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APPLICATION

The performance of PV-t systems for residential application in Bangkok

Thipjak Nualboonrueng[1,2]*, Pongpith Tuenpusa[3], Yuki Ueda[1] and Atsushi Akisawa[1]

[1] Graduation School of Bio-Applications and Systems Engineering, Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei, Tokyo 184-8588, Japan
[2] National Science and Technology Development Agency, 111 Thailand Science Park, Pahoyothin Road, Klong1, Klong Luang, Pathumthani 12120, Thailand
[3] Rajamangala University of Technology Thanyaburi, 39 Muh1, Rangsit-Nakhonnayok Road, Klong Hok, Thanyaburi Pathum Thani 12110, Thailand

ABSTRACT

This paper focused on the performance of photovoltaic-thermal (PVT) systems working in Bangkok for residential applications.

The PVT system is one which produces both electricity and low temperature heat at the same time. This paper investigated the performance of PVT systems that use different types of commercial solar PV panels. The characteristics of the PV panels were used as input parameters in the simulation. Each system comprises 2 m^2 of PVT collector area. Water draw patterns are those with a typical consumption of medium size houses in Bangkok, and the measured monthly average city water temperature of Bangkok has been used to estimate the energy output. The results show that the optimum water flow rate is 20 kg/h for all types of PVT collectors and the effect of water flow can improve the cell efficiency of PV cells. Moreover, the total energy output from the PVT collectors, which had glass covers is very significantly higher than those without one. The c-Si PVT panel gave the best performance with the highest rate of primary energy reduction. The payback time of each system is 6.4, 11.8, and 13.4 years for a-Si, mc-Si, and c-Si types of PVT system, respectively. This investigation concludes that from the viewpoint of system performance, c-Si PVT is the most promising type than whereas from the viewpoint of economy, a-Si PVT has the fastest payback time. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS
PVT systems; photovoltaic; PVT system performance; residential applications; Bangkok climate

***Correspondence**
Thipjak Nualboonrueng, Graduation School of Bio-Applications and Systems Engineering (BASE), Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei, Tokyo 184-8588, Japan.
E-mail: thipjak@yahoo.com (preferred), 50008701206@st.tuat.ac.jp

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1. INTRODUCTION

At present, the global demand of energy usage is increasing dramatically as can be seen from the oil prices that have significantly been increased. The governments of many countries attempt to develop their own policy and research work in renewable energy utilization. Solar energy is one of the solutions to reduce the national energy consumption on fossil fuel and it becomes very often the first choice for government policy. Solar energy has been developed to reduce the usage of conventional energy source such as coal and petroleum. Recently, in addition to photovoltaic (PV) panels that can produce electricity and solar water heating appliances that can produce heat in form of hot water or hot air, the two approaches can now be combined into one collector as a hybrid PV-thermal (PVT) collector serving both heat and electrical demand. This has been achieved in this study by assembling a heat extraction device with a normal PV panel to be PVT collector generating the heat and electricity required by most consumers.

Typical PV modules can only converted 10–20% of solar radiation to electricity. Although some part of the energy is reflected back to the sky, the rest of solar energy is transformed to heat. Also, for a PVT collector, the absorbed solar radiation is only partly converted to electricity by PV cells, whereas the other excess energy will be transformed to heat. However, for a PVT system, the generated heat will be utilized as low temperature heat. The PVT collector concept offers an opportunity to increase overall system efficiency using the waste heat that generated from PV module. Because it is well-known that the efficiency of a solar cell decreases with an increasing of operating temperature, the generated electrical energy should be theoretically improved by the cooling effect of heat extraction part in the PVT collector. Thailand has a huge potential of solar energy which is 18.2 MJ/m^2-day for this tropical climate [14]. The ambient temperature in summer can typically reach over 40 °C, whereas the average wind speed is probably low. This study is based on the assumption that Thailand may be suitable for the usage of PVT technology.

