

Annual performance comparison between solar water heating system and solar photovoltaic/thermal system—a case study in Shanghai city

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Abstract

Based on the typical meteorological year data of Shanghai city, annual performances of solar water heating (SWH) system and photovoltaic/thermal (PV/T) system are comparatively analyzed under three different cases. The results show that when only solar energy is used, the effective day number of SWH system is more than PV/T system under the same case every month; for the PV/T system, heat loss at the nighttime dissipates most of the absorbed solar energy under the continuous heating mode considering the nighttime heat loss case; initial water temperature determines system electric efficiency. On the whole, PV/T system offers competitive performance only under the auxiliary heating mode, no matter from the points of primary efficiency and static payback period.

Keywords: solar water heating; photovoltaic/thermal; annual performance; primary efficiency

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1 INTRODUCTION

Energy demand conflicts with the environmental protection. Renewable energy utilization is a practical way to overcome this problem [1]. As one of renewable energy, solar energy is a promising alternative energy source because it is extensive, environmental friendly and safe [2]. At present, solar water heating systems (SWH) have been widely used in the building energy saving field [3]. It is estimated that a solar water heating system with 2 m² collectors can save ~1500 kWh of electricity per year [4].

Photovoltaic/thermal (PV/T) systems, which can simultaneously supply both electricity and hot water [5], show a better prospect in building energy saving, and have been popular in recent years. In a PV/T system, the cooling effect of the working fluid can improve the system photovoltaic efficiency [6], which brings a better overall performance compared with SWH system [7].

There are mainly two ways for the domestic SWH systems to meet the user-required water temperature. One is the continuously heating mode; the other is the auxiliary heating mode. For the first mode, if the water is not heated to the set temperature due to the low solar irradiation or low initial water temperature, the heating will be continued in the next day, all using solar energy. This mode cannot guarantee the daily hot water demand of the users. For the second mode, auxiliary heater is utilized to increase the water temperature to the set value when the water is not adequately heated by solar energy. This mode can meet the user daily demand. Compared with the SWH collectors, the typical PV/T collectors have larger heat transfer resistance. Besides, on the surface of the collectors, PV cells on the PV/T collectors have higher emissivity than the selective absorption coating on the SWH collectors. Therefore, PV/T collectors have higher thermal loss coefficient and lower thermal efficiency [8, 9]. For the continuous heating mode, low thermal efficiency results in relatively high daily final water

temperature (but lower than the set temperature), and will cause larger heat loss in the nighttime.

In the published literatures, performance comparisons between the SWH and PV/T systems are mostly under high solar irradiation or short-term running. However, long-term comparison of the two systems is rare. In this paper, annual performances of domestic SWH and PV/T systems are calculated and compared based on the typical meteorological year data of Shanghai city. Three cases are analyzed: (1) the continuous heating mode ignoring the nighttime heat loss (INHL); (2) the continuous heating mode considering the nighttime heat loss (CNHL); (3) the auxiliary heating mode (AH). The ratio of the nighttime heat loss can be reflected when compare the first and the second cases.

2 ANALYSIS MODEL

The photothermal efficiency (η_t) of the SWH and PV/T system with natural circulation can be estimated as follows [10]:

$$\eta_t = \alpha - U \frac{T_i - \bar{T}_a}{H} \quad (1)$$

where \bar{T}_a is the daily average ambient temperature, °C; T_i is the initial water temperature, °C; H is the daily cumulative solar radiation on unit area, MJ/m²; α is the typical photothermal efficiency when the initial water temperature equals the daily average ambient temperature; U is the daytime heat loss coefficient. The values of α and U can be obtained by the linear fitting based on the experimental data. The obtained regression equation can be used to estimate the photothermal efficiency under different climatic conditions.

In general, an inclination angle will be set when the collector is installed. The solar radiation H_T on the inclined surface should be calculated based on the irradiation data of the horizontal surface. The formula is as follows [11]:

Where

$$H_T = R_b(H_c - H_{cd}) + H_{cd} \frac{1 + \cos \beta}{2} + H_c \rho \frac{1 + \cos \beta}{2} \quad (2)$$

$$R_b = \frac{\frac{\pi}{180} \omega'_s \sin(\varphi - \beta) \sin \delta + \cos(\varphi - \beta) \cos \delta \sin \omega'_s}{\frac{\pi}{180} \omega_s \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin \omega_s} \quad (3)$$

$$\omega'_s = \min \left[\cos^{-1}(-\tan \varphi \tan \delta), \frac{\pi}{2} \right] \quad (4)$$

$$\omega_s = \cos^{-1}(-\tan \varphi \tan \delta) \quad (5)$$

$$\delta = 23.45 \sin \frac{360(284 + n)}{365} \quad (6)$$

where H_T is the solar radiation on the inclined surface, W/m²; H_c is the total solar radiation on the horizontal plane, W/m²; H_{cd} is the scattering radiation on the horizontal plane, W/m²; ρ

is the reflectivity factor of the ground, normally the value is 0.2; R_b is the ratio of direct radiation on the inclined surface and the horizontal plane; φ is the geographical latitude; β is the inclination angle; δ is the solar declination angle; ω_s is the hour angle of sunrise and sunset on the horizontal plane; ω'_s is hour angle of sunrise and sunset on the inclined plane, n is the serial number in the year.

