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Evaluation of the Primary Energy and Carbon Dioxide Emissions of a Passive Ventilation System with a Solar Air Heater

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Abstract: Improvements in envelope performance have reduced heat loss from insulation, and the ratio of heat loss through ventilation load has become relatively large. In recent years, the use of heat recovery ventilation systems (HRV) has particularly increased. However, ventilation generates not only ventilation load but also air conveying fan power, such that conserving energy for both is important. Therefore, this paper focuses on a passive ventilation system with a solar air heater (PVSAH), which is a passive ventilation system that does not use air conveying fan power and uses a solar air heater that uses solar energy. The total energy consumption of the PVSAH, the widely used mechanical exhaust ventilation system (EV), and the HRV, which has high energy efficiency, was compared with the ventilation load plus air conveying fan power. The primary energy evaluation and carbon dioxide (CO_2) emissions were compared by region, and the optimal system was proposed according to regional characteristics. In warmer zones, the PVSAH saved the most energy, while the HRV increased energy consumption. The comparison of CO_2 emissions by ventilation systems when using heat pumps for cooling and heating showed that PVSAH > MEV > HRV for Heating Degree-Day (HDD) 1500 and below, PVSAH > HRV > MEV for HDD 1500 to 2750, and HRV > PVSAH > MEV for HDD 2750 and above. MEV were favored in that order. As the CO_2 emission factor decreases, the difference in CO_2 emissions between systems decreases. If the difference in emissions becomes smaller, then considering the initial and running costs and the risk of failure of the system is crucial. A simple system configuration with low risks of failure and maintenance, such as PVSAH, may prove advantageous in the future.

Keywords: solar air heater; passive ventilation; ventilation load; residential house; heat recovery; primary energy consumption; carbon dioxide emission

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1. Introduction

To achieve a decarbonized society by 2050, expanding renewable energy, and further innovating energy-saving technology are necessary initiatives. In addition, the sharp increase in global energy prices triggered by the war between Ukraine and Russia, which began last year, and the need to secure energy for security reasons and drastically reduce energy use. In Japan, the residential sector accounts for approximately 14% of energy consumption, and current energy conservation standards are scheduled to become mandatory in 2025. Moreover, this sector expects to reach the level of net zero-energy housing for newly constructed homes and buildings in 2030.

In recent years, energy-saving technologies in housing have greatly evolved, and energy-saving products have increased. In particular, high-performance windows and heat insulators have been used to improve the performance of homes. The Housing

Performance Indication System, which was revised in October 2022, has raised the standard for inducing higher-performance housing. This initiative has brought Japan closer to the European standard.

The increase in outer skin performance reduces heat loss from insulated areas, and the heat loss ratio due to ventilation becomes relatively large. Currently, various ventilation systems have been developed and marketed to reduce ventilation loads. In recent years, the use of heat recovery ventilation systems (HRV) has particularly increased. In buildings, ventilation is a very important device for protecting the health of residents. However, ventilation generates not only ventilation load but also energy to transport air, such that conserving energy for both is important.

HRV reduces ventilation load by recovering heat. However, the disadvantages are the increased air resistance of the heat exchanger and the need for fans to convey air for air supply and exhaust, respectively, which significantly increase the air conveying fan power compared to a mechanical exhaust ventilation system (MEV).

Laverge et al. [1] examined the trade-off between reducing ventilation load through heat recovery and increasing system pressure drop and air conveying fan power. In warmer climates, the effect of heat recovery is small, such that the heat recovery effect cannot be obtained without a small air transportation power. Therefore, the author suggests that the ventilation system be selected on the basis of the initial and maintenance costs. HRVs, which are advantageous in cold climates, also need to be more energy efficient in terms of primary energy consumption and carbon dioxide (CO_2) emissions. To achieve this ideal setup, a system with much lower air conveying fan power and a lower pressure drop is required.

Dodooa et al. [2] evaluated the relationship between the energy reduction of heating loads due to HRV and the power consumption of air conveying fans in the case of district heating systems. In terms of buildings with these systems, the impact of energy savings due to the efficiency of the heat supply system was larger, and the percentage reduction in heating energy due to HRV was smaller. In addition, the impact of the airtightness and air conveying fan power of buildings was greater than the reduction in heating energy consumption due to HRV. Thus, scholars have pointed out that HRV is unsuitable for buildings with low levels of airtightness.

Furthermore Wu et al. [3] investigated the trade-off between heating energy reduction and air conveying fan power by HRV in an annual simulation in an office building. The calculations were performed using TRNSYS. Occasionally, the air conveying fan power exceeds heat recovery due to outdoor air conditions, in which case HRV does not function in an energy efficient manner during these times. Therefore, the authors demonstrate the optimization of periods of heat recovery operation that require air conveying fan power as energy-saving periods, which maximizes the energy-saving effect of HRV.

Similarly, El Fouiha et al. [4] scrutinized the HRV trade-off in terms of by the day. In the case of office buildings, HRVs were found to be disadvantageous due to the shorter daytime hours of use and reduced heating load due to solar radiation. In the case of residential buildings, HRV is more energy efficient than MEV, but demand controlled ventilation with humidity control (HCV) is more advantageous in warmer climate zones below Heating Degree-Day (HDD) 1800. Scholars have reported that HCV is also advantageous when HRV has a high efficiency and low specific fan power (SFP), and that HRV does not necessarily save energy. As previously mentioned, evaluating the air conveying fan power for HRV is important.

Zhang et al. [5,6] studied defrost operations when HRV (sensible heat exchange) is used in cold climates. The heat exchange elements of HRV freeze when the outdoor air is cold; thus, the defrosting operation is necessary for melting ice. This defrosting operation also uses energy but is usually not reflected in energy-saving calculations. To improve these defrosting operation issues, the authors proposed an energy recovery ventilator (ERV), which can recover sensible and latent heat, and investigated the increase in energy consumption due to defrosting operation through simulation. They reported that ERV displayed better frost resistance and thermal performance than did HRV, which only recovers sensible heat. In addition, they found that ERV is superior to HRV in terms of energy efficiency. Thus, considering issues related to defrost operations is necessary.

HRV requires maintenance, such as filter cleaning, to maintain the performance of the heat exchanger. The maintenance frequency is higher than that of ventilation systems without filters, and the homeowner incurs the burden of maintenance. In this regard, Fisk et al. [7] compared the energy efficiency and cost of HRV according to zone and energy source. The authors found that HRV exhibited issues regarding the burden and cost of maintenance and upkeep. The result demonstrated that HRV is not necessarily cost-effective, depending on the conditions.

Dorer et al. [8] illustrated that HRV is an important option for energy savings but faces various challenges such as difficulty in construction, noise problems, and maintenance management. In particular, the burden of maintenance on homeowners is significant, and paid services are available for a price. Other costs involve periodic filter replacement and long-term replacement of motors and parts. If HRV is not properly maintained, then air quality cannot even be ensured. Although this aspect lacked evaluation in terms of energy conservation, it is a crucial point of view when considering a system.