Several theoretical and experimental studies of PVT system have already been performed. For analytical works, Florschuetz L.W. [1] extended the well-known equation of Hottel–Willier that analyzed the flat plate solar collector to a 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 a PVT collector may be exactly determined in the same way as a pure (normal) collector, except that wherever U_L and S appear in the relevant $\tilde{U}_L$ and $\tilde{S}$. Soteris A. Kalogirou[2], reported the PVT performance of a system including optimum water flow rate, mean annual efficiency of PV and payback time of the system. The TRNSYS computer program developed by the University of Wisconsin was used for the simulation in his study. His work had been done on the performance of a PVT module with 5.1 m^2 of collector area, 150 liter of water consumption per day and a solar absorber using mono crystalline in the Cyprus. His result concluded that the optimum flow rate was found at 25 l/h and the PVT system could increase mean annual PV efficiency from 2.8% to 7.7% and in addition it covered 49% of the hot water needed for one house. The system could increase the annual efficiency of system to 31.7% and the payback time is 4.6 years. Zondag et al. [3] have evaluated nine different designs of PVT collectors with an analytical model. Their results showed that the best efficiency of PVT occurred using multicrystalline silicon as the absorber with the channel-below-transparent-PV type. They further concluded that the annual efficiency of the PV-on-sheet-tube type is only 2% worse although it is easier to manufacture, and they concluded that this design was considered to be a good alternative. Maurice Jong[4] examined three different PVT systems with a numerical method. The first system was used as a hot water system on house in the Dutch climate. The PVT area was 6 m^2 with 200 L of storage tank for the hot water demand of 175 L. The result of his first system showed that the thermal and electrical efficiencies were 22.1% and 6.8%, respectively, with a solar fraction of 50.5% for the total demand of hot water. The second system preheated ventilation air for a boarding house in London. The PVT collector area was 183 m^2 and it generated electricity and heat used in the boarding house. TRYNSYS has been used for this system under the climate of Hoddesdon district of London. The simulation results showed that the thermal and electrical efficiencies were 27% and 6.9%, respectively, with a solar fraction of 55.3% for the total demand of hot water. The third PVT system was a low temperature heating system that used the generated heat for floor heating. The simulation was executed in the Netherlands using a 5 m^2 PVT collector area. However, the system efficiency was not reported for this system. G. Vokas *et al.* [5] reported the theoretical study of a PVT system for domestic heating and cooling in various locations in Greece and for different 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 result of analysis showed that for the PVT system working in different geographical regions, the coverage percentage of the domestic heating and cooling load is greatly affected by its geographic location. Between Heraklion and the region of Thessaloniki, there was a difference in solar coverage percentage of 15.23%. Furthermore, the increase of total PVT surface area increased the solar coverage percentage during both summer and winter period. Their research leads to the conclusion that a PVT collector could produce a remarkably large amount of thermal energy. It was proved in addition that this thermal energy could be used to cover a significant part of the domestic heating and cooling load. Marco Beccali *et al.* [6] presented a detailed analysis of the energy and economic performance of a desiccant cooling system (DEC) equipped with both single glazed standard air and PVT collectors for applications in hot and humid climates. Their work showed the results of detailed simulations conducted for a set of DECs operating without any storage. In part of PVT, their simulation showed that configurations with a large PVT collector surface were technically not very suitable. M. Adsten *et al.* [7] investigated the influence of climate and location on collector performance in northern part of Europe. They used the MINSUN simulation program and investigated for three cities which were Lund, Stockholm, and Lulea in Sweden. Two different types of commercial standard solar thermal collectors, namely a flat plate solar collector and a tubular vacuum collector, were modeled. The result showed that the thermal output was strongly correlated to the annual global irradiation at a horizontal surface. Moreover, they reported that the vacuum tube collector was less dependent on climate variations due to its smaller thermal loss. Based on this report, because PVT is also a flat shape, we can imply that the performance of a PVT collector will also strongly depend on the specific location.