When the collector faces the south and the inclination angle β equals the local latitude, the above equations can be simplified as:

$$R_b = \frac{\sin \omega'_s}{\frac{\pi}{180} \omega_s \sin \varphi \tan \delta + \cos \varphi \sin \omega_s} \quad (7)$$

Considering that the electric energy and heat energy have the different quality, so the primary efficiency η_{pvt} of a PV/T system can be estimated by the following equation [12]:

$$\eta_{pvt} = \eta_t + \frac{\zeta \eta_e}{\eta_{power}} \quad (8)$$

where η_{power} is efficiency of the conventional coal-fired power plant, the general value is 0.4; ζ is the photovoltaic coverage ratio, which is the ratio between PV area and collector area.

When the solar irradiation or the initial water temperature is low, the final water temperature of the day may not reach the set temperature for the SWH and PV/T system. In the continuous heating mode, if consider the nighttime heat loss, the nighttime heat loss coefficient has to be calculated. If ignoring the heat loss of the pipes and the sidebar of collectors, the main heat loss of the system consists of the heat loss at the top of collectors, at the bottom of collectors and the heat loss of the water tank.

The top heat loss coefficient of the collector U_t can be calculated by the following equation [13]:

$$U_t = \left\{ \frac{N}{\frac{c}{T_p} \left[\frac{T_p - \bar{T}_a}{N + f} \right]^e + \frac{1}{h_w}} \right\}^{-1} + \frac{\sigma(T_p + \bar{T}_a)(T_p^2 + \bar{T}_a^2)}{(\epsilon_p + 0.00591N h_w)^{-1} + \frac{2N + f - 1 + 0.133\epsilon_p}{\epsilon_c} - N} \quad (9)$$

Where

$$f = (1 + 0.0892h_w - 0.1166h_w \epsilon_p)(1 + 0.07866N) \quad (10)$$

$$c = 520(1 - 0.000051\beta^2) \quad (11)$$

$$e = 0.43(1 - 100/T_p) \quad (12)$$

$$h_w = 5.7 + 3.8V \quad (13)$$

where N is the number of glass cover, normally the value is 1; T_p is the average temperature of the absorbing plate, C . ϵ_p is the emissivity of the absorbing plate; ϵ_c is the emissivity of the glass cover; V is the wind speed, m/s; σ is the Boltzmann constant, its value is $5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \text{ K}^4)$.

The heat loss at the bottom of the collector consists of the conductivity resistance of the insulation and the convective resistance between the environment [14]:

$$U_b = \frac{1}{h_w + L_b/\lambda_b} \tag{14}$$

The heat loss of the water tank is also composed of the conductivity resistance of the tank insulation and the convective resistance between the environment [14]:

$$U_w = \frac{1}{h_w + L_w/\lambda_w} \tag{15}$$

In Equation (14 and 15), L_b and L_w are the thicknesses of the insulation, m; λ_b and λ_w are the thermal conductivities of the insulation, W/(m K).

3 MODEL SETTING AND CALCULATION PROCESS

According to the Chinese national standard, the daily per capita water consumption is set as 50 L, and the lowest water temperature is 48°C [15]. Thus, the volume of the storage tank is 150 L for a family of three, which infers the area of the collector as 2 m² [16]. For the PV/T collector, the PV module is assumed to be made up of 72 PV cells of size 125 × 125 mm in series, with the total area of 1.12 m² and the PV coverage ratio of 0.56. Photothermal efficiencies of the SWH and PV/T system can be evaluated as follows [9]:

$$\text{SWH system: } \eta_{t,\text{swh}} = 0.547 - 0.052 \frac{T_i - \bar{T}_a}{H} \tag{16}$$

$$\text{PV/T system: } \eta_{t,\text{pvt}} = 0.400 - 0.195 \frac{T_i - \bar{T}_a}{H} \tag{17}$$

The photoelectric efficiency of the PV/T system can be evaluated in the form of Equations (16–17). Considering the effect of temperature, the linear fitting result is as follows ($R^2 = 0.90$):

$$\eta_e = 0.1284 - 0.0198 \left(\frac{T_i}{H} - 0.868 \right) \tag{18}$$

Detail information of the SWH and PV/T systems are shown in Table 1.

System annual performances of SWH and PV/T system are evaluated based on the following assumptions:

Table 1. Parameters values of SWH&PV/T system

System	ϵ_p	ϵ_c	L_b (m)	L_w (m)	λ_b W/(m K)	λ_w W/(m K)
SWH	0.05	0.88	0.05	0.05	0.04	0.02
PV/T	0.80	0.88	0.05	0.05	0.04	0.02

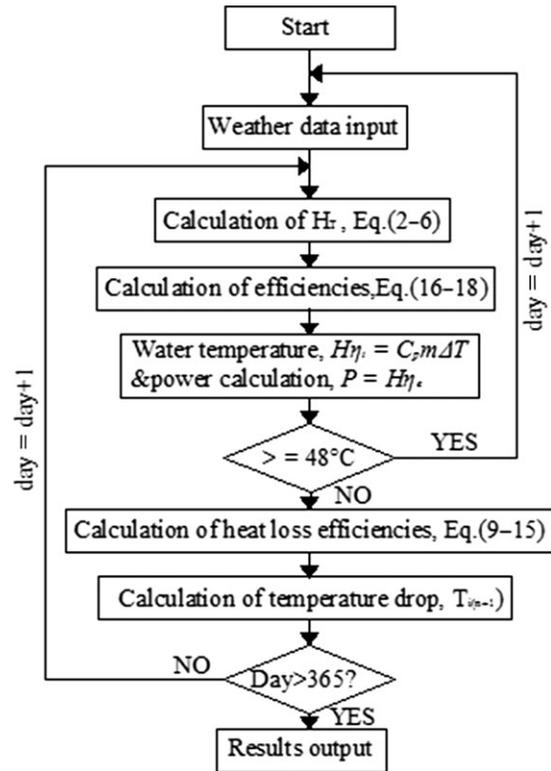


Figure 1. Annual system performance calculation flow chart of the CNHL case.