HRV is used to maintain indoor air quality (IAQ) and improve energy efficiency, but its performance is calculated based on fixed values derived from laboratory tests. However, according to a report by Choi et al. [9], HRV field experiments demonstrate that heat recovery efficiency varies between 25% and 75%, which is not fixed. When comparing the case of calculations based on fixed values versus the variable heat exchange efficiency measured in the field, the authors found that heating energy consumption increased by 69% in the latter case. This finding suggests that the energy-saving effect may be overestimated through calculations based on fixed values, such that considering the variable performance in actual field conditions is necessary.

Maier et al. [10] conducted a study on the operational problems of four ventilation systems in a real house. HRV resulted in an energy savings of 10–30%, but MEV resulted in better air quality than did HRV with respect to CO_2 concentration. The study observed no obvious differences in IAQ or comfort for each system in the survey. Residents adjusted the thermal environment by opening windows, which improved their sense of comfort. Moreover, the study found a strong correlation between CO_2 concentration and window opening, and a correlation between CO_2 concentration and a sense of comfort. Thus, residents responded to the improvement in comfort by opening windows instead of adjusting the air flow rate, which leads to wasteful heat loss. Thus, window ventilation is permanently related to human habits and is greatly influenced by human behavior. Therefore, achieving the objective by taking mechanical energy conservation measures alone is difficult, which suggests that energy conservation measures cannot be successfully implemented through desk calculations alone.

Alternatively, certain cases focus on demand control to reduce the heat loss of ventilation using strategies apart from heat exchange, and energy-saving efforts are being made. Laverge et al. [11] examined the potential for energy savings of four types of demand control methods and reported that 25–60% of the ventilation load can be reduced.

Cho et al. [12] investigated the energy-saving performance of HRV combined with air purification and demand control in apartment complexes through measurements and simulations. The authors reported that the system could reduce energy use by approximately 20% compared with conventional systems.

Fisk et al. [13] reviewed the literature on sensor-based demand control ventilation (DCV). Many examples of sensor-based CO_2. CO_2 sensors are widely used, especially in offices with fluctuating occupancy rates, and are introduced as a cost-effective system that can pay back its investment in a few years. However, in residential buildings, although energy-saving effects can be expected, the level of cost-effectiveness is frequently low due to the high cost of sensors.

In a survey by Guyot et al. [14], more than 20 DCV systems have been approved and widely used in Belgium, France, and the Netherlands, among others. A review of the literature indicates that demand control can reduce ventilation loads by up to 60% without compromising IAQ.

Southall [15] used demand control with temperature, humidity, and CO_2 sensors, and Turner et al. [16] proposed a passive ventilation system combined with a ventilation controller to control fans and mechanical flow dampers to prevent over- and under-ventilation. Jreijiry et al. [17] demonstrated that demand control combined with CO_2 and motion sensors can reduce heating energy and fan power consumption while meeting IAQ requirements through simulation.

Therefore, in a previous paper [18], we proposed a new system called the passive ventilation system with a solar air heater (PVSAH), which can contribute to energy without using HRV. This system was confirmed to be capable of reducing ventilation loads. However, to evaluate energy-saving performance related to ventilation, including not only ventilation load but also air conveying fan power is necessary. In addition, making proposals that consider maintenance and system operation is important.

The current study compares the PVSAH with other ventilation systems as a method for solving the abovementioned problems of various ventilation systems. Energy-saving performance was evaluated on the basis of the primary energy evaluation. In addition, as we aim for zero carbon emissions by 2050, the study also focuses on the reduction of the CO_2 emission factor and evaluates changes in this factor. Evaluation is then conducted on a regional basis, and the optimal system is discussed in accordance with regional characteristics.

2. System and Conditions of Consideration

2.1. Passive Ventilation System with a Solar Air Heater

This study was conducted with the proposed system in a previous paper [18]. Figure 1 provides an overview of the system, and Figure 2 illustrates a solar air heater panel (SAH) installed in an outdoor air intake area. The system has two outdoor air inlets, with a SAH installed in each outdoor air inlet. A total of two SAHs are installed. Air heated by the solar heat from the SAH is supplied to the room by built-in fans, which are driven by electricity from the photovoltaic panel built into the panel. The system requires no external energy. The maximum capacity of the SAH is approximately 100 m^3/h of outdoor air, which can be heated by approximately 30 °C, with a maximum capacity of approximately 1000 W. Outdoor air heated by solar heat and supplied under the floor is heated by an underfloor heating system and rises. While heating and ventilating the room, the air is discharged from the chimney through an exhaust vent mounted in a high place. The system is a passive ventilation one that does not use any energy to convey air. The study was conducted for installation directly south, where the highest heat collection rate of SAH can be expected.

The most important feature of the PVSAH is that it lacks air conveying fan power. In addition, by using SAH for air supply, the system reduces ventilation load. In addition, the system requires no maintenance, such as filters, and thus has a low maintenance burden. The passive ventilation system fluctuates according to the temperature difference between indoors and outdoors and the outside wind. Especially during the daytime, the outdoor temperature rises and the temperature difference between the indoor and outdoor parts of the room decreases, which results in decreased ventilation. However, since it is in operation, the SAH acts as a source of ventilation to compensate for the reduced volume of ventilation.

To accurately predict the heat collection capacity of the air heater installed in a building, calculating the time variation of the heat collection capacity is necessary. In general, the heat collection capacity of the solar air heater is expressed as Equation (1) in a steady state. Equations (2) and (3) are thermal equilibrium equations based on the air temperature blown from the SAH and show the time variation of the heat balance in the air layer inside the panel of the solar air heater. M in Equation (2) is defined as the equivalent heat capacity, which is the combined heat capacity of the air and components in the device.

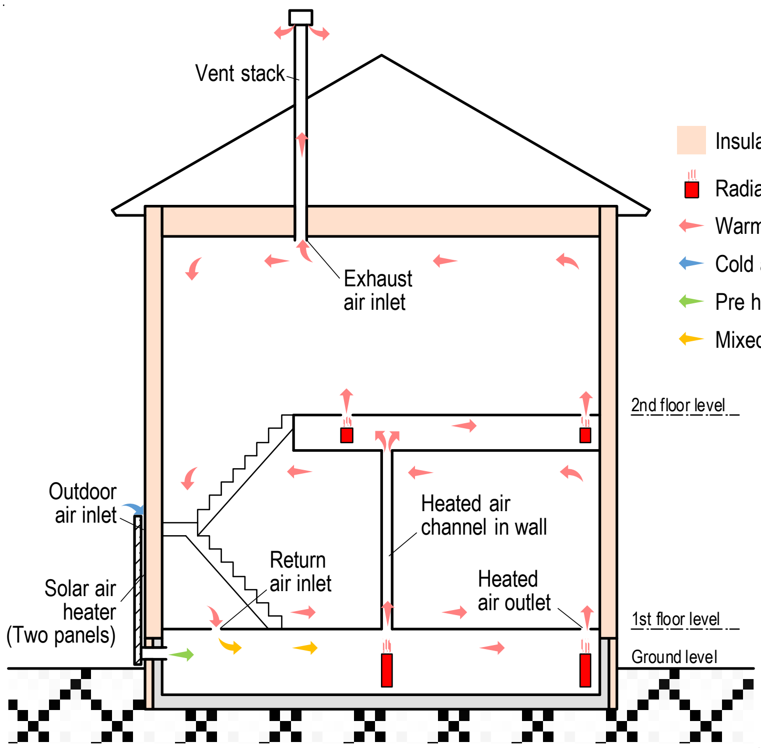


Figure 1. Overview of the passive ventilation system with a solar air heater (PVSAH) [18].