For experimental work, T.T. Chow *et al.* [8] studied the development of PV's performance in PVT technology by using water as a coolant by numerical analysis and experiment. They constructed a flat-box type PVT collectors and tested them in China. The system was designed for residential applications running in a thermosyphon mode. Their experimental rig consisted of a flat-box PVT collector having aperture area of 1.64 m^2 and a thermally insulated 100 L water storage tank. Polycrystalline silicon solar cells with a conversion efficiency of 14.5% were used as solar absorber. The PV modules were adhered to the upper portion of the aluminum alloy thermal absorber with the packing factor lower than 1. The flat-box was built from a number of extruded aluminum alloy box-structure modules, which were assembled to produce a flat smooth absorber to surface. Their results showed that a developed numerical model based on the finite-difference control volume method gave accurate prediction of daily performance and the model has been used to evaluate the steady state collector performance as well as the typical daily operation under hot summer and cold winter climatic conditions in China. The overall performance of the PVT collector system was reported to be a promising system for providing an alternative means of energy source for the domestic sector in China. M. Bakker *et al*. [9] reported the outdoor performance of uncovered PVT panels. Their PVT panels were built from multicrystalline silicon cells and laminated between a copper sheet-and-tube absorber and a low-iron glass sheet. They also modified their PVT in lamination process by laminating an additional transparent foil between the PV cells and the copper absorber to prevent the copper from short-circuiting the PV cells. Their PVT panels had an area of $80 \times 80\,\mathrm{cm}^2$ and were framed with standard aluminum PV frames. Their results showed that the module efficiency measured by a flash tester was found to be 11.2% as expected. For thermal performance, the outdoor testing results reported that the loss was much higher than expected. Y. Tripanagnostopoulos *et al*. [10] reported the outdoor performance of various kinds of PVT collectors by using typical sizes of commercial PV modules. Their results showed that PV cooling can increase the electrical efficiency of PV modules and also the total efficiency of the system. They also reported that an improvement of PVT performance can be achieved using an additional glazing to increase thermal output and a booster diffuse reflector to increase both of electrical and thermal output. Hisashi Saitoh *et al*. [11] reported a field experiment and analysis on a PVT solar collector in Sapporo, Japan. Their experiments were achieved using a constant temperature of water supply with a crystalline silicon PVT collector and compared with a separate PV panel and a normal solar collector. Field experiments were carried out from November 1998 to October 1999 at a low energy house at Hokkaido University. The results showed that the PVT collector was roughly equivalent to normal PV in electrical efficiency, but for thermal efficiency, the PVT collector is lower than a normal solar collector. A. Nakajima *et al*. [12] investigated the spectral effect of an amorphous silicon solar cell on outdoor performance in various locations. They reported that the output current of an a-Si module depends not only on module temperature and annealing effect but also the spectral effects of sunlight of such seasonal variation of the air mass and the atmospheric condition also effect to its energy output. Y. Sukamongkol *et al*.[13] reported the experimental validation of the condenser heat recovery with a PVT air collector with a desiccant for reducing the energy use of room air conditioning. Their results showed that the PVT system was useful for the developed system. The thermal energy produced from the system can produce warm dry air up to 53 °C and 23% relative humidity. They also state that using PVT incorporated with heat recovered from the condenser to regenerate the desiccant for dehumidification can save the energy use of the air conditioning system by approximately 18%.

Because the performance of PV or the thermal systems depend on the ambient temperature and the solar spectrum, Research and Development activities have been carried out at various locations. As mentioned above in literature review, most of the studies were carried out in Europe and a few have been carried out in East Asia, mainly in Japan and China. On the other hand, no work has been carried out in a tropical climatic region, where (i) the ambient temperature is very hot through the year which should strongly affect PV performance, and (ii) the solar spectrum is suitable for PV cells, which are very sensitive to the short wavelength spectrum, for example, amorphous silicon.

This work has been focused and reported on a PVT's performance at specific location in tropical climatic region namely Bangkok and it reports the system performance with various types of commercial PV panel used as the absorber in PVT collectors. The area of collectors was about $2\,\mathrm{m}^2$ for all types of PVT systems because this is the typically most used area for residential houses in Bangkok. Moreover, the report in term of energy reduction rate would be a good indicator in order to find out the benefit in primary energy consumption. The results of this study can be used by consumers and installers to make their decisions in employing this technology.

The results, because of the present work, differ significantly from the previous studies in different locations. For example, past work can be seen in the publication by A. Nakajima *et al*.[12].