- (1) The hot water will be used only at night and will be all used if the water temperature is higher than the set point. There is no heat loss during the hot water usage.
- (2) Water recharge is at the sunrise time (if needed), and the consumed time is ignored.
- (3) In the CNHL case, if the water has been heated to a temperature higher than the set value at the daytime, the heating continues until there is no solar irradiation.
- (4) The water temperature can drop to the ambient temperature at night, but not below 0°C.

The calculation flow chart of the CNHL case is shown in Figure 1. The other two cases, which are relatively easy, are not listed here.

4 RESULT ANALYSIS

Monthly average R_b and monthly average ambient temperature of Shanghai city are presented in Figure 2, as well as the monthly cumulative solar irradiation on the horizontal plane and

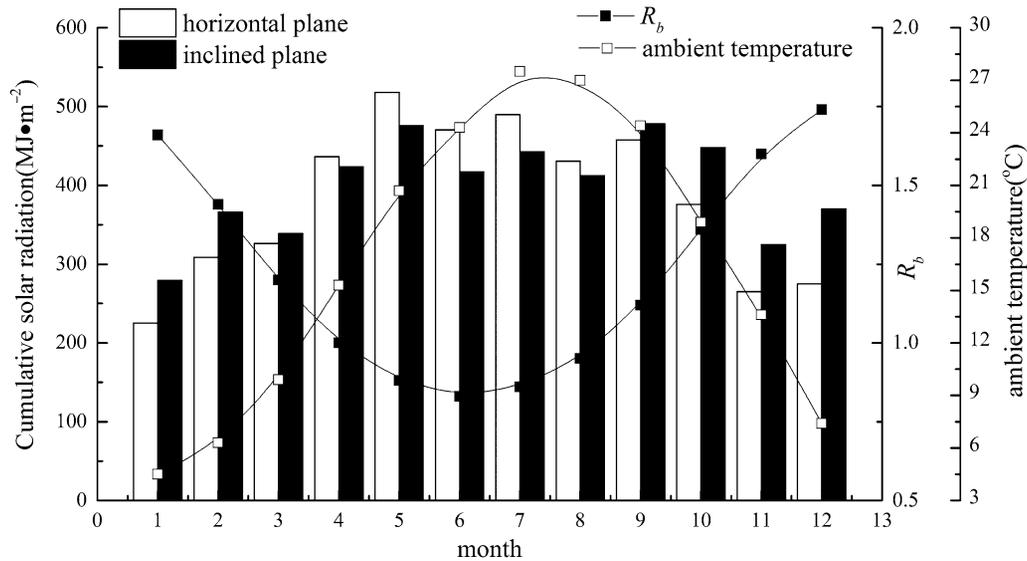


Figure 2. Variation in monthly cumulative solar irradiation, R_b and monthly average ambient temperature.

inclined plane. It can be seen that the monthly average R_b shows a trend of decreased first and then increased with the value range between 0.83 and 1.74, the maximum and minimum value in June and December, respectively. From Equations (3–7) it is known that the value of R_b is related to the solar declination angle δ , the hour angle of sunrise and sunset on the inclined plane ω'_s and the hour angle of sunrise and sunset on the horizontal plane ω_s . However, the values of ω'_s and ω_s are determined by geographical latitude ϕ and solar declination angle δ . When $0^\circ < \delta < 23^\circ 24'$, $\omega'_s = \pi/2$, the hour angle of sunrise and sunset on the horizontal plane ω_s increases with the increase of δ . So during the spring equinox to the summer solstice, R_b gradually decreased with the δ gradually increased. During the summer solstice to the autumnal equinox, R_b gradually increased with δ gradually decreased. When $-23^\circ 24' < \delta < 0^\circ$, $\omega'_s = \omega_s$, ω'_s decreases with the increase of δ ; so during the autumnal equinox to winter solstice, the R_b gradually increased with the δ gradually decreased. During the winter solstice to the spring equinox, and the R_b gradually decreased with the δ gradually increased.

It can be seen from Equation (2) that the solar radiation on the inclined surface is positively linear correlated with the R_b , when the collector inclination angle β is a constant value. Therefore it displays a similar trend with R_b . During May to August, the value of R_b is small than 1, so the cumulative solar irradiation on the inclined plane is smaller than the horizontal plane, while the other months are on the contrary. Monthly cumulative solar irradiation on the inclined surface is between 279.3 and 478.0 MJ/m², the maximum and minimum value in September and February, respectively. Yearly cumulative solar irradiation on the horizontal plane is 4578.6 MJ/m², while the value, which is 4776.7 MJ/m², is slightly larger on the inclined plane when the inclination angle equals to local latitude.

The monthly average ambient temperature, which has an overall trend of increase first and then decrease, fluctuates

between 4.5 and 27.5°C, the minimum and maximum value in January and July, respectively.

4.1 Comparison of annual thermal performance between SWH system and PV/T system

When only solar energy is used, the day number of SWH and PV/T system when the water temperature met the user demand is shown in Figure 3. It can be seen from the figure that the day number of a SWH system is more than the PV/T system under the same case every month. Both the SWH system and the PV/T system have the maximum value under the INHL case, and have the minimum value under the AH case.

