研究論文

A simulation of the performance of PV-thermal (PVT) systems for residential application in Tokyo

Thipjak NUALBOONRUENG [*1]　　Kaoru HIRAYAMA [*]
Yuki UEDA [*]　　Atsushi AKISAWA [*]

Abstract

Although PV-thermal (PVT) technology which simultaneously produces not only electricity but also heat has a long history, they are still under development. The objectives of this study are investigating PVT performance installed in Tokyo by simulation, evaluating matching with PV cell type and estimating possible primary energy reduction when PVT systems are used in 12 sample houses. PV cells of crystalline silicon, amorphous silicon and multi-crystalline silicon were examined in this study. TRNSYS modeling technique was employed to simulate the behavior of PVT systems with a hot water storage tank. The results indicate that optimal water flow rate in the collector loop is 35 kg/h for all types of PVT collectors for the collector areas of 4 and 6 m^2. According to the comparison with individual PV and solar water heater of the same aperture area, it was found that PVT system would replace primary fuel consumption with solar energy the most effectively, approximately 1.5-2 times larger reduction than the conventional devices. PVT with crystalline silicon cells achieves the highest primary energy reduction among three PV cell types. The results suggest that PVT for residential application is enough useful to utilize solar energy under the climatic conditions of Japan.

Key Words: PVT systems, Photovoltaic cell, Solar Thermal, Primary energy reduction

1. Introduction

Electricity in Japan is generated predominately by fossil fuels and nuclear power plants, but renewable energy, such as Photovoltaic (PV), is popular in Japan. Japan also has a world-class ranking of PV production and R&D activity. The residential sector in Japan has adopted the use of both PV and SHW for houses, and there have been incentive programs for them in Japan in recent years. PV-Thermal (PVT) systems simultaneously provide electricity and heat and can be presented to users as an optional or alternative choice for employing renewable energy in their houses. Typical PV modules can only convert 10-20% of solar radiation to electricity; part of it is reflected back to the sky, and the rest is transformed into heat. The same is true for PVT collectors, where the absorbed solar radiation is only partially converted to electricity by PV cells while the other excess energy is transformed into heat which is utilized as low-temperature heat energy corresponding to hot water applications. The PVT collector concept offers an opportunity to increase overall system efficiency with a certain solar intake.

[*1] Graduate School of Bio-Applications and Systems Engineering, Tokyo University of Agriculture and Technology (2-24-16 Naka-cho, Koganei, Tokyo 184-8588 Japan)
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Because it is well known that the efficiency of PV cells decreases with increasing operating temperature, the generated electrical energy by PVT should be theoretically improved by the cooling effect of heat extraction in the PVT collector.

The studies of PVT system by number of researchers, Florschuetz [1] extended the well-known equation of Hottel-Willier, who analysed the flat plate solar collector to PVT collector, by assuming that the electrical conversion efficiency of the solar absorber is a linear decreasing function of the absorber temperature over its operating temperature ranges. He concluded that the thermal performance of the PVT collector may be exactly determined in the same way as a pure (normal) collector. The proposed equation of Florschuetz can also be used for many other works in solar the energy field using Hottel-Willier's equation. Kalogirou [2] reported PVT performance regarding the optimum water flow rate, the mean annual efficiency of the used PV and the payback period of the system. His work has been conducted on the performance of PVTs with 5.1 m^2 of collector area, 150 litres of water consumption per day and a mono-crystalline solar absorber under the climate of Cyprus. He concluded that the optimum flow rate was 25 l/h, that the PVT system could increase the mean annual PV efficiency from 2.8% to 7.7% and that it covered 49% of the hot water needed for one house. The system could increase its annual efficiency to 31.7%, and the payback was 4.6 years. Zondag et al [3]. evaluated nine different designs of PVT collectors with an analytical method. Their results showed that the best efficiency of PVT using multi-silicon as an absorber was with the channel-below-transparent-PV type. The annual efficiency of the PV-on-sheet-tube type is 2% worse, but it is easier to manufacture. Jong [4] examined three different PVT systems .The first was used as a hot water system for a house under a Dutch climate. The PVT area was 6 m^2 with a 200-litre storage tank for a hot water demand of 175 litres. The result of his first system showed that the thermal and electrical efficiencies were 22.1% and 6.8%, respectively. The second system was the preheating of ventilation air for a boarding house in London. The PVT collector area was 183 m^2, and it generated electricity and heat used for a boarding house. The simulation results showed that the thermal and electrical efficiencies were 27% and 6.9%, respectively. The third PVT system was a low-temperature heating system that used the generated heat for floor heating. The simulation was executed under a Dutch climate using a 5 m^2 PVT collector area. Vokas et al [5] . reported a theoretical study of a PVT system for domestic heating and cooling in various locations and areas of collectors. The study locations were Athens, Heraklion and Thessaloniki, and the varied areas were 30 m^2, 50 m^2 and 70 m^2. The analysis results showed that for the PVT system operating in different geographical regions, the coverage percentage of the domestic heating and cooling load is greatly affected by the region. For Heraklion and the region of Thessaloniki, there was a difference in solar coverage percentage of approximately 15%. Their research led to the conclusion that a PVT collector could produce a remarkably large amount of thermal energy. In addition, it was proved that this thermal energy could be used to cover a considerable percentage of the domestic heating and cooling load.