1.1. The advantages of the PVT system are as described in the following:

- Higher energy yield per square meter of surface area
- Simultaneously, both electricity and heat are generated by one device
- Reduced manufacturing and installation cost
- One solar produce for all of consumer product's need

It is obvious that both electricity and heat are the fundamental need for all consumers. PVT technology may be a good choice to use solar energy in an efficient way and it can be a promising technology in the future.

2. DESCRIPTION OF THE SYSTEM

In this study, three types (a-Si, mc-Si, and c-Si) of PV panels have been used as solar absorbers in PVT collectors. Figure 1 shows the schematic diagram of system modeling. The system consists of a series of PVT panels having $2\,\mathrm{m}^2$ of aperture area and a hot water storage tank with a water draw pattern corresponding to the measured data of water

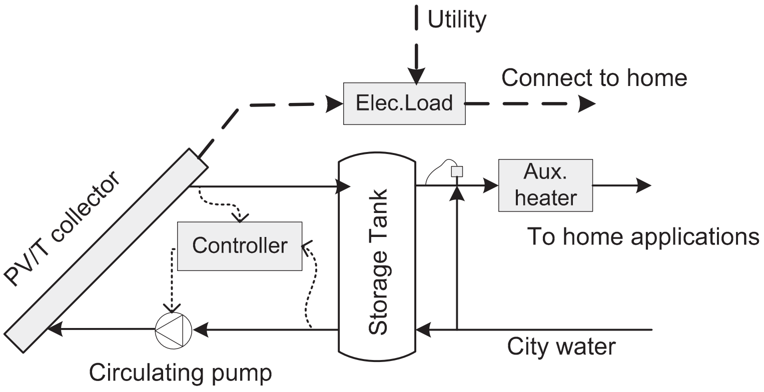

Figure 1. Schematic of photovoltaic-thermal system in system model.

consumption for a medium size family living in Bangkok, whereas electricity produced from the system is connected to the home via an inverter. The produced hot water is used within the home with an external auxiliary energy backup to ensure that the user can get the expected temperature level. The circulation pump is controlled by a differential controller to prevent the heat rejection from storage tank to the collector.

The configuration of PVT collector has been shown in Figures 2 and 3. The configuration of the PVT system in this study is a PV-on-sheet-and-tube type which is the most practical in use and easiest to manufacture as Zondag *et al.* [3] mentioned in their report. PV-on-sheet-and-tube type PVT can be described its configuration in details as follows. The PV panels used in this study had a glass as the top surface and a polymer sheet as back encapsulation. The PV panels were glued on the top of a metal plate by thermal epoxy. There were longitudinal circular channels beneath the metal plate, which were prepared to receive the circular copper tubes of the thermal collector. The rear side of the copper tubes had a rock wood insulator layer to prevent bottom heat losses. The low iron and high transparency glass cover was used to reduce convection losses to the ambient air from the top surface of the PV module. The existing oftop glass cover was also considered in this study to investigate the difference in energy output of PVT system.

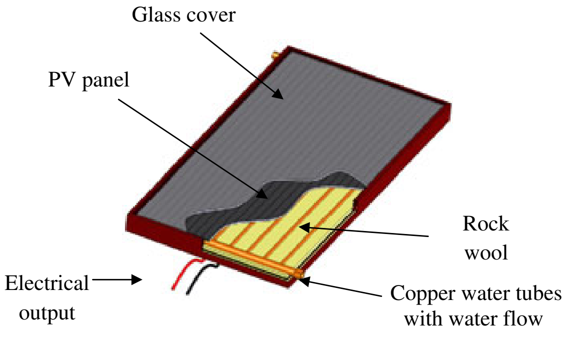

Figure 2. Configuration of photovoltaic-thermal collector.

The nominal conversion efficiency of the PV panels was 6.3%, 12.7%, and 13% for a-Si, mc-Si, and c-Si PV, respectively. The monthly average city water temperature of Bangkok has been used in the simulation to estimate the energy output of the systems.