For the SWH system, no matter the nighttime heat loss is considered or not, there are a certain day number when the water temperature can meet the required temperature every month under the continuous heating mode. However, when under the auxiliary heating mode, because of the water re-fill every morning, there are no days in which the water temperature can reach the set value when solar irradiance and the initial water temperature are both low, such as January and December.

For PV/T systems, since only part of the solar irradiation is transformed into thermal energy, it has low thermal efficiency. Besides, compared with the SWH collector, the structure of the PV/T collector is more complex, so there is considerable heat loss no matter in the day or at night. The two reasons lead to the fact that the heat gain of PV/T systems is limited. For example, in January, November and December, no day can meet the user demand under all the working cases. In February and March, even ignoring the nighttime heat loss that is under the INHL case, there are only two days that satisfy the user demand.

The maximum, minimum and total day numbers that meet user demand of SWH and PV/T system under different cases are shown in Table 2. It can be seen from Table 2 that the

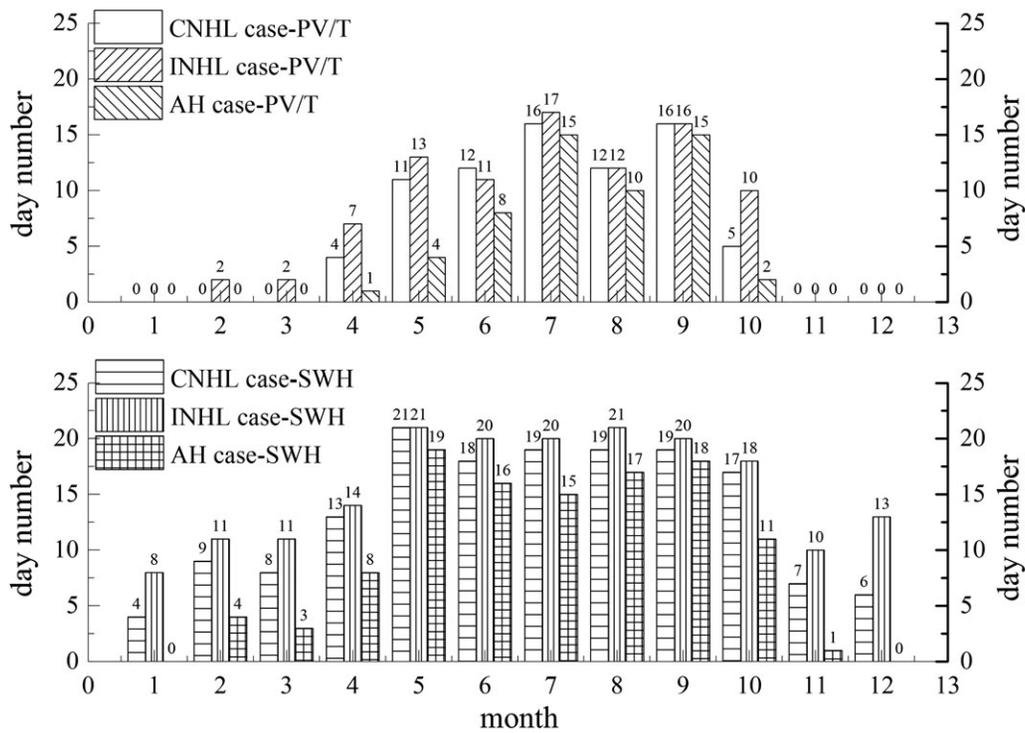


Figure 3. Monthly effective day number under different working cases.

Table 2. Monthly effective day number under different cases

Case	Monthly max (day)	Monthly min (day)	Annual (day)
INHL SWH	21	8	187
PV/T	17	0	90
CNHL SWH	21	4	160
PV/T	16	0	76
AH SWH	19	0	112
PV/T	15	0	55

annual effective day number of the SWH system under the INHL, CNHL and AH cases are 187, 160 and 112, respectively; The monthly maximum day number are ~20; the day number under the continuous heating mode is much more than that of the auxiliary heating mode. Compared with the CNHL case, the day number of the INHL case increases 17%, so reduce the system nighttime heat loss can effectively improve the contribution rate of solar energy.

For the PV/T system, under the three cases using only solar energy, the effective annual day number is 90 days, 76 days and 55 days, respectively, about half of the day number of SWH system in the corresponding modes. For the PV/T system, the maximum effective day number in a month is ~15 days. Ignoring the nighttime heat loss can increase the effective day number 18% comparing to consider the nighttime heat loss, slightly larger than the SWH system. The reason is because PV/T collectors have higher emissivity and the heat loss.

Figure 4 shows the monthly heat gain of the SWH system and the PV/T system under different operating conditions.

According to the figure, different from the varying pattern of the day number, both SWH or PV/T system have the maximum heat gain under AH case, middle heat gain under INHL case, and minimum heat gain under CNHL case. It is because according to previous assumptions, since the nighttime heat loss is ignored, so the heat gain under the AH case is larger than that of CNHL case; furthermore, the daily initial water temperature under the AH case is lower than or equal to that of the INHL case, which cause the photothermal efficiency of the former is bigger than that of the later one, thus the heat gain under the AH case is bigger than that of INHL case.

For the SWH system, the maximum heat gain under different cases are all deserving in September, in which month there is maximum monthly cumulative solar irradiation and relatively higher ambient temperature. For the PV/T system, the maximum heat gain under AH case is deserving in July, but it deserves in September under the continuous heating mode. However, photothermal performance in July and September is much closed.