The advantages of the PVT system are the following：

- Higher energy yield per square meter of surface area due to simultaneous generation of electricity and heat
- Reduced installation costs

Electricity and heat are fundamental needs for all consumers. PVT technology can be a good choice for sustainably minded individual, who intend to replace fossil fuel consumption with renewable solar energy. However PVT technology is still under development although it has a long history.

The main objective of this study is investigating annual performance installed in Tokyo by simulation. Most of past studies on PVT investigated a typical specific house. In contrast, this study analysed the performance using actual load data of 12 houses of various size families in order to capture more realistic and reliable performance of PVT systems.

This study also examined the system

performance of three types of PV panels crystalline Silicon (c-Si) cells, amorphous silicon (a-si) cells and multi-crystalline silicon (mc-Si) cells used as the absorbers of the PVT collectors. The areas of the collectors are 4 and 6 m^2 for all types of PVTs. Moreover, PVT system performance is evaluated from the viewpoint of primary energy reduction which is defined in this study to combine both effects of electricity generation and heat supply.

2. Description of the system

2.1 PVT system

Figure 1 represents a schematic of the system model. The system consists of PVT collectors, a hot water storage tank and a circulation pump controlled by a differential controller to prevent heat rejection from the storage tank to the ambient environment via the collector. The electricity produced by the system is connected to the house via an inverter. The hot water produced is used for home applications with an external auxiliary backup heater to ensure that the user can obtain expected temperature level. The set point of temperature controller to enable the heater was set at 55 ℃. The effect of the collector area (4 m^2 and 6 m^2) was also investigated in this study.

2.2 PVT collector

The configuration of the PVT collectors is shown in Figs. 2-3. The configuration is a PV-on-sheet-and-tube type, which is the most practical for use and is easier to manufacture, as Zondag et al [3]. mentioned in their report. The configuration of the PV-on-sheet-and-tube type PVT is described in detail as follows.

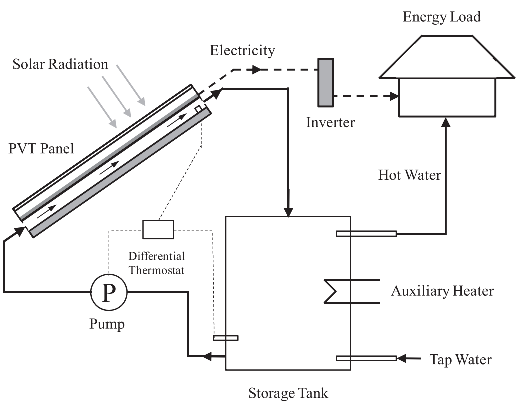

Fig. 1 Schematic of PVT system in system simulation

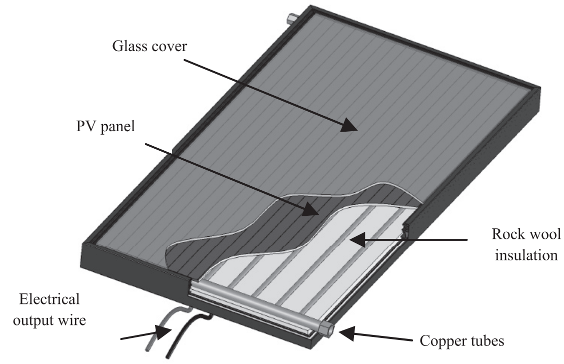

Fig. 2 Schematic of PVT collector

The PV panels are adhered on the top of the metal plate by thermal epoxy. There are longitudinal circular channels beneath the metal plate, which are prepared for attaching the circular copper tubes. The rear side of the copper tubes has a rock wool insulation layer to prevent heat losses from the bottom. The low iron and high transparency glass covers (with 90% transparency) are used to reduce heat loss from the top surface of the PV to the ambient environment caused by wind convection.

In this study, three types (a-Si, mc-Si and c-Si) of PV panels are adopted as solar absorbers in the PVT collectors. The nominal conversion efficiency of