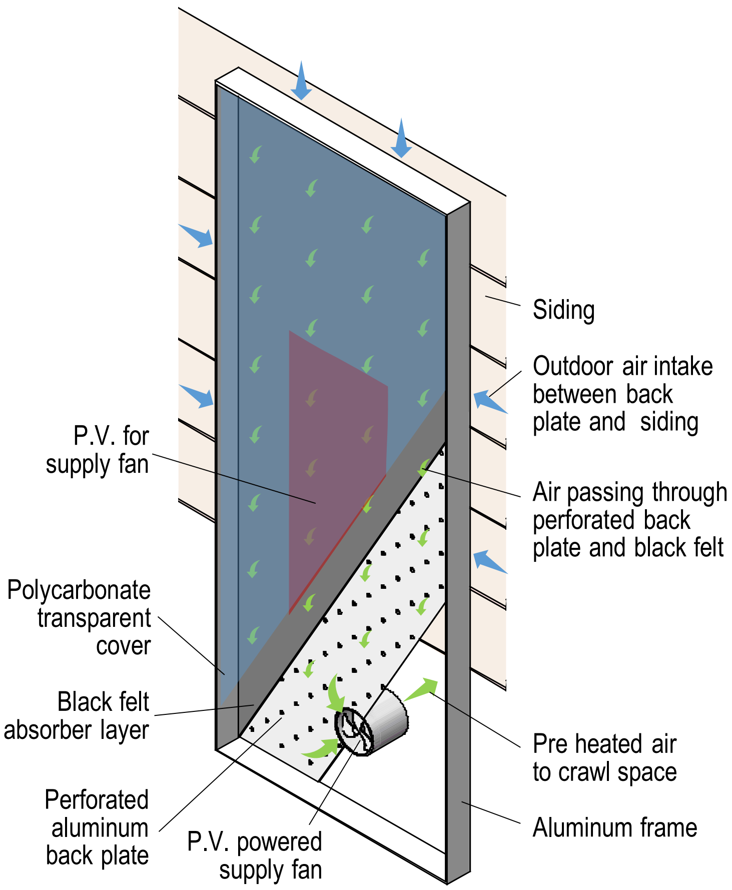


Figure 2. Overview of the solar air heater (SAH) [18].

Once M is obtained, calculating the amount of heat collected by entering numerical values into these equations is possible. Once these values are obtained and the time variation of the temperature is known, calculating the heat collection volume with consideration of the time variation is possible.

$$Q_c = 0.348 Q_p (T_o - T_p) \tag{1}$$

$$M \frac{dT_p}{dt} = Q_c + U_f A_f (T_o - T_p) + U_b A_b (T_o - T_p) + J_R A_f \tag{2}$$

$$M = M_A + M_B \tag{3}$$

$$\eta = Q_c / J_R \tag{4}$$

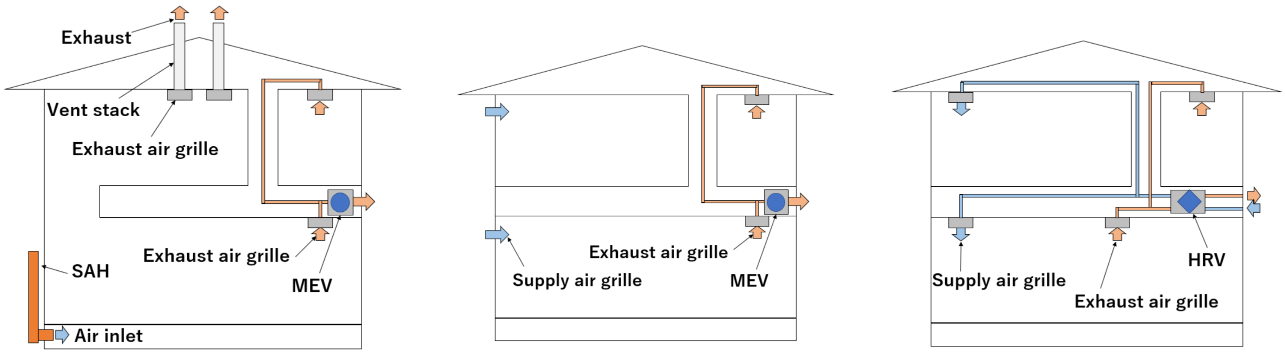
2.2. Comparison System

Table 1 and Figure 3 list the systems considered and evaluated in this study. We selected the proposed PVSAH, HRV, and MEV, which are the generally available ventilation systems of choice. In Japan, MEVs are generally adopted in large numbers, but the use of HRVs has been increasing in recent years as homes have become increasingly sophisticated. In the energy conservation standards in Japan, the air conveying fan power of a ventilation system is evaluated as an SFP. Specifically, the SFP indicates the amount of energy that can be conveyed with 1 m^3 of air. The study used the default values of SFP and heat exchange efficiency in the Japanese energy conservation standard [19]. PVSAH displayed a lower capacity for natural ventilation in the middle of the year and in the summer, when the temperature difference is small. Therefore, the evaluation of the SFP was conducted under conditions in which the MEV was operated and ventilated during the intermediate and summer seasons. Ventilation frequency was set to 0.5 h^{-1}, which was also the standard value in Japan and obtained from an international survey on ventilation frequency [20]. The heat collection efficiency of the SAH in the PVSAH was 60% according to the indication of the manufacturer, but the heat collection efficiency was obtained through Equation (4). Actual measurements in the previous paper [18] showed 58%. The current study calculated heat collection efficiency through simulation to obtain Qu. We calculated a total floor area of 120 m^2 and a building volume of 288 m^3. The building was examined under the same conditions, and the building envelop load was the same. Therefore, we did not examine the envelop load but only the ventilation load.

Table 1. Comparison of ventilation systems.

System		Specific Fan Power Wh/m^3	Air Change per Hour h^{-1}	Heat Exchange Efficiency -	Heat Collection Efficiency of SAH -
Mechanical Exhaust Ventilation System		0.24	0.5	-	-
Passive Ventilation System with a Solar Air Heater	Heating period	0.00	0.5	-	0.6 [1] (Rated efficiencies)
	Non-heating period	0.24	0.5	-	-
Heat Recovery Ventilation System		0.49	0.5	0.8	-

[1] The calculation uses Equation (4). This number is variable.



(**a**) (**b**) (**c**)

Figure 3. Overview of the system diagram. (**a**) PVSAH, (**b**) MEV, and (**c**) HRV.

2.3. Study Zone

This study examines the energy-saving effects of each area. The Japanese energy conservation standard [20] divides the country into eight zones according to climate. The zones are divided by degree-days. The study selected representative cities with large populations in each zone. However, the study excluded Zone 8, which is a hot region with low heating demand, and Zone 1, which has a population of less than 50,000.