2.1. System model

A well-known computer simulation program TRYNSYS has been used in this study to investigate the system performance. TRYNSYS consists of many subroutines, which model system components. TRYNSYS works by interconnecting components graphically in the work sheet, and the user can define input and output parameters of each system component. TRYNSYS has the capability of

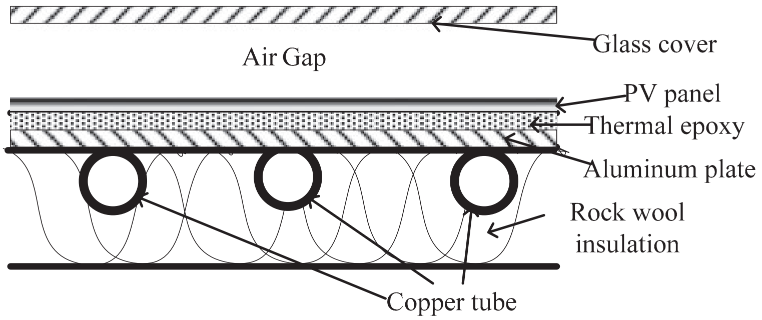

Figure 3. Cross-sectional of photovoltaic-thermal collector.

interconnecting system components together as the user desires, facilitating information collection and formulating a general mathematical description of each component. Figure 4 shows the flow diagram of the model and how the components interact with each other.

TRNSYS components referred to TYPEs [15], which have a mathematical description inside, and then a number of many TYPEs were interconnected to form a system. As shown in Figure 4, the system flow diagram consisted of TYPE50 PVT Collector, TYPE3 circulating pump, TYPE38 hot water storage tank that was working in Plug flow mode, TYPE2 differential temperature controller and TYPE 14 electricity and water consumption load profile. In the simulation, the measured data of the hot water consumption pattern for medium size families (160 L per day) has been also used as an input parameter.

2.2. Typical meteorological year

To predict the annual performance of a solar energy using a simulation program usually requires hourly meteorological data, which covers the period for the whole year. The typical meteorological year (TMY) data is used in a wide range of simulation programs instead of using several normal year meteorological data sets, which may vary widely. The TMY is composed of hourly metrological data for 12 months. Each month in TMY was called a typical meteorological month which was sorted from various years with the condition that it has to represent the statistical characteristics of the meteorological conditions of that month. In this study, the TMY database of Bangkok investigated by S. Janjai [14] which had been collected in many provinces of Thailand for a 10-year period was used to make these simulation results with high accuracy.

2.3. Input parameters

In this study, the input parameters were focused on the application of home use, the performance in the specific location of Bangkok, the various types of PV panels that were used as the solar absorber, and the TMY of Bangkok. The system input parameters are shown in Table I.

2.4. Hot water consumption and city water temperature profile

The hot water consumption of medium size families living in Bangkok was used as an input parameter. The pattern of water consumption that represents the daily behavior of water usage has been estimated from the houses in Bangkok. On average, the amount of daily hot water consumption is 160 L per day and the time of use is shown in Figure 5. Both patterns of water consumption and average monthly city water temperature in Bangkok were measured by Rajamangala University of Technology, Thailand during a year as shown in Figure 6.

3. RESULTS AND DISCUSSION

The simulation output of this study can be used to predict the performance of a PVT system in Bangkok. PVT