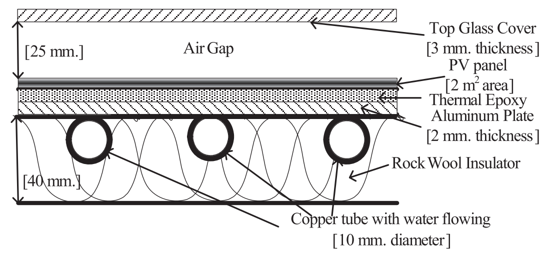

Fig. 3 Cross section of PVT collector

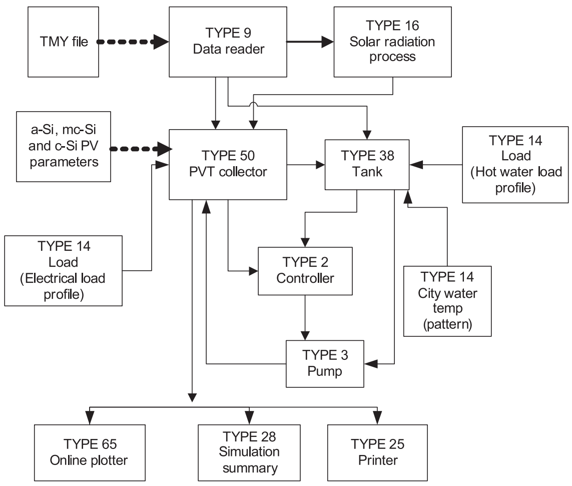

Fig. 4 TRNSYS information flow diagram of PVT system

the PV panels is 6.3%, 12.7% and13% for a-Si, mc-Si and c-Si PV, respectively.

2.3 System settings

This study focused on the application of home use in a specific location, namely, Tokyo.The settings of the PVT systems in this study are 35 degree of collector slope, zero degree of azimuth, 0.12 m^3 storage tank with heat loss coefficient of 1.4 W/K (5.0 kJ/h.K) and temperature difference controller with 10 ℃ setting point.

3. Simulation model

3.1 TRNSYS model

A well-known computer simulation tool, TRNSYS, was used in this study to investigate the dynamical system performance. TRNSYS consists of many subroutines that represent system components. The user can define the input and output, including the parameters of each system component. TRNSYS has the capability of interconnecting system components as desired, facilitating information acquisition and the formulation of general mathematical description of components. Figure 4 illustrates the flow diagram describing the structure of simulation model and the relationship among the components to simulate PVT system behaviour in this study. TRNSYS components are referred to as TYPEs, which have mathematical equations inside. Many TYPEs are then interconnected to form a system. As shown in Fig. 4, the system flow diagram consists of a TYPE50 PVT Collector, TYPE3 circulating pump, TYPE38 hot water storage tank, TYPE2 differential temperature controller, TYPE 14 electricity and hot water consumption load profile.

The modifiedHottel-Willier's equations proposed by Florschuetz [1)] were used to calculate heat recovery and electricity generation. The heat recovery equation is described as :

$$Q_u = A_c \tilde{F}_R[\tilde{S} - \tilde{U}_L(T_i - T_a)] \cdots\cdots (1)$$

and electricity generation is :

$$Q_e = \frac{A_c S \eta_a}{\alpha}\left\{1 - \frac{\eta_r \beta_r}{\eta_a}\left[\tilde{F}_R(T_i - T_a) + \frac{\tilde{S}}{\tilde{U}_L}(1 - \tilde{F}_R)\right]\right\} \quad (2)$$

Here, A_c is collector area, S is solar radiation absorbed by absorber. $\tilde{S}$ is modified solar radiation ($\tilde{S} = S(1-(\eta_a/\alpha))$) .$\eta_a$, η_γ are cell efficiencies valuated at ambient temperature and reference temperature respectively. β_γ is temperature coefficient of PV cell, α is effective absorptance of absorber, $\tilde{U}_L$ is overall unit thermal conductance for collector heat loss. ($T_i - T_a$) is collector fluid inlet-to-ambient temperature difference and $\tilde{F}_R$ is collector heat removal factor (0.13-0.90) .

3.2 Typical Meteorological Year (TMY)

Predicting the annual performance of solar technologies usually requires hourly meteorological data covering an entire year. Typical Meteorological Year (TMY) is used in a wide range of simulation programs instead of normal several-year meteorological data sets. TMY is composed of hourly metrological data of 12 months. Each month in TMY is called a typical meteorological month, which was derived from various years with the condition that it needs to represent the statistical characteristics of the meteorological conditions of that month. In this study, the TMY database of Tokyo investigated by AMeDAS (*A*utomated *Me*teorological *D*ata *A*cquisition *S*ystem) was used to predict PVT system performance.

3.3 PVTParameters

The input parametersfor PVT collectorsare shown in Table 1.

Table 1 PVT collector parameters

PVT type	c-Si	mc-Si	a-Si
Collector area (m^2)	4, 6	4, 6	4, 6
Packing factor (ratio of PV cells area to absorber area)	0.9	0.9	0.9
Nominal PV efficiency(%)	13	12.7	6.3
Number of glass covers	1	1	1
Temperature coefficient of PV cell (/°C)	-0.0043	-0.0043	-0.0023
Glass cover transparency (%)	90	90	90
Emissivity of absorber	0.09	0.09	0.09
Diameter of copper pipe (mm)	10	10	10
Overall unit thermal conductance for collector heat loss ($W/m^2.K$)	5	5	5
Effective absorptance of absorber	0.9	0.9	0.9