Table 2 lists the characteristics of the selected cities. The study used extended AMeDAS weather data (2010 standard year) [21] as meteorological data. Degree-day (DD) was set to DD-18, which is used in the Japanese energy conservation standard [20]. Data on heating periods were derived from the Technical Information on Energy Conservation Standards [20], cooling and heating heat pump efficiencies from the Society of Heating, Air-Conditioning, and Sanitary Engineers of Japan [22], and gas thermal efficiency from 0.87, which is the default value in the Japanese energy conservation standards [20].

Table 2. Selected zones and their regional characteristics.

City	Zone	North Latitude / East Longitude	Heating Degree-Day (HDD18-18)	Maximum Air Temperature (°C) / Minimum Air Temperature (°C)	Annual Snowfall (cm)	Annual Amount of Solar Radiation (MJ/m²)	Heating Period / Cooling Period	Heating APF / Cooling APF	Gas Boiler Efficiency
Sapporo	2	43°03′51″	4499~3500	32	479	4436	9/26~6/4	3.2	0.87
		141°20′49″		−11.4			7/15~8/31	6.6	
Morioka	3	39°42′13″	3499~3000	31.9	209	4538	9/30~5/31	3.8	
		141°09′09″		−12.2			7/10~8/31	6.6	
Nagano	4	36°39′05″	2999~2500	35.7	163	5354	10/1~5/30	4.6	
		138°10′52″		−8.2			7/10~8/31	6.4	
Sendai	5	38°16′08″	2499~2000	35.4	59	4495	10/10~5/15	5.1	
		140°52′19″		−4.2			7/6~8/31	5.7	
Tokyo	6	35°41′22″	1999~1500	35.2	8	4713	11/4~4/21	5.6	
		139°41′30″		−0.5			5/30~9/23	6.2	
Kagoshima	7	31°33′37″	1499~500	34.6	2	5223	11/26~3/27	5.7	
		130°33′29″		−0.3			5/15~10/13	6.3	

2.4. Energy Conversion Factor

Table 3 presents the primary energy conversion factors for electricity and gas. These factors were derived from the Design Guidelines for Low Energy Housing with Validated Effectiveness [23]. Table 4 indicates the CO_2 emission factor per unit of primary energy. To achieve Japan's goal of zero carbon emissions by 2050, the CO_2 emission factor must be reduced in the future. In the calculation of CO_2 emissions, the emission factor greatly varies according to the composition of the power sources. According to IEA data [24], the emission factor for Japan in 2019 is 0.44 (kg-CO_2/kWh). Therefore, we first evaluate the current CO_2 emissions in Japan. If the emission factor improves in the future, then changes in the emission factor are set as levels in a stepwise manner. Each level was defined with reference to the emission factors of Germany and England, which are the leading countries in emission factors. For Level 3, the study used an emission factor of 0.04 (kg-CO_2/kWh) for France in 2019.

Table 3. Conversion factor per unit of primary energy.

Energy Type	Conversion Factor per Unit	Calorific Value per Unit
Electricity	9.76 MJ/kWh	1.000 kWh/kWh
Gas	45.00 MJ/m^3	12.083 kWh/m^3

Table 4. CO_2 emission factor.

Level	Japan in 2019	Level 1	Level 2	Level 3
Electricity CO_2 emission factor [kg-CO_2/kWh]	0.44	0.3	0.15	0.04
Gas CO_2 emission factor [kg-CO_2/m^3]	2.21			

2.5. Calculation Method for Ventilation Systems

The current study examined the ventilation load of the ventilation system. Outdoor air temperature was calculated using the extended AMeDAS weather data, and indoor temperature was calculated assuming a 20 °C setting. Equation (1) is used for the calculation of the heat collection rate of the SAH. Equations (5), (8), and (10) were used for the ventilation load of the ventilation system per system. Equations (9) and (11) were used for MEV and HRV for the air conveying fan power of the ventilation system, respectively. PVSAH does not use fans during the heating season; thus, the study used Equations (6) and (7) for the heating and non-heating periods, respectively. Tables 1–4 present HRV performance, primary energy conversion, CO_2 emission factor, and cooling/heating unit efficiency.

PVSAH

$$Q_u = (T_i - T_o)0.348\mathrm{Q} - Q_c \tag{5}$$

$$\text{Heating Period: } \mathrm{E} = 0 \tag{6}$$

$$\text{Except for heating period: } \mathrm{E} = \mathrm{FQ} \tag{7}$$

MEV

$$Q_u = (T_i - T_o)0.348\mathrm{Q} \tag{8}$$

$$\mathrm{E} = \mathrm{FQ} \tag{9}$$

HRV

$$Q_u = (T_i - T_o)0.348\mathrm{Q}(1 - \eta_t) \tag{10}$$

$$\mathrm{E} = \mathrm{FQ} \tag{11}$$

3. Result

3.1. Consideration of Installation Conditions for the Solar Air Heater

The study examined the optimal installation conditions for SAH. Panels can be installed not only on the wall but also at an angle. Figure 4 illustrates the calculated heat collection during the heating period according to the angle of the installation. As shown in Figure 5, the installation angle is 90° for vertical (wall installation) and 0° for horizontal, relative to the ground. The heat collection rate increases as the angle becomes slower. In each zone, the maximum heat collection angle is 40° to 50°, in which case the heat collection rate is 40% to 50% higher than that for wall installation. However, at less than 70°, the rate of increase in the heat collection rate decreases, and the rate of increase of the maximum heat collection rate from the heat collection rate at a 70° installation is approximately 10%. Conversely, a 30-degree angle resulted in a decrease in heat collection compared with a 40-degree angle.

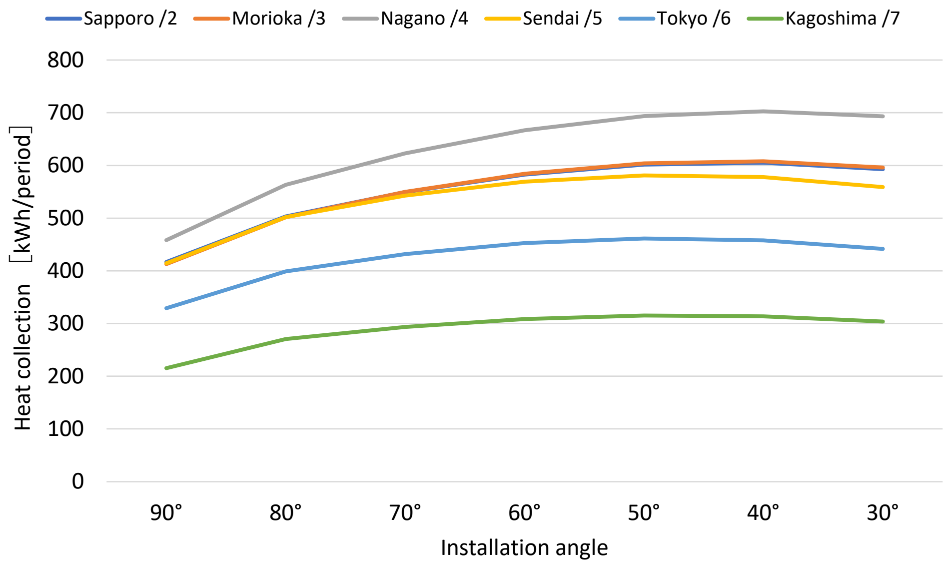


Figure 4. Comparison of heat collection by the angle of SAH installation by zone.