The day numbers that meet user demand of a PV/T system under different cases are zero in at least three months, which are January, November and December. The heat gains in these months are also relatively low. The reason is that in January, November and December, the monthly cumulative solar irradiation and ambient temperature are relatively low. Considering the low photothermal efficiency and the large heat loss coefficient of the PV/T system, water will be heated to a relatively high temperature but not high enough to meet the user demand during the daytime. While in the nighttime, there is a big

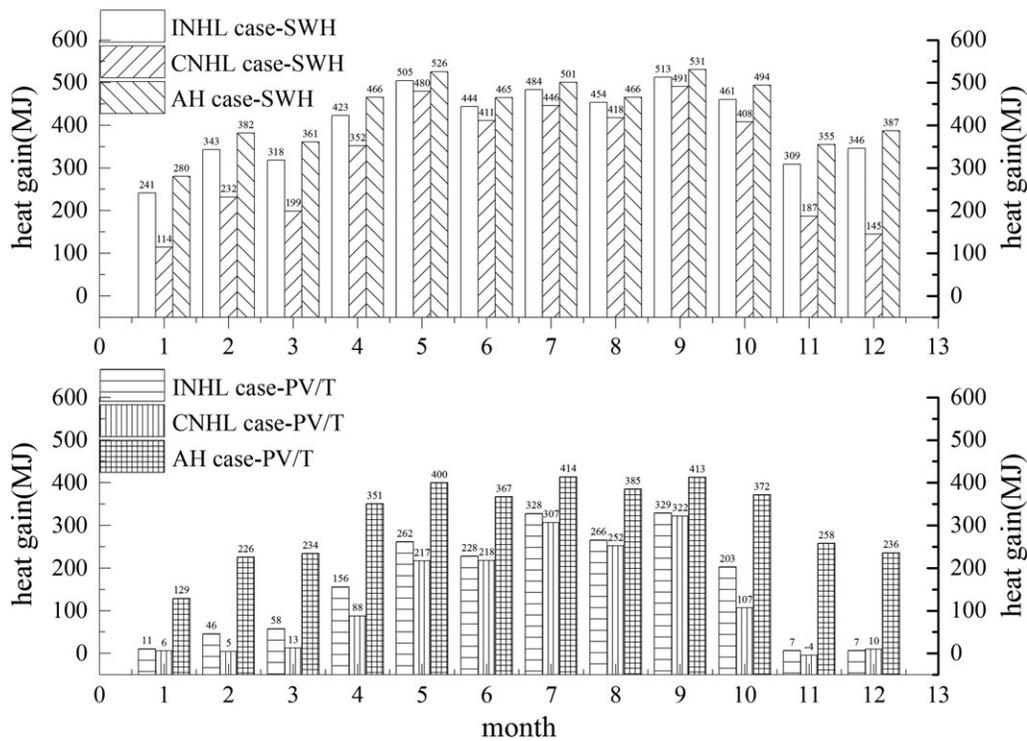


Figure 4. SWH&PV/T systems monthly heat gain under different cases.

temperature drop because of the big temperature difference between the water temperature and the ambient temperature, which will be leading a low initial water temperature in the next day. This condition recycles every day in the mentioned months, and the water temperature always lower than the set value, so the effective day number is zero. More information can be observed in Figure 4 that the heat gain in November is negative under the CNHL working condition. It is because the water temperature at the end of November is lower than that of at end of October.

The heat gain under the auxiliary heating mode reflects the maximum heat gain of the system. The INHL case is the ideal condition of the continuous heating mode, and the heat gain under this condition is also an ideal heat gain of continuous heating mode. The ratio between the nighttime heat loss and maximum heat gain (NHL/MHG), and the ratio between the nighttime heat loss and the ideal heat gain (NHL/IHG) is calculated and compared in Figure 5. Due to unreasonable fluctuation, comparisons in November, December and January are not taken into account in this paper. The figure shows that all the curves present an overall trend of decreased first and then increased. The curves of the SWH system are relatively smooth and the values are relatively small. So one can find that performance of the PV/T system is more sensitive to the ambient.

One can further see from Figure 5 that the ratios of NHL/MHG and NHL/IHG of the SWH system and the PV/T system during June, August and September are all around 0.1. It is because the solar irradiation and ambient temperature are

relatively high in these months; the final water temperature can reach or exceed the set value in the daytime most of time. Depending on the assumptions, there is no heat loss in the days in which the water temperature can meet the user demand. At the same time, the effective day number of the SWH system and PV/T system in these three months are all relatively large. Therefore, heat loss in these months is small. However, in the other months, the ratios are all relatively big, especially the ratios of NHL/MHG of PV/T system. It is because the monthly effectively day numbers in these months are relatively small, there is nighttime heat loss nearly every day, which leads a big ratio.

For the PV/T system, it is calculated that the annual average value of NHL/MHG is 52%, which means most of the absorbed energy are dissipated at nighttime under the CNHL case. The annual average value of NHL/IHG is 18%. Therefore, the AH case is the recommended operation mode when a PV/T system integrated with the building. However, when a PV/T system operates under the continuous heating mode, techniques that can lower the heat loss should be proposed, for example, decrease the emissivity of the absorbing plate [17], set up the check valve to prevent the hot water backflow to collector, employ the gravity assisted heat pipe as the heat transfer device [18], and so on.

For the SWH system, it is calculated that the annual average values of NHL/MHG and NHL/IHG are 18% and 13%, respectively. Therefore, both the AH case and the CNHL case are practicable when a SWH system integrated with the building. Methods mentioned above that can reduce the heat loss are equally applicable in SWH system.