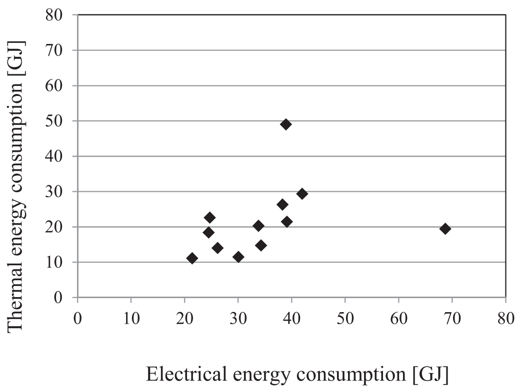

Fig. 5 Annual energy consumption of 12 houses

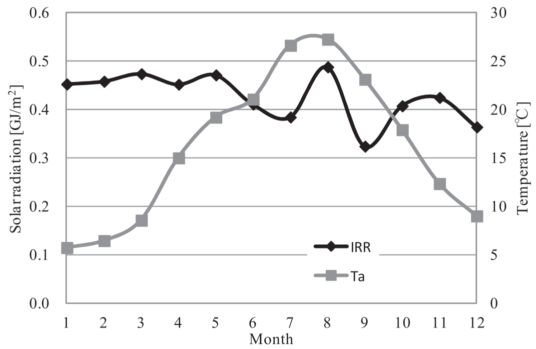

Fig. 7 Total radiation and ambient temperature

3.4 Energy demand data

This study used actual data of electricity and hot water consumption measured at 12 houses in Tokyo. The data of every hour throughout a year were provided to investigate hourly system behavior. Not one typical sample but 12 samples were employed so that this study could evaluate the influence of energy loads on PVT performance. The sample houses cover 92 m^2 – 330 m^2 in terms of floor areas and 3 – 6 persons of family size. They are all detached houses located in Tokyo. Figure 5 indicates the profiles of annual electricity and hot water consumption for each house. It can be seen that the samples distribute widely, which means various energy demand profiles were investigated in this study.

3.5 City water temperature, ambient temperature and total radiation profile

Figure 6 shows the city water temperature of Tokyo measured by the Bureau of Waterworks, Metropolitan Government, Tokyo [15]. Fig. 7 shows the total radiation (IRR) that strikes the coplanar of PVT collector and ambient temperature (Ta) of Tokyo. These data were used in the PVT simulation as shown in Fig.4.

4. Results and Discussion

4.1 PVT system behaviour

Figures 8-9 show a sample of simulated behaviour of 4 m^2 collector area of c-Si PVT, the solar energy input and energy generation of the PVT collector in hourly basis. In Fig. 8 both electricity generation and thermal energy curves follow the pattern of solar radiation as expected. The maximum energies productions were occurred around noon and minimum in morning and evening time. In Fig. 9 the temperature of hot water supplied to the house and electrical production are curves with the solar radiation shape while the temperature of water in storage tank is higher than the water supply due to the backup auxiliary heater.