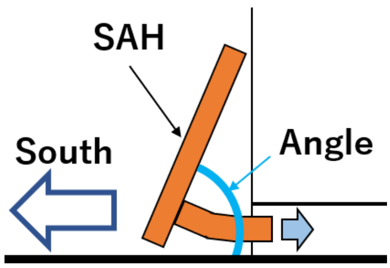


Figure 5. Installation angle of SAH.

Figures 6 and 7 depict the ventilation load by the angle of the PVSAH installation during the heating season and the percentage reduction in ventilation load, respectively. Installing the SAH on the wall (90°) reduces ventilation load by 15–20%. In this study, heat collection that exceeds the ventilation load did not lead to a reduction in ventilation load. Therefore, when mounted on a building, the increase in heat collection due to the installation angle exceeds the ventilation load and is passed on to the auxiliary heating effect. Even if the heat collection rate is increased by lowering the installation angle compared with that of the wall installation, the reduction rate is only 2–3% at maximum. Given the effects of snow accumulation in cold regions, strong winds such as typhoons in hot and humid regions, and obstruction caused by protrusion from buildings, a wall installation (90°) was considered, which is advantageous from a design standpoint. However, excess heat collection (overheating) by the SAH beyond the ventilation load contributes to energy savings as supplemental heating. Therefore, if conditions permit, an angled installation at no additional cost would be more desirable because it would increase energy efficiency.

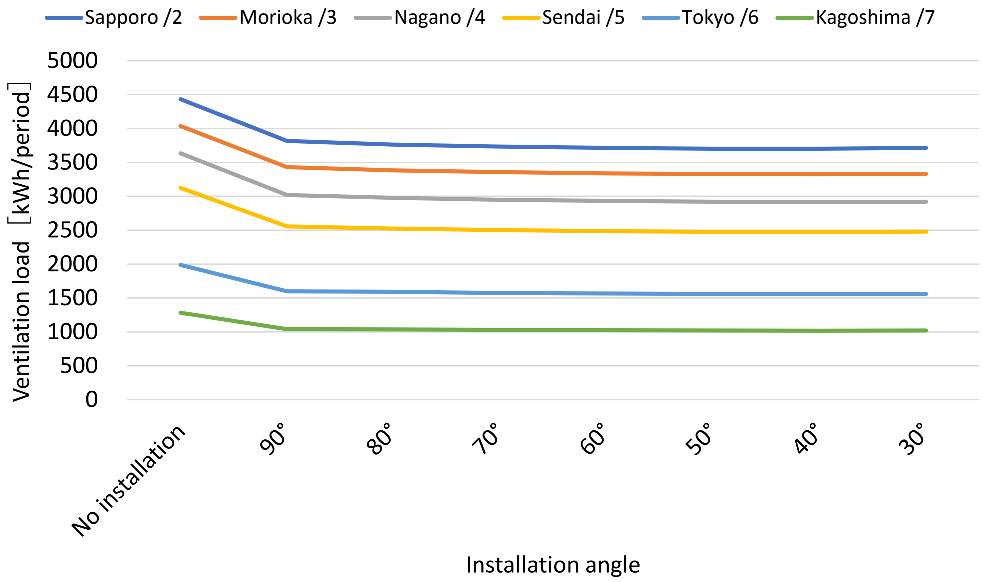


Figure 6. Ventilation load during the heating period by the angle of SAH installation by zone.

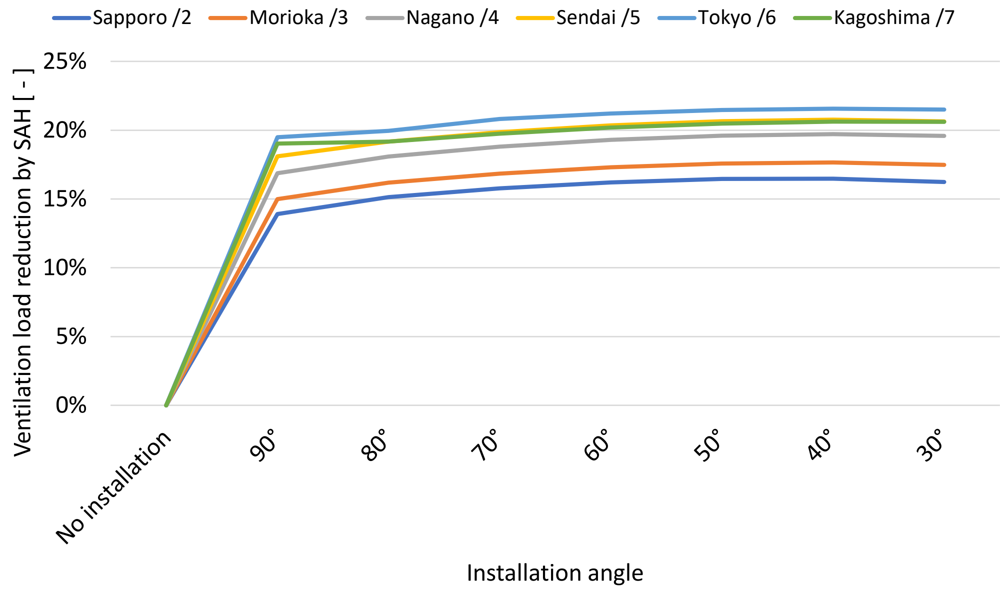


Figure 7. Reduction of ventilation load during the heating period by SAH by zone.

3.2. Evaluation of Primary Energy Consumption by Ventilation System

To understand the characteristics of each system, Figures 8–10 illustrate the monthly primary energy consumption when heating and cooling with heat pumps are used in Tokyo (Zone 6). SAHs installation was studied with wall installation (90°). PVSAH does not generate air conveying fan power during the heating season, which results in significant energy savings. Heat collection by the SAH reduces ventilation load, and the amount beyond that contributes to energy savings in the form of an auxiliary heating effect. The negative values in Figure 8 represent the ventilation load and auxiliary heating effect reduced by the heat collection of the SAH. The auxiliary heating effect is only shown in the graph and is not included in the calculation of energy savings. The primary energy consumption of the PVSAH is 4.6 GJ/year, which is significantly lower than the 6.6 GJ/year of a typical MEV.

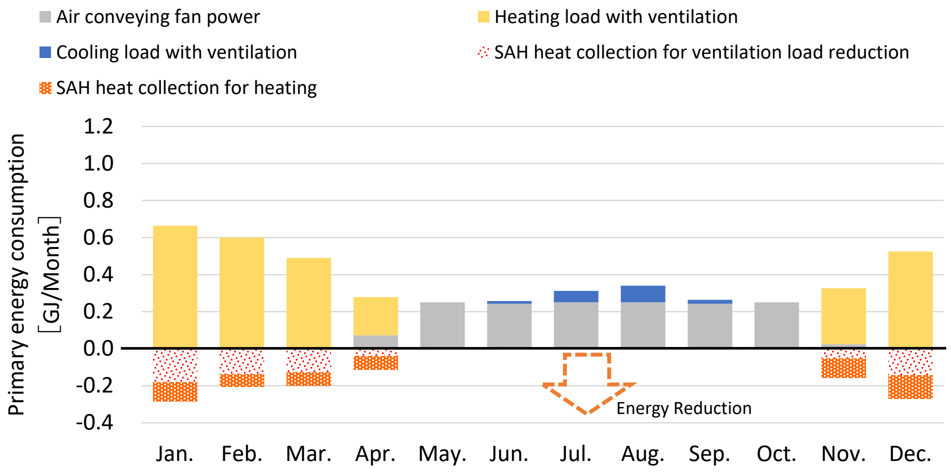


Figure 8. Monthly primary energy consumption of PVSAH.