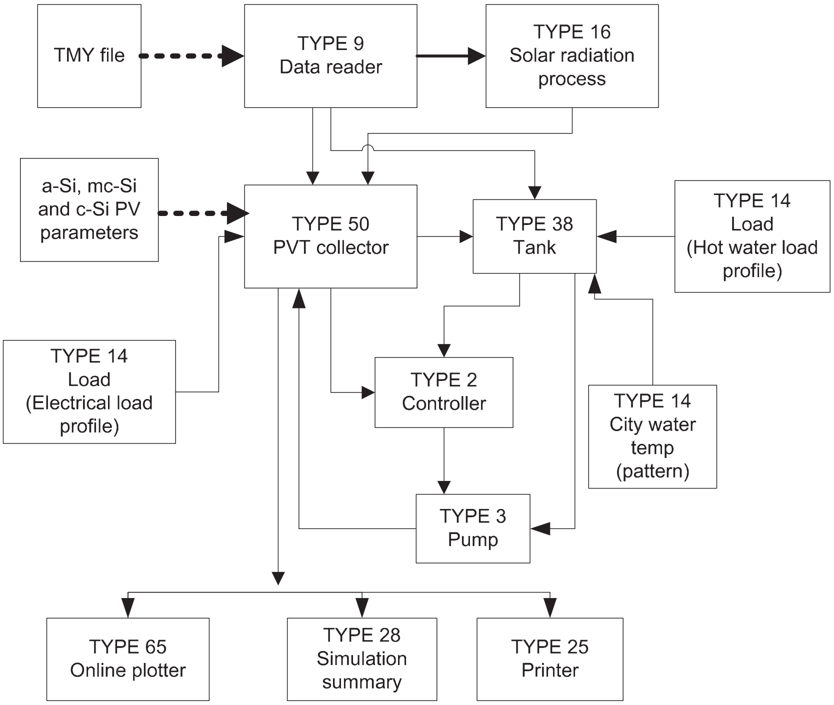

Figure 4. TRYNSYS information flow diagram of photovoltaic-thermal system.

Table I. System input parameters.

Item	a-Si PVT	mc-Si PVT	c-Si PVT
Collector area (m^2)	1.9	1.96	2.1
Packing factor	0.9	0.9	0.9
Working fluid thermal capacitance (kJ/kg.°C)	4.19	4.19	4.19
Nominal efficiency of PV panel (%)	6.3	12.7	13.0
Collectors slope (degree)	15	15	15
Number of glass cover	0/1	0/1	0/1
Glass cover transmittance	0.92	0.92	0.92
Storage tank volume (m^3)	0.12	0.12	0.12
Temperature coefficient of PV cell eff.	−0.0023	−0.0043	−0.0043
Loss coefficient of bottom and edge losses (kJ/h.m^2.K)	1.1	1.1	1.1
Electrical load connection		All are connected to the home	

PVT, photovoltaic-thermal; PV, photovoltaic.

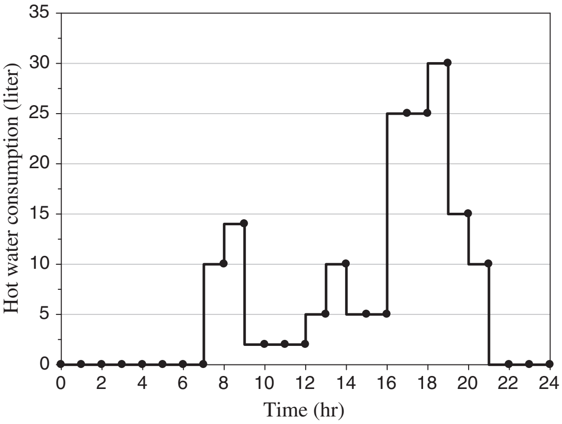

Figure 5. Average daily water consumption profile.

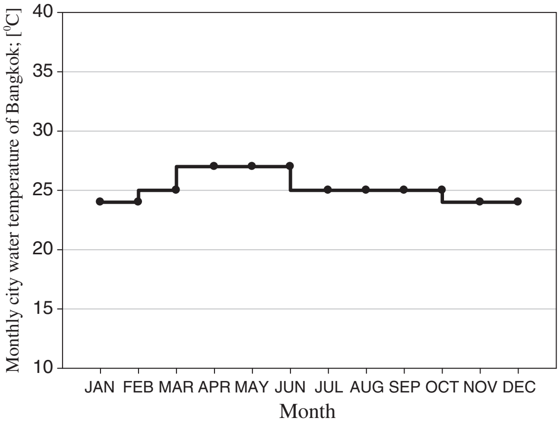

Figure 6. Monthly city water temperature profile of Bangkok.

collectors can produce hot water, which is similar to normal solar thermal collectors and can be supplied to various applications in the house. The generated electricity has been connected to home. This paper reports yearly and monthly performance of the system working under Bangkok's climate and the results have been shown as follows:

3.1. Optimization of the water flow rate

The water flow rate in the PVT collector loop was varied to determine the optimum water flow rate for each type of PVT collector. In simulation, the water flow rate was varied from 10 to75 kg/h versus the annual energies output are shown in Figures 7 and 8. The maximum of thermal energy output (Qc) and electrical energy output (Qe) were found at a water flow rate of 20 kg/h for all types of PVT collectors. For the PVT panels assembled with a top glass cover (Qc and Qe with subscript **g**), the optimum flow rate was also found at 20 kg/h. The letters a, m, and c in the graph mean amorphous, multicrystalline, and single crystalline silicon type PV, respectively.