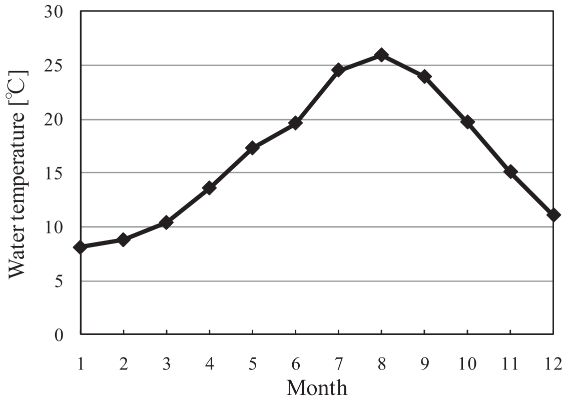

Fig. 6 City water temperature of Tokyo

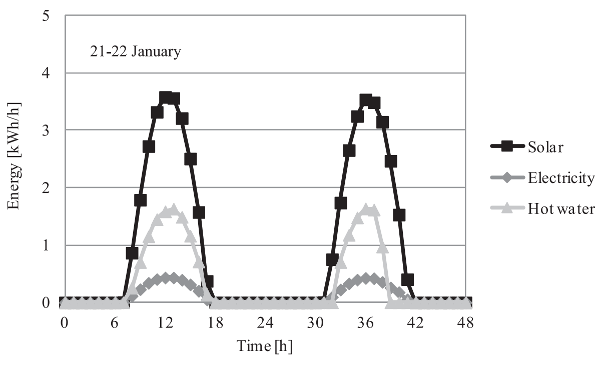

Fig. 8 Simulation example of energy production

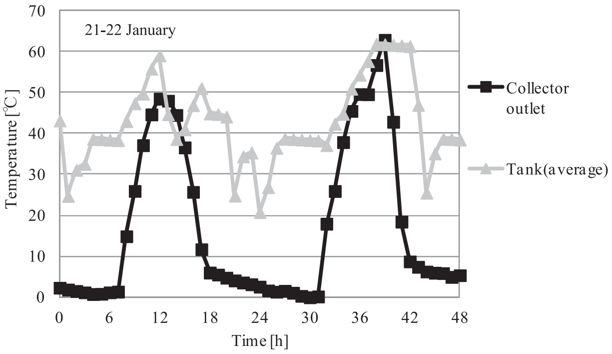

Fig. 9　Simulation example of temperature behaviour

4.2 Energy output from the PVT system and optimum water flow rate

Figures 10-12 show the electrical and thermal energy outputs of the c-Si, mc-Si and a-Si PVT systems with collector areas of 4 m^2 and 6 m^2. The results show the average value of 12 houses within the consideration range of water flow rate between 10 to 75 kg/hr. The results also show that the maximum energy output was achieved at 35kg/hr for both considered collector areas and for all types of PVT collectors. The PVT system has a temperature differential controller that manages the circulating pump to switch on when the temperature difference between water outlet and inlet of the collector greater than the setting point. Since the water flow rate increases higher, the temperature difference drops significantly, which results in losing the time of operation of the circulating pump. Therefore it can be seen that the annual heat outputs decreases at high water flow rate.

When the optimal flow rate is normalized with the collector areas of 4 m^2 and 6 m^2, the values are represented as 2.4 x 10^{-3} kg/ (s.m^2) and 1.6 x 10^{-3} kg/ (s.m^2) respectively. For a quantitative report that can be used for system installers, the maximum values are presented in Table 3, whereand are the thermal energy output and electricity output from the PVT collector, respectively.

Figures 13-15 show the electrical and thermal

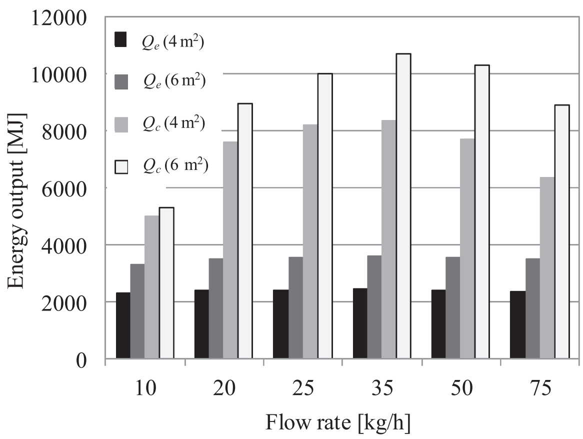

Fig.10　Electrical and thermal energy of c-Si PVT

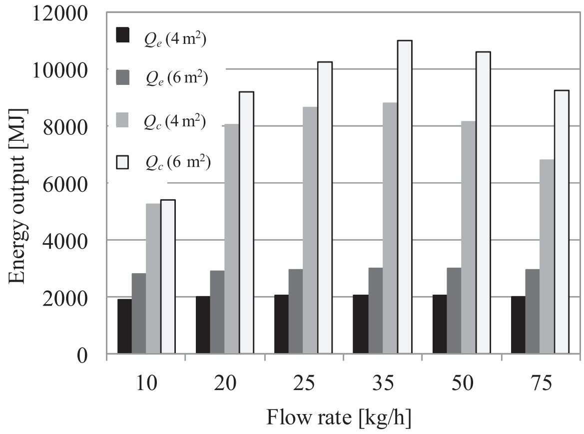

Fig.11　Electrical and thermal energy of mc-Si PVT

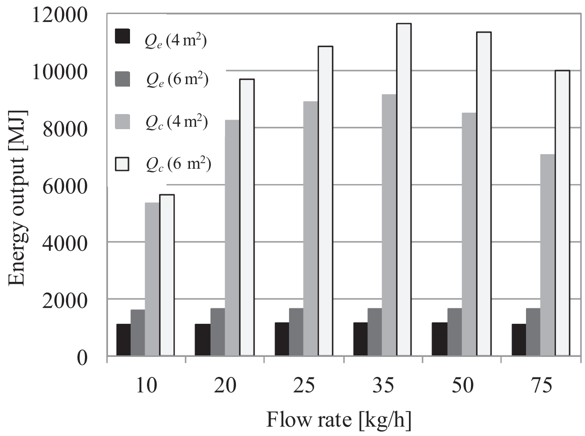

Fig.12　Electrical and thermal energy of a-Si PVT

Table 3　Energy outputs of PVT systems at the water flow rate of 35 kg/hr

	4 m^2 collector area			6 m^2 collector area		
	c-Si	mc-Si	a-Si	c-Si	mc-Si	a-Si
Qc [MJ]	8.3x10^3	8.8x10^3	9.1x10^3	1.1x10^4	1.1x10^4	1.2x10^4
Qe [MJ]	2.4x10^3	2.0x10^3	1.1x10^3	3.6x10^3	3.0x10^3	1.7x10^3

Table 4　Thermal and electrical efficiencies of PVT systems at the water flow rate of 35 kg/hr

	4 m^2 collector area			6 m^2 collector area		
	c-Si	mc-Si	a-Si	c-Si	mc-Si	a-Si
Thermal eff. [%]	41	43	45	35	36	38
Electrical eff. [%]	12	9.9	5.5	12	9.7	5.4