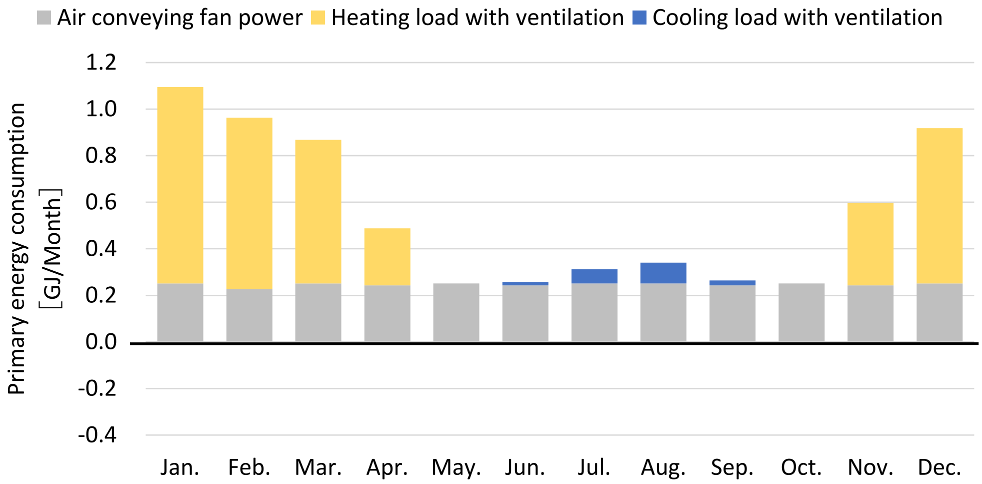


Figure 9. Monthly primary energy consumption of MEV.

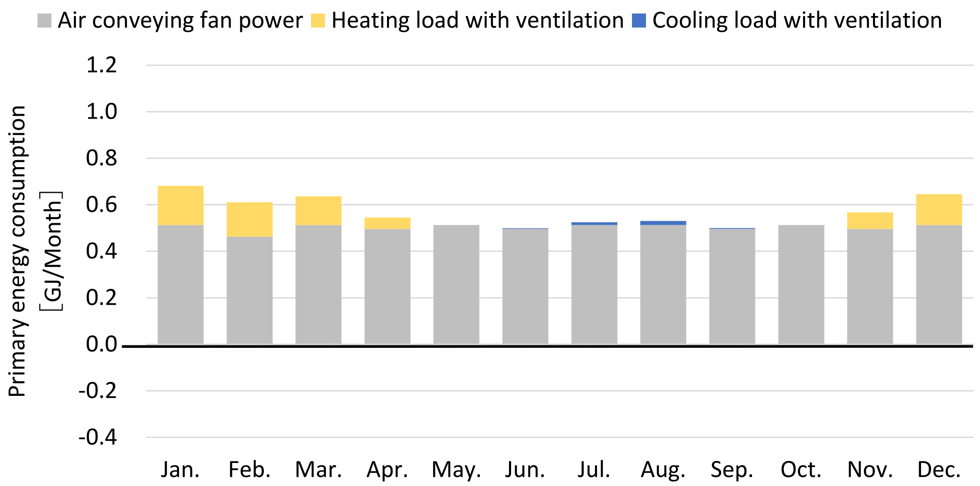


Figure 10. Monthly primary energy consumption of HRV.

Conversely, HRV consumes air conveying fan power throughout the year, even during periods without the heating load, and consumes significantly more energy than the ventilation load. In addition, the ventilation load during summer cooling is relatively small compared with the reduced ventilation load in winter, and energy savings are limited. As a result, the annual primary energy consumption of the HRV was 6.8 GJ/year, which is

0.2 GJ/year more energy than that of the MEV, and the HRV consumed significantly more energy than the PVSAH.

The study then compared the primary energy consumption by zone for each ventilation system. Figures 11 and 12 illustrate the case of heat pump heating and cooling and the case of gas heating, respectively. In the case of heat pump heating, PVSAH saves more energy than HRV in Zone 4 and the south. In Zones 2 and 3, even PVSAH without heat recovery can save significantly more energy than MEV can. In cold regions, HRV is more energy efficient than the PVSAH, but the PVSAH is also more energy efficient than the MEV. Given the effects of maintenance, defrosting, and differences in building airtightness, PVSAH also poses merit in being selected as an energy conservation measure. Comparing the energy conservation effect of HRVs with that of MEVs, HRVs present an advantage in the cold regions of Zones 2 to 5, but the opposite is true for Zones 6 and 7, in which energy consumption increases. In contrast, the energy-saving effect of PVSAH on MEV was stable at 25–30% regardless of region. The amount of heat recovered from HRV decreases in warmer regions, and the ratio of energy used by air conveying fan power increases, such that PVSAH with less air conveying fan power is advantageous.

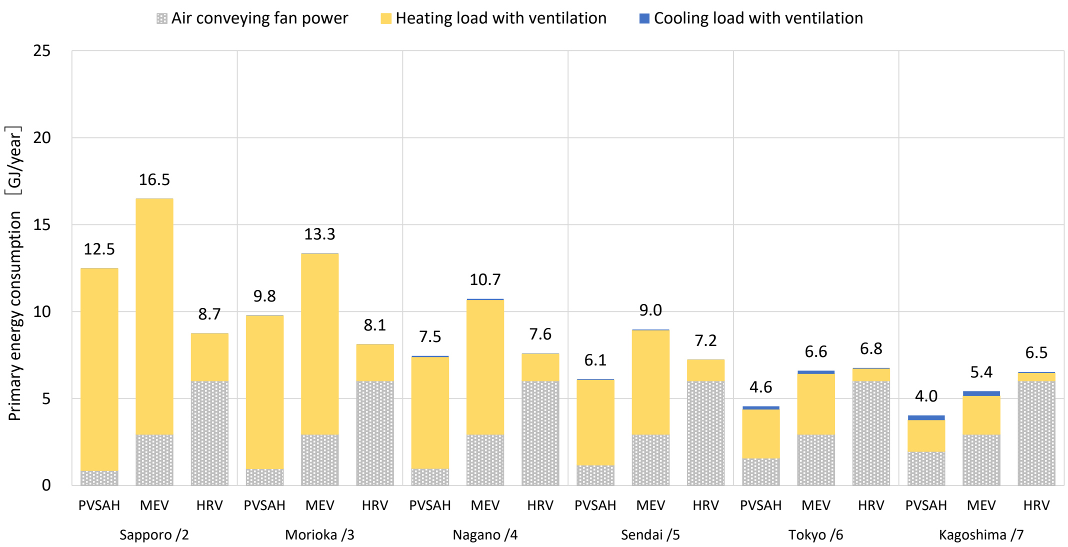


Figure 11. Annual primary energy consumption of a heat pump.