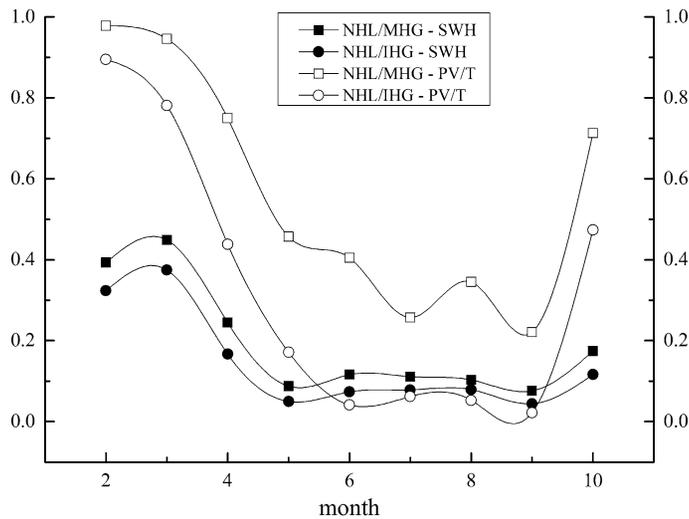


Figure 5. Ratios of NHL/MHG & NHL/IHG of SWH&PV/T systems.

To some extent, Figure 5 can reflect the heat loss dissipating at night on the whole. However, the heat loss caused by the collector is not presented. Ratios of heat loss caused by the collector have been presented in Figure 6, as well as the total heat loss at night.

From Figure 6, one can see that heat loss caused by the solar collector deserve a relatively stable high proportion every month; the annual average value is 91.3% for the PV/T system, while the value is 87.1% for the SWH system. So, reduce the collector heat loss at the nighttime is the main method to improve system performance for both of PV/T and SWH system under the CNHL case. Higher emissivity of the absorber plate and fewer effective day numbers of the PV/T system are responsible for the higher ratio when compared with SWH system. Besides that, one can further see that the ratios of SWH system and PV/T system both present a trend of decrease in August. It is because there are relatively higher effective day numbers and ambient temperature in August. The reason why PV/T system also has a decrease in March is because there is relatively higher ambient temperature in March when compared with January and February; in those three months, the effective day numbers are all zero. However, the water temperature cannot drop below the ambient temperature based on the assumption; the heat loss is comparatively small compared with January and February, which cause a ratio decrease in March.

Total heat loss curves are present different fluctuation trend compared with the heat loss ratio curves. For the PV/T system, the total heat loss curve presents a trend of increase first and then decrease and then increase with month; in the first three months, in which months the effective day numbers are zero, the heat loss increases with the solar irradiation increase and decreases with the ambient decrease; then, the total heat loss decreases with the effective day numbers increase and increases with the effective day numbers decrease. For the SWH system, the total heat loss curve presents a trend of decrease first and

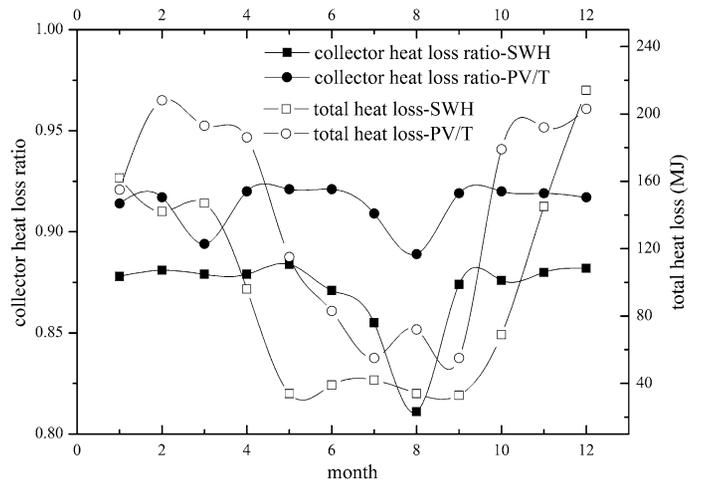


Figure 6. Collector heat loss ratio and total heat loss under different system.

then increases with the month and the curve under that of the PV/T system most of the time; the effective day numbers also play the main role in the curve fluctuation. Based on the calculation, for the PV/T system, 1696MJ is dissipated at the nighttime, while the value is 1157MJ for the SWH system.

4.2 Annual electrical performance of PV/T system

The monthly cumulative power generation (kWh) and monthly average electrical efficiency of the PV/T system under different cases are illustrated in Figure 7. The monthly average initial water temperature is shown in Figure 8. According to Figure 7, the monthly cumulative power generation and monthly average power efficiency always deserve the maximum value under AH case, and deserve the minimum value under INHL case expect in January, Figure 8 is on the contrary. Equation (18) shows that the electric efficiency is related to the initial water temperature, a high initial water temperature leads to a low electric efficiency. Water is recharged every morning under AH case, thus the system has the lowest initial water temperature and therefore the highest electrical efficiency. Similarly, system has the highest initial water temperature under the INHL case leads to a lowest electric efficiency. The corollary is in accordance with the temperature variation presented in Figure 8.

From Figure 7, one can further see that the average monthly electric efficiency of the INHL case is obviously lower than that of the other two cases, especially in the months which the effective annual day number are limited. The reason is same as above, the initial water temperatures in these months are obviously higher than that of the other two working conditions, which can also be verified in Figure 8. The abnormal wave of the electric efficiency in November under the INHL case can also explain in the same way.