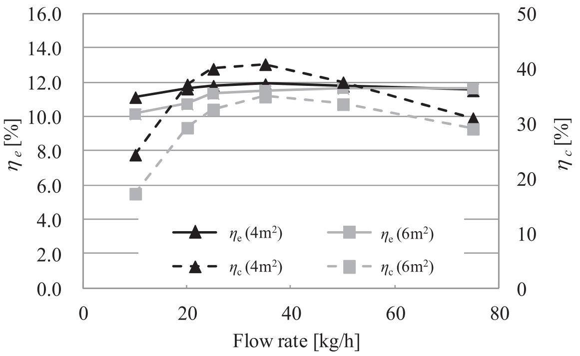

Fig. 13 Electrical and thermal efficiency of c-Si PVT system

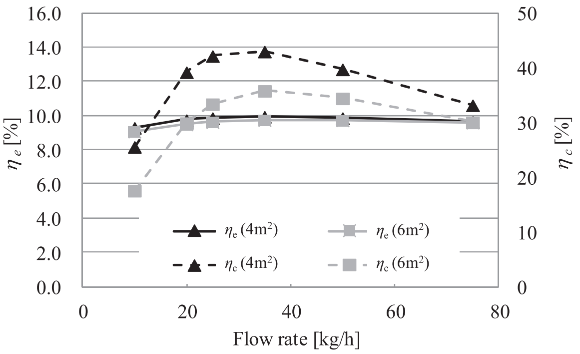

Fig. 14 Electrical and thermal efficiency of mc-Si PVT system

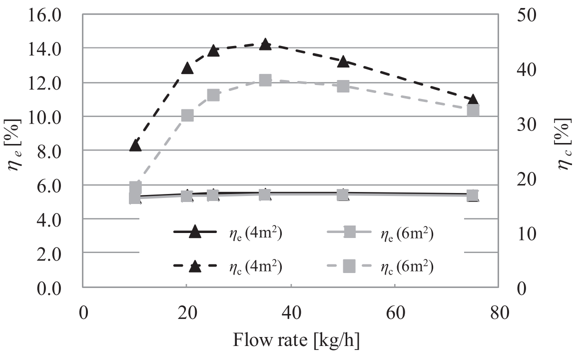

Fig. 15 Electrical and thermal efficiency of a-Si PVT system

efficiency of all types of PVT collectors with collector areas of 4 m^2 and 6 m^2. The maximum efficiencies are found at the water flow rate of 35 kg/hr and are presented in Table 4.

4.3 Improvements of electrical efficiencies of PV cells

Figures 16 – 18 show the variation of monthly electrical efficiency of the PVT and PV panels with 6 m^2 area. As shown, the cell efficiencies of both the PVT and normal PV panels are at their maximum during the winter and their minimum during the summer. This result is due to the ambient temperature which directly affects by the electricity production of PV panels. The cooling effect produced by water flowing into the PVT collector can slightly increase the cell efficiencies for all types of PV panels. The improvements of yearly average electrical efficiencies are 0.31%, 0.11% and 0.08% for c-Si, mc-Si and a-Si PVT system, respectively. The improvement of electrical efficiency by the cooling effect for c-Si PVT is higher than the other types of PVT because the value of the temperature coefficient of c-Si is higher than the other PV types.

4.4 Effect of primary energy reduction

To indicate the performance of the PVT system used in residential application, the effect of primary energy reduction is calculated here to evaluate the

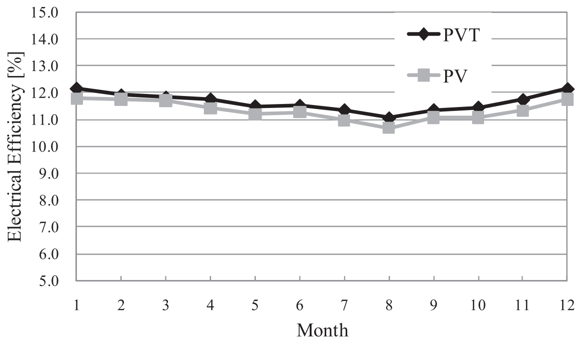

Fig. 16 Electrical efficiency of PVT and PV (c-Si)

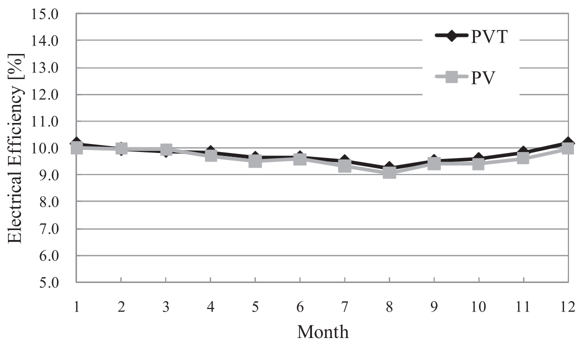

Fig. 17 Electrical efficiency of PVT and PV (mc-Si)

