temperature of the water in the storage tank was kept at approximately 80°F (27℃) until the middle of December, before the demand for the heating system increased. It was confirmed that the solar heat collected in autumn was effectively utilized at midwinter. As a result, the actual annual usage of solar heat was about 103% of the simulation in the design phase, as shown in Figure 12.

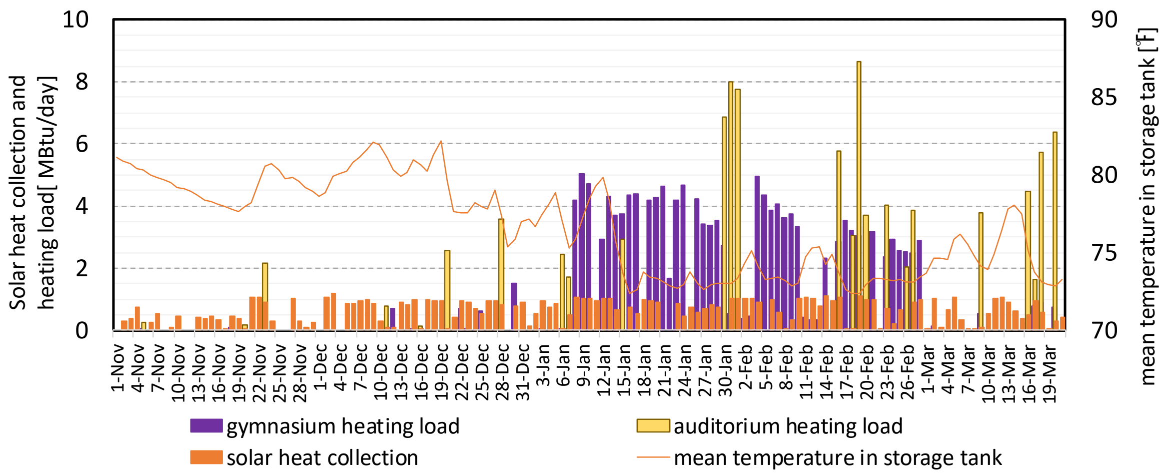


**Figure 11.** Accumulated heat, accumulated thermal load, and average tank water temperature.

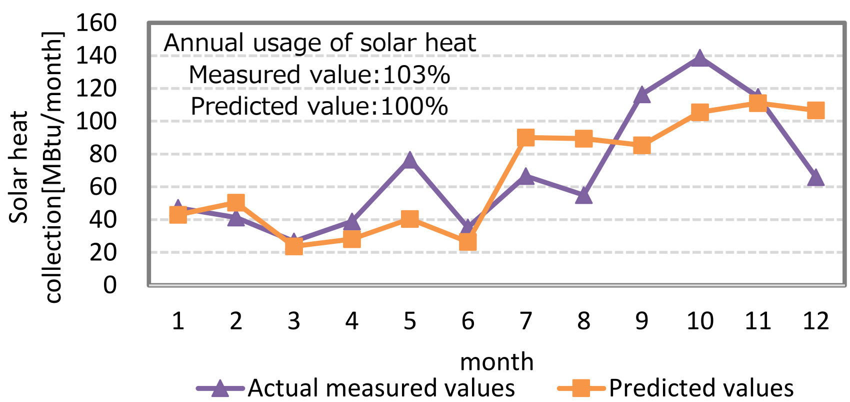


**Figure 12.** Annual usage of solar heat collection.

Based on the measured data in winter (from December to March), the actual values of the heat source efficiency were calculated. Since the calculations were made on the assumption that the water heat source pumps were constantly in operation, only the data at times before and after the pumps were constantly working for 30 min were extracted. Figure 13 shows the frequency distribution of COP of the water heat source pump unit. A COP between 5.5 and 6.0 occurred most frequently, and the average COP was 6.8 during the period [3]. A COP in a rated condition is about 4.4 in 41ºF (5℃) of the outlet temperature of heat source water. It was confirmed that the water source heat pump worked about 1.5 times more efficiently than in the rated condition by utilizing heat source water kept at approximately 68ºF (20℃) by solar heat.