The reason why the monthly average electric efficiency of the CNHL case is slightly higher than that of AH case in January is that the water temperature can drop to the ambient

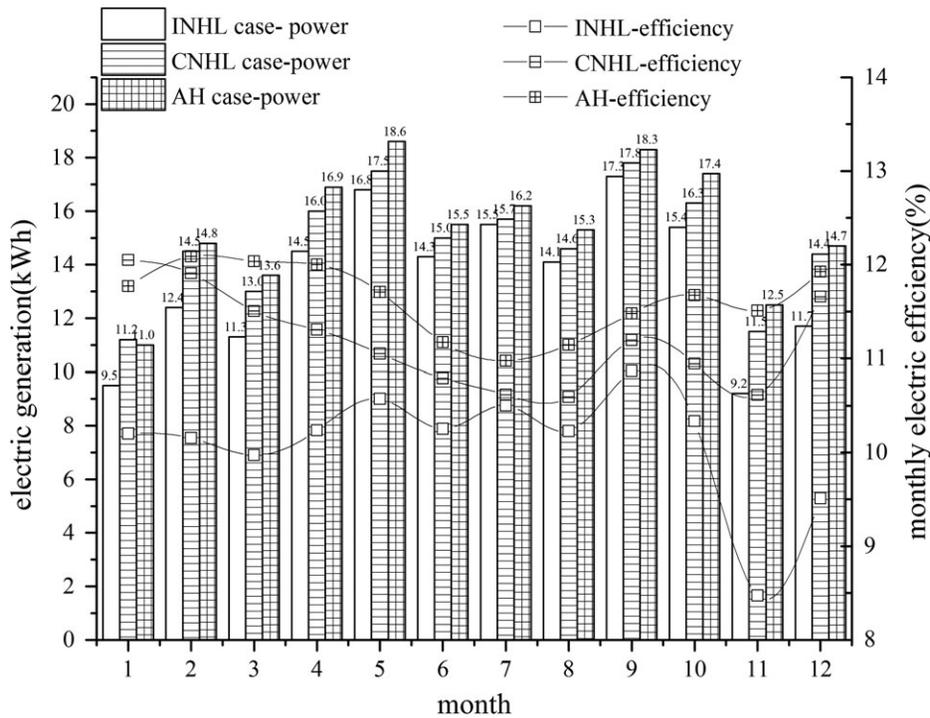


Figure 7. PV/T system monthly cumulative electric generation and monthly electric efficiency under different cases.

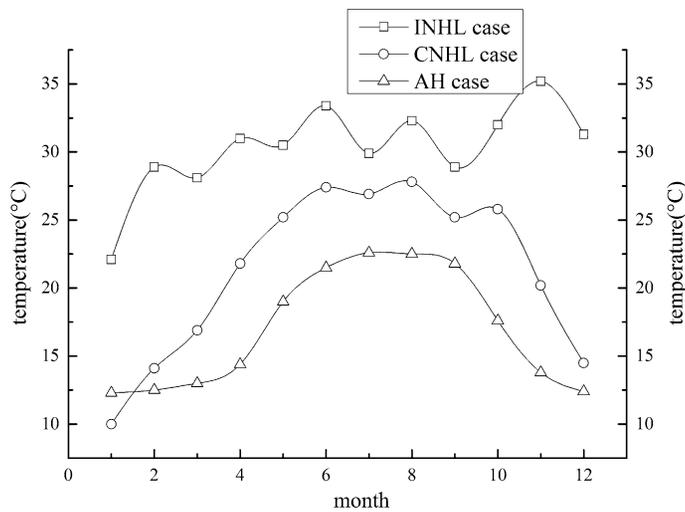


Figure 8. Monthly average initial water temperature of PV/T system under different cases.

temperature (but not below 0°C) because of the big heat loss in nighttime under the CNHL case, however, the recharge water, which is usually the municipal water, normally deserve a temperature higher than the ambient temperature in winter.

It is calculated that under different cases, the annual power generation of PV/T system is ~9.2–18.6 kWh. Overall, in May and September the larger total solar radiation leads to the larger power generation. Under different case, the average monthly power efficiency of the system in most months fluctuates between 10.0% and 12.1%, and is less than 10% in only 2

months. In the INHL case, the lowest monthly average electrical efficiency is in November, the value is only 8.5%.

4.3 Comparison of system primary efficiency

Primary efficiency of the SWH system is the photothermal efficiency because the system only gains heat. While for the PV/T system, it gains both heat and electricity, the quality of electricity is higher than that of the heat, thus its primary efficiency is calculated by Equation (8). Under different cases, system overall performance is shown in Figure 9.

According to the figure, in general, the SWH system and PV/T system both have the highest primary efficiency under the AH case and the lowest primary efficiency under CNHL case. The overall performance of a SWH system is obviously higher than that of PV/T system in continuous heating mode. In addition, the AH and INHL cases of SWH system and the AH case of PV/T system deserve smooth curves, while the others fluctuate remarkably.

For the PV/T system, it has a high overall performance under AH heat mode, while in continuous heating mode, fiercely fluctuations are presented due to the low thermal efficiency and big heat loss coefficient. It is calculated that when the solar irradiation is weak or the ambient temperature is low, the overall efficiency of the system is relatively low; the values are only around 20% in winter and early spring.

For the SWH system, it has big fluctuations only under the CNHL case. While in this condition, system present unsatisfactory only in January and December. In the other words, SWH

system shows a relatively stable and expected performance under any conditions.

The monthly average maximum, monthly average minimum and annual average overall efficiency of SWH and PV/T under different cases are given in Table 3.