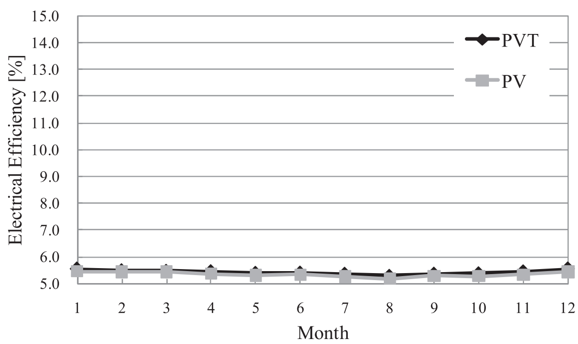

Fig. 18 Electrical efficiency of PVT and PV (a-Si)

contribution of electricity and heat supply totally. Because electricity and heat are different secondary energy, it is not appropriate to sum both of them directly. The expression of the primary energy reduction is given as follows：

$$C=\frac{E}{\eta_e}+\frac{Q_{aux,0}}{\eta_h} \quad \cdots\cdots (3)$$

$$M=\frac{Q_e}{\eta_e}+\frac{Q_{aux,0}-Q_{aux}}{\eta_h} \quad \cdots\cdots (4)$$

$$R=\frac{M}{C}\times 100 \quad \cdots\cdots (5)$$

where

C [MJ]：Primary energy consumption

E [MJ]：Electrical energy load

M [MJ]：Primary energy reduction

$Q_{aux,0}$ [MJ]：Auxiliary heating rate without solar heat

Q_{aux} [MJ]：Auxiliary heating rate with solar heat

Q_e [MJ]：Electrical power output

η_h [-]：System gas boiler efficiency (＝ 0.85)

η_e [-]：System power generation efficiency (＝ 0.428)

R [%]：Rate of primary energy reduction

Here all types of the PVT systems for 12 sample houses were investigated from the view point of primary energy reduction. The vertical axis of Figs 17 – 19 indicates annual primary energy reduction while the horizontal axis means annual primary energy consumption of houses. The data of the 12 houses are plotted in the graphs which clearly show very wide range of samples from 70 up to 200 GJ/year in terms of energy consumption.

Figures 17 – 19 intend to compare the performance of PVT system with individual PV or SHW collector which has the same aperture area. The results show that for all types of considered PVs and collector areas, the PVT has higher primary energy reduction than the individual PV and SHW collectors. It can be seen that c-Si PVT systems have the most significant primary energy reduction that is, approximately 1.5-2 times as much as individual SHW or PV for medium size houses.

Figure 20 shows the rate of primary energy reduction for the three types of PVT collectors for the 12 houses. The figure reveals that the rate of primary energy reduction decreases with increasing energy consumption of the houses and that the c-Si PVT has the highest value, with arrange between 8