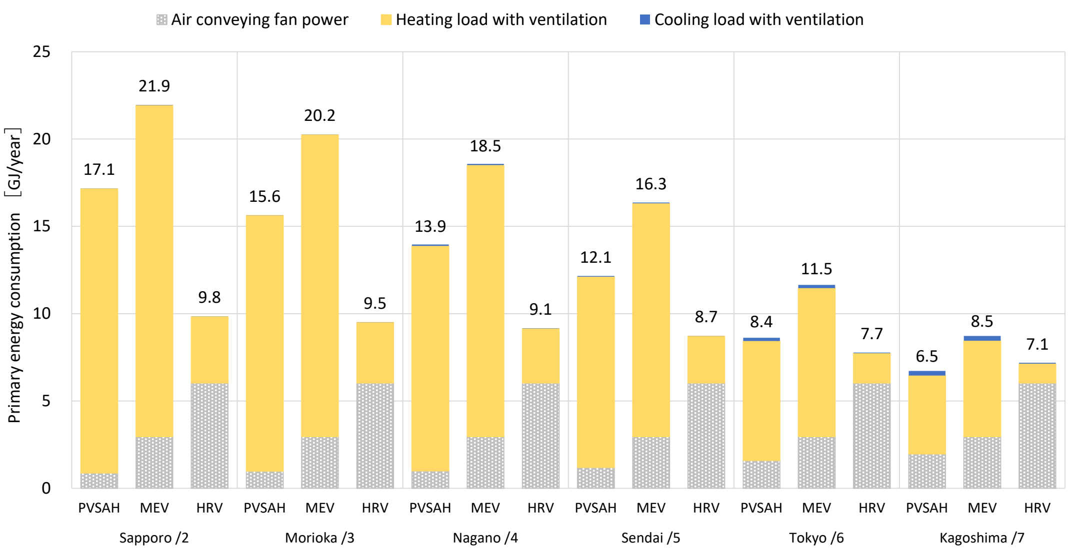


Figure 12. Annual primary energy consumption of a gas boiler.

Alternatively, in the case of gas heating + heat pump cooling, the ratio of air conveying fan power is lower due to the lower energy efficiency of the heating system. Therefore, HRV generally presents an advantage. In Zone 7, the PVSAH is more energy efficient than the HRV, but in the north of Zone 6, the HRV is more energy efficient. However, the PVSAH is 20–25% more energy efficient than the MEV, which makes the PVSAH an effective energy conservation option apart from the HRV. In addition, the value of using PVSAH is expected to increase in the future because its heating efficiency is likely to improve with the evolution of energy conservation technology and building renovation.

Against this background, PVSAH will have a high energy-saving effect in warm zones where heating energy efficiency is high and the energy-saving effect of HRV will be limited.

3.3. Comparison of CO_2 Emission per System

Figures 13 and 14 illustrate the results of the comparison of the annual CO_2 emissions of the ventilation systems for each zone. SAHs were studied with wall installation (90°) as well as primary energy consumption. Specifically, Figure 13 presents the calculation results for heat pump heating and cooling, and Figure 14 demonstrates those for gas heating + heat pump cooling. The study also focuses on the reduction of the CO_2 emission factor and evaluates changes in this factor. The values in Table 4 were used to calculate CO_2 emissions.

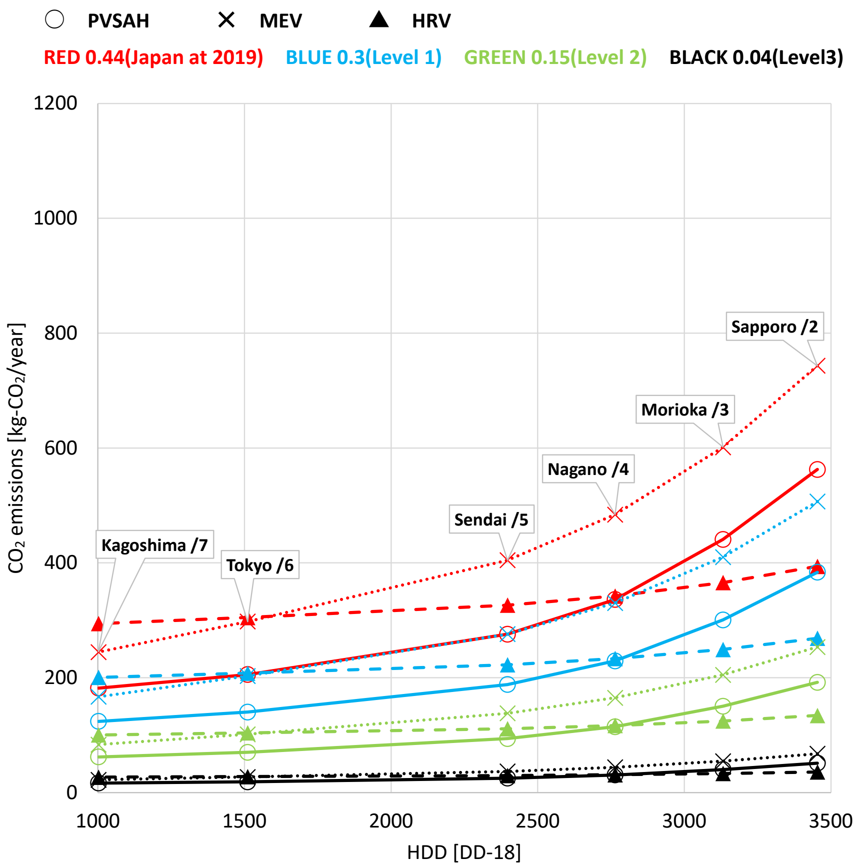


Figure 13. Annual CO_2 emissions of a heat pump.