Wealth information can be seen from Table 3. For the PV/T system, the average annual efficiency under the AH case is significantly higher than that of the other two cases. The nighttime heat loss has a significant effect on the heat gain of the PV/T system, while it has little effect on the overall performance of the system. This is mainly because that the heat loss reduces the heat gain, but also reduces the initial water temperature at the same time, improves the photoelectric efficiency instead. For the SWH system, nighttime heat loss significantly

influences system performance, but the superiority of the AH working condition is not obvious here.

Therefore, when integrated with the buildings, the actual annual performance of the SWH and PV/T systems presents a different conclusion of the published papers that based on short-time running. The results are directly related to the operating modes. Synthesize the above analyses; the auxiliary heating mode is the only way that recommends for the PV/T system. For the SWH system, both the auxiliary heating mode and the continuous heating mode are appropriated.

4.4 Economic analysis

The economic benefits of the SWH system and the PV/T system are calculated based on the static payback period. In this paper, the conventional electric water heaters and gas water heaters are compared with. The prices of electricity and natural gas are ¥0.667/(kWh) and ¥3.62 /m³, respectively, coincide with the second tiered electricity price of Shanghai city. The heat value of natural gas in Shanghai city is 34MJ/m³, and the thermal efficiency of gas water heaters is 0.88 [19]. The thermal efficiency of the electric water heater is 0.9 [20]. The initial investment of a SWH system and a PV/T system with 2 m² collector is ~¥2300 and ¥3500 based on the market research. Detail information about the payback period under different working conditions is presented in Table 4.

From Table 4, one can see that for the SWH and PV/T system, there is a relatively short static payback period when compared with the electric water heater, it is because the price of per MJ energy of gas is nearly 80% more than the electric. Compared with the SWH system, the PV/T system has a longer static payback period under the same working condition, and the difference taking the minimum value under the AH case at which time the PV/T system deserves the best performance.

Compared with the electric water heater, the static payback period of the SWH system is ranging between 2.1 and 2.8 years, while the value is 3.8–7.9 years for the PV/T system. Compared with the gas water heater, the static payback period of the SWH system is ranging between 3.6 and 4.9 years, while the value is 6.0 and 1.4 years for the PV/T system. Both the SWH system and the PV/T system have the shortest payback period under the AH case. Besides, one can further see that the SWH system deserves a closed value under different working condition.

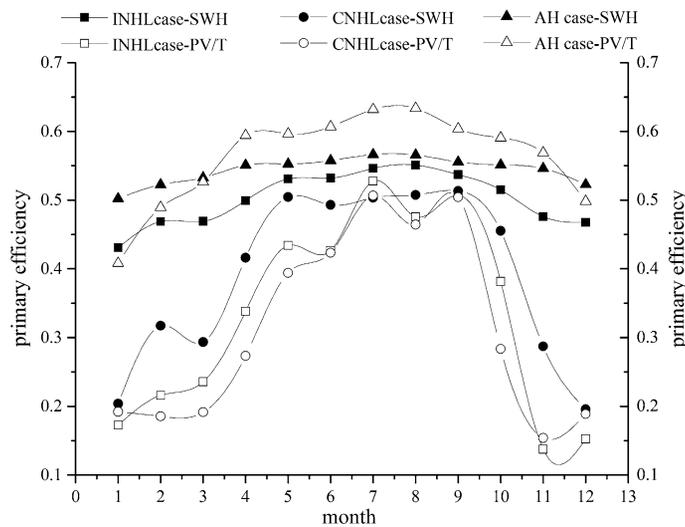


Figure 9. System primary efficiency under different cases.

Table 3. Summary of SWH & PV/T systems primary efficiency

Case		Monthly max (%)	Monthly min (%)	Annual average (%)
INHL	SWH	55	43	51
	PV/T	53	14	35
CNHL	SWH	51	20	41
	PV/T	51	15	35
AH	SWH	57	50	55
	PV/T	63	41	61

Table 4. SWH&PV/T systems static payback period under different working conditions

Case		Annual heat gain (MJ)	Annual electric generation (kWh)	Electric water heater (year)	Gas water heater (year)
INHL	SWH	4841.23	/	2.3	3.9
	PV/T	1900.61	161.85	6.9	10.3
CNHL	SWH	3882.40	/	2.8	4.9
	PV/T	1541.25	177.53	7.9	11.4
AH	SWH	5215.43	/	2.1	3.6
	PV/T	3783.71	184.77	3.8	6.0

5 CONCLUSIONS

Published studies on the performance comparison of the solar water heating system (SWH) and photovoltaic thermal (PV/T) system were mainly under high solar irradiation and short-term operating, while the comparison of energy saving characteristics in long-term operating is rare. In this paper, the annual operating performance and economic efficiency of the domestic SWH system and the PV/T system under three working conditions are compared and analyzed based on the meteorological data of Shanghai city. The main conclusions are below:

- (1) Under different cases, when only utilizing solar energy, the effective annual day number that can meet user demand of SWH system is ranging between 112 and 187, while the value is 55–90 of PV/T system. Both take the maximum value under the continuous heating mode ignoring the nighttime heat loss.
- (2) Nighttime heat loss influences the PV/T performance obviously, especially under the continuous heating mode. The annual electricity generation of the PV/T system is ranging between 9.2 and 18.6 kWh, electricity efficiency is mainly affected by the initial water temperature.
- (3) The overall performance of the PV/T system is better than that of the SWH system only under auxiliary heating mode; when under different working conditions of continuous heating mode, the PV/T system has the same performance but significantly less than the SWH system.
- (4) Compared with the traditional water heater, the SWH system has a shorter static payback period, and always presents a promising economic efficiency under different working conditions. However, the static payback period of PV/T system is only satisfactory under the auxiliary heating mode.

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