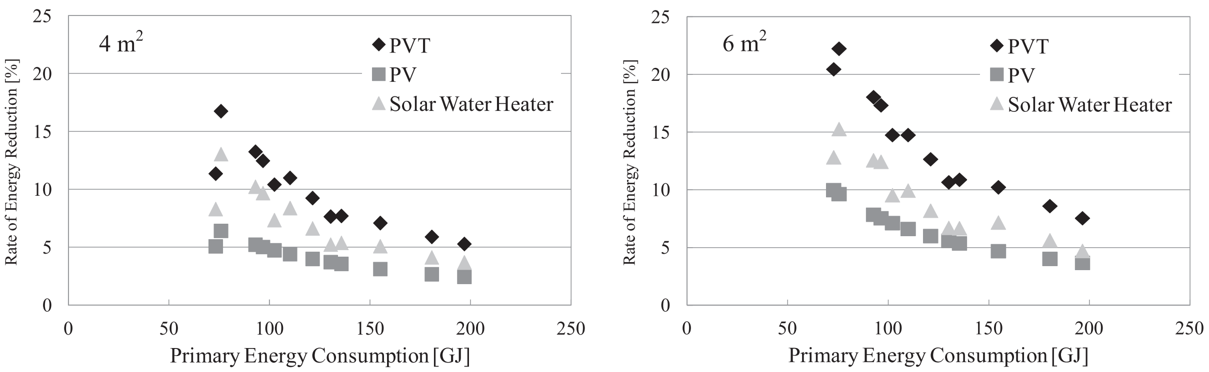

Fig. 19　Rate of primary energy reduction of c-Si PVT

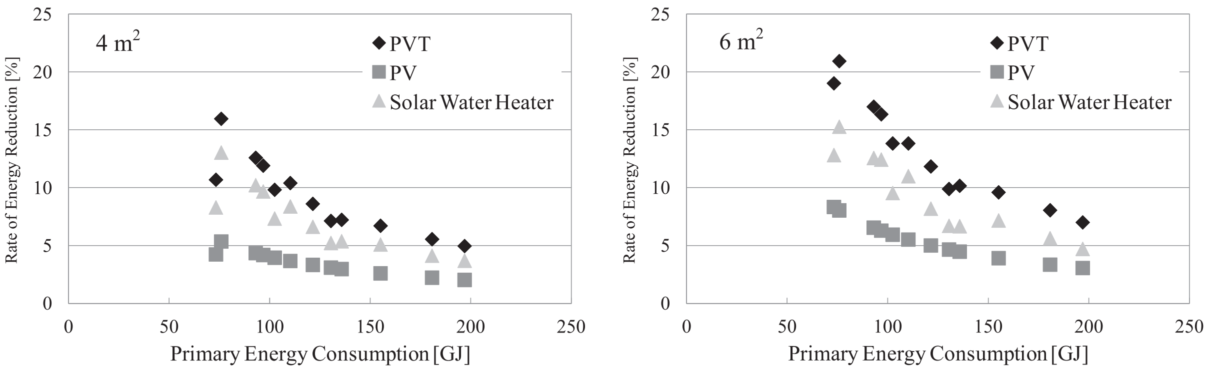

Fig. 20　Rate of primary energy reduction mc-Si PVT

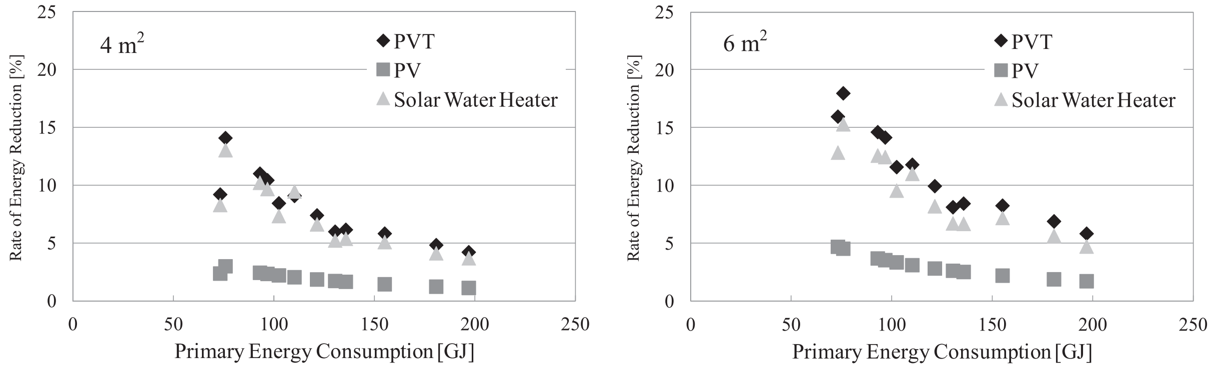

Fig. 21 Rate of primary energy reduction a-Si PVT

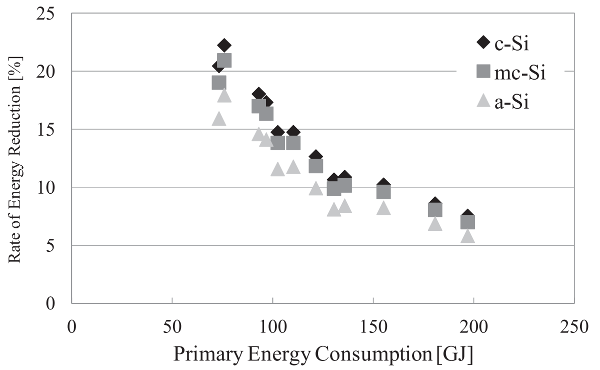

Fig. 22 Rate of Primary Energy Reduction by 3 types of PVT collectors (6 m^2)

to 22%, while a-Si PVT has the lowest value at 6 to 18%. It should be noted that the difference of the performance between c-Si PVT and mc-Si PVT is not significant.

5. Conclusion

This study investigated and evaluated the performance of PVT systems in Tokyo by TRNSYS simulation. The findings from the simulation in this study can be summarised as follows：

1. For the energy consumption behaviour of 12 houses in Tokyo, the simulation results show that the optimum of water flow rate for all types of PVT systems is 35 kg/hr for both collector areas of 4 m^2 and 6 m^2.
2. The effect of water flow can slightly increase the electrical efficiency of the used PV cells. Especially c-Si PVT has been enhanced the most effectively among three types of cells by 0.31% as yearly average electrical efficiency.
3. PVT systems can contribute to more primary energy reduction than individual PV or SHW with the same aperture area. The improvement is expected to range approximately 1.5-2 times for c-Si PVT systems compared with individual PV or SHW.
4. The primary energy reduction of the c-Si PVT is higher than those of the mc-Si and a-Si PVTs throughout the investigated energy consumption range.

The results presented in this paper clearly demonstrate that PVT systems are a promising technology for residential application under the considered conditions. The PVT system using c-Si PV as a solar absorber offers the best performance of all the PVTs investigated in this study. Further investigation into the experimental performance of the PVT system to determine its real performance is needed. Additionally, because the prices of PV panels are different year-by-year and depend on the types of PV cells, the payback year should be investigated in future work.

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