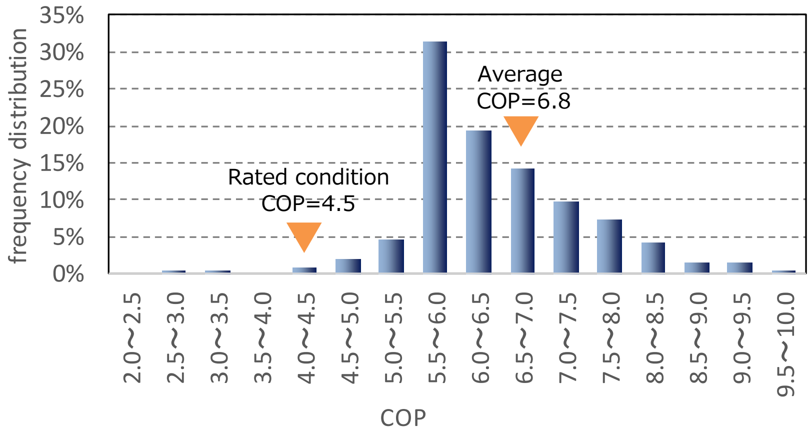


**Figure 13.** Frequency distribution of COP of water source heat pump unit.

## 7. Energy performance

As indicated in Figure 14, the consumption of primary energy was 31 kBtu/ft$^2$/year (353 MJ/m$^2$/year) in the first year of building operation. Additionally, the consumption of renewable energy generated by solar power and solar heat was 6.3 kBtu/ft$^2$/year (71 MJ/m$^2$/year). This means that the consumption of primary energy decreased by 45% compared to 56.3 kBtu/ft$^2$/year (639.4 MJ/ m$^2$/year) (the reference standard), which is the actual value of the average in FY2010 of 183 public high schools that have a cooling system.

The annual solar heat collection was 143 MBtu/year (151 GJ/year), and the solar power generation was 48,600 kWh. Converted into primary energy, this amounts to a total of 592 MBtu/year (625 GJ/year). It was confirmed that the renewable energy was fully utilized as planned. Solar heat collection accounted for approximately 4.9% of the annual consumption of primary energy, and solar power generation was approximately 15.3%. The total consumption of renewable energy accounted for 20.2% of the total energy consumption.

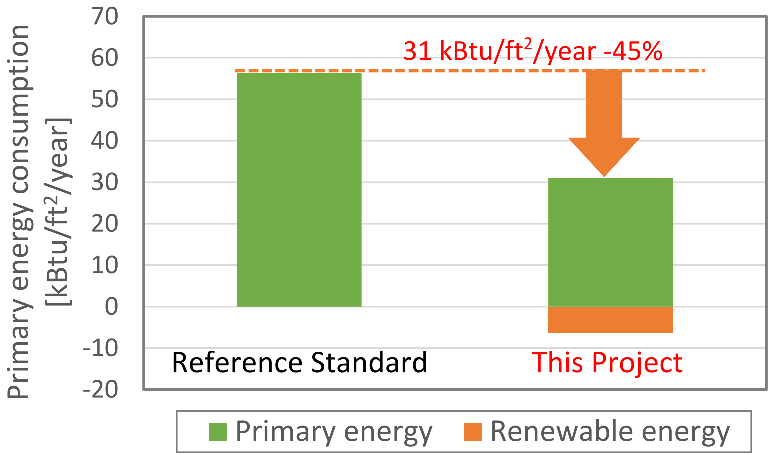


**Figure 14.** Annual energy consumption.

Figure 15 shows the annual consumption of primary energy at the high school, including other buildings on the site, after reconstruction (July 2014 to June 2015), as compared with that before construction (April 2010 to March 2011). While neither the auditorium nor the gymnasium had air conditioning (AC) before reconstruction, they have had AC since the reconstruction was completed. The consumption of primary energy decreased by 7% after reconstruction. It was confirmed that the air conditioning systems worked very efficiently after reconstruction compared to the facilities before reconstruction.

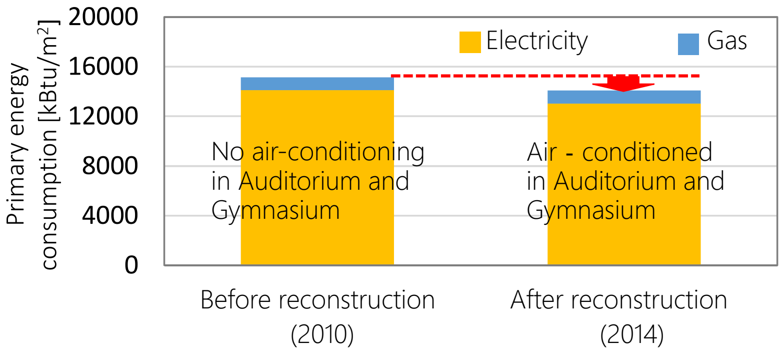


**Figure 15.** Actual energy consumption before and after reconstruction.

## 8. Conclusion

For this project, a highly efficient heat source system was planned by using heat storage tanks to store solar heat with water source heat pumps and a waste heat recovery chiller. The actual measured data were analyzed for the calculations of the heat-source COP. It was confirmed that the highest performance was measured as assumed during the design phase. This paper shows a method to utilize solar heat energy stably and efficiently for school buildings. Consequently, the consumption of primary energy per year was reduced to 31 kBtu/ft$^2$/year (353 MJ/m$^2$/year), which is 45% less than that of the average of 183 public high schools with air conditioners in Tokyo. Solar heat collection accounted for approximately 4.9% of the annual consumption of primary energy, and solar power generation was approximately 15.3%. Renewable energy accounted for 20.2% of the total energy consumption.

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