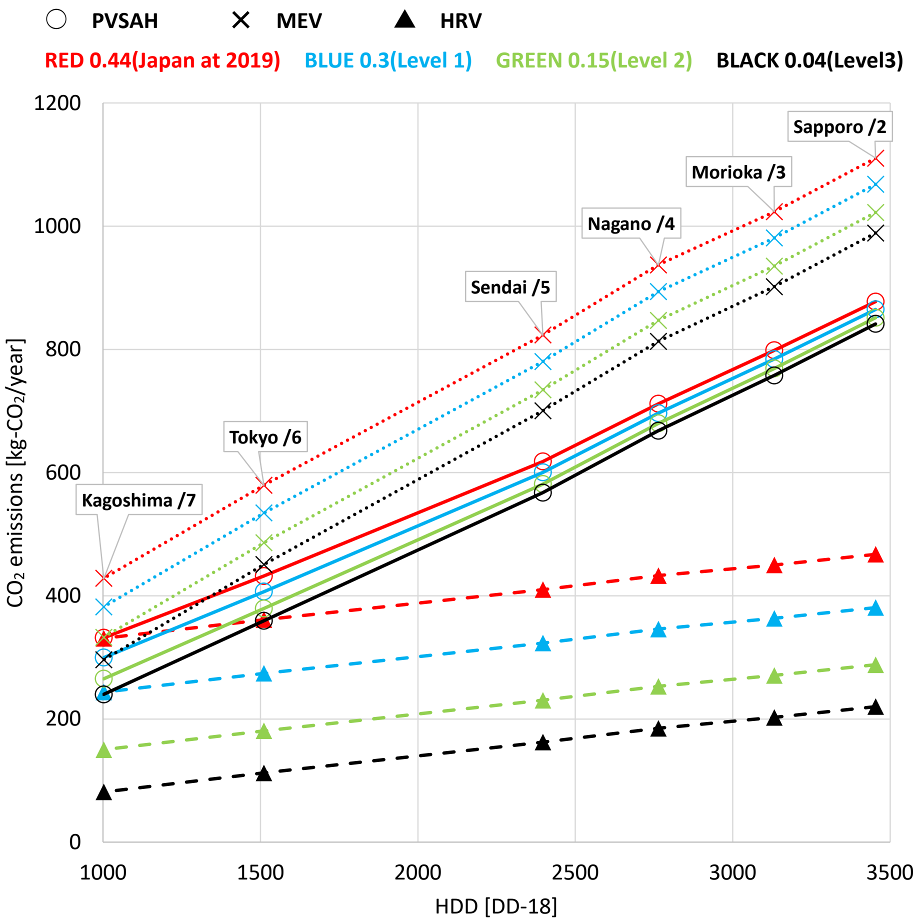


Figure 14. Annual CO_2 emissions of a gas boiler.

In the case of the gas heating and heat pump cooling systems, the study observed a small change in CO_2 emissions despite the change in the CO_2 emission factor of electricity because the gas combustion energy efficiency of heating remained the same. Therefore, HRV, which can reduce heating energy, poses a significant advantage.

In the case of heat pump heating and cooling, HRV can significantly reduce CO_2 emissions at all emission factor levels in cold climates. However, in warmer climates, systems with less air conveying fan power are favorable, and the difference in CO_2 emissions for the total ventilation load is reduced. At HDD 2750, PVSAH reverses with HRV, and CO_2 emissions are lower. PVSAH presents the largest advantage in the south below HDD 2750. MEV reverses its advantage with HRV after HDD 1500. In warmer climates, HRV does not work to save CO_2. In addition, the level of emission factors will increase with the increased prevalence of renewable energy sources, and CO_2 emission factors will decrease with the goal of decarbonization. As the level of the emission factor increases, the difference in CO_2 emissions between ventilation systems will decrease. A comparison of HRV and MEV at Level 3, which presents the lowest CO_2 emission factor, illustrates a maximum of 32 kg/year in cold climates and only a small difference of 5 kg/year in warm climates. Since the difference among systems is very small, factors apart from energy conservation performance, such as initial and running costs, including maintenance and management costs, and the risk of failure, are also important for system selection. A simple system configuration with a low risk of failure and maintenance, such as PVSAH, is expected to be highly advantageous in the future.

4. Conclusions

As an energy-saving technology for ventilation, the evaluation considered not only ventilation load but also air conveying fan power. The study obtained the following findings by comparing the energy conservation performance of the proposed PVSAH with that of HRV and MEV:

(1) The installation angle of the SAH used in the outdoor air intake area was examined. An angled installation increases heat collection compared with that of a wall installation (90°). For each zone, the maximum heat collection was achieved at installation angles of 40° to 50°. The effect of SAH installation at 90° is 15–20% but changing the angle of installation only improves reduction by a maximum of 2–3%. In addition, the installation of the system on a building at an angle requires consideration of the effects of snow accumulation in cold regions, the effects of typhoons and other strong winds in hot regions, and obstructions caused by the protrusion of the system from the building. Therefore, the study conducted a 90-degree installation on a wall. The results indicated that an angled installation is preferable if conditions permit because it is less expensive, reduces ventilation load by 2–3%, and provides an auxiliary heating effect.

(2) The monthly primary energy consumption of each ventilation system was evaluated in Zone 6 (Tokyo) for heat pump heating and cooling. PVSAH exhibited the highest energy savings because it does not generate air transfer power during the heating season and because of the reduction in ventilation load due to SAH. HRV can reduce ventilation load, but it also generates large air conveying fan power throughout the year, even without heating load. The reduction in ventilation load was a trade-off, which resulted in an energy increase.

(3) The primary energy consumption was evaluated by zone. In the case of heat pump heating with high heating efficiency, PVSAH was superior to HRV in Zone 5 and in the south and displayed the same energy-saving performance in Zone 4. In warmer zones (6–7), HRV was at a disadvantage compared with MEV, with HRV presenting an advantage in colder climates but a disadvantage in warmer climates. However, PVSAH can save more energy than MEV can, even in cold regions. Given the impact of maintenance, defrosting, and differences in building airtightness, selecting PVSAH as an energy conservation measure apart from HRV could lead to advantages. In the case of gas heating with low heating efficiency, PVSAH was equal to HRV in Zone 7, while HRV was advantageous in other zones. However, PVSAH saves 20–25% energy compared to MEV, which makes PVSAH an effective energy conservation option apart from HRV. In addition, the value of using PVSAH is expected to increase in the future due to the evolution of energy conservation technology and the possibility that heating efficiency will increase with the renovation of building facilities.

(4) The CO_2 emissions of different ventilation systems were compared. In the case of gas heating + heat pump cooling, the change is small, despite the change in the CO_2 emission factor of electricity, because the gas combustion energy efficiency of the heating remains the same. Therefore, HRV is significantly more advantageous because heating energy can be significantly reduced. In the case of heat pump cooling and heating, however, HRV poses an advantage in cold climates but a disadvantage in warmer climates because the amount of air conveying fan power does not decrease. HDD 1500 and below: PVSAH > MEV > HRV; HDD 1500 to 2750: PVSAH > HRV > MEV; and HDD 2750 and above: HRV > PVSAH > MEV, in this order. In addition, as the CO_2 emission factor decreases, the difference in CO_2 emissions between systems decreases. If the difference in emissions becomes smaller, then considering the initial and running (including maintenance and upkeep) costs and the risk of failure of the system is crucial. A simple system configuration with low risks of failure and maintenance, such as PVSAH, may prove advantageous in the future.

In this paper, we propose PVSAH as a simple system that is less burdensome to maintain and manage, in contrast to HRV, which is high performance but poses issues with maintenance, management, and performance demonstration. It is not only an energy-saving system but also a simple system that considers the initial, running, and maintenance costs.

The study found that the system can be fully utilized according to regional characteristics, characteristics of the residents, energy efficiency, and power supply configuration.

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Nomenclature

Q_p	SAH air flow rate	m^3/h
Q_c	Heat collection capacity	W
Q	Air flow rate	m^3/h
Q_u	Ventilation load	W
M	Equivalent heat capacity	J/K
M_A	Heat capacity of air in panel	J/K
M_B	Part of the heat capacity of surrounding components	J/K
U	U-value	$W/(m^2K)$
A	Area	m^2
T	Temperature	°C
J_R	Amount of solar radiation transmitted into the panel	W/m^2
t	Time	s
η	Heat collection efficiency of SAH	-
η_t	Heat exchange efficiency	-
E	Fan power	Wh
F	Specific fan power	Wh/m^3
f	front of panel	
b	back of panel	
p	hollow layer in the device	
o	outside air	
i	indoor air	

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