Table II shows the energy output for all types of PVT collectors. The existing glass cover significantly effects to the thermal energy output, whereas the electrical energy is slightly decreased by the glass cover. The reduction of electrical output is because of the optical loss caused by the glass cover. The result also shows that the lowest value of electrical energy reduction was found for the a-Si type panel, because of the lower temperature coefficient of a-Si PV cells.

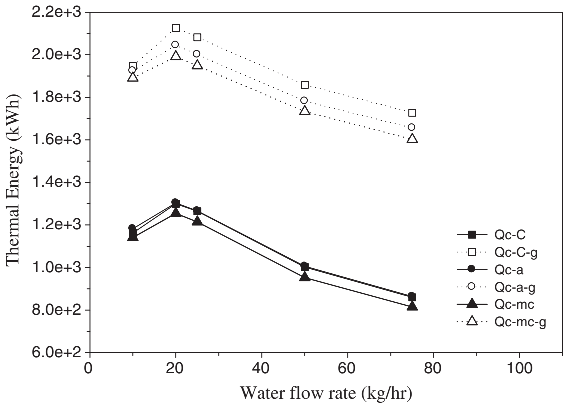

Figure 7. Thermal energy of photovoltaic-thermal collectors.

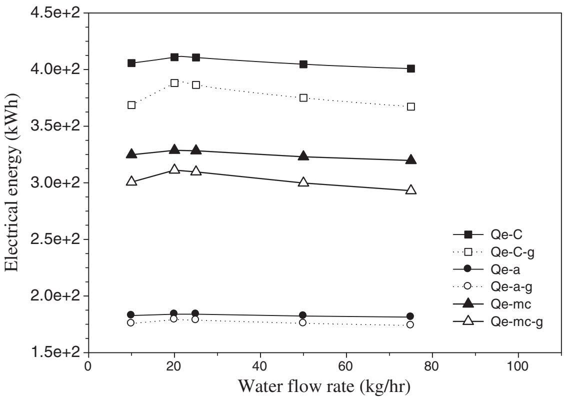

Figure 8. Electrical energy of photovoltaic-thermal collectors.

3.2. Monthly performance of PVT systems

Monthly energy outputs for all types of PVT systems have been shown in Figures 9–11. The figures show monthly energy output of each PVT system that was assembled with a glass cover and operated at optimum flow rate of 20 kg/h. The total heat output from the PVT systems (Qc), electrical output (Qe), the energy required from utility to cover the electrical consumption (Qutil), and thermal auxiliary energy demand to cover hot water load consumption (Qaux) are also shown in Figures 9–11. For all types of systems, the results show that the hot water load was a maximum in December and January during winter and the minimum hot water load occurred in June during the summer. The results also show that the maximum values of heat output from PVT systems occurred in the month of March, which were 0.75GJ, 0.73GJ, and 0.8GJ for a-Si PVT, mc-Si PVT, and c-Si PVT, respectively. The electrical energy outputs are almost constant throughout the year but with a maximum in March which were 0.06GJ, 0.11GJ, and 0.14GJ for a-Si, mc-Si, and c-Si PVT, respectively. It can also be seen in these figures that the required additional thermal auxiliary energy was a maximum in winter and minimum during summer.

Figure 12 shows the variation of monthly electrical cell efficiency for normal PV and PVT collectors (with water flowing). It is clearly seen that the cooling effect of water flowing in the PVT device can increase cell efficiency for all types of PVT collectors and it can be seen that for Bangkok, the cell efficiencies are nearly constant through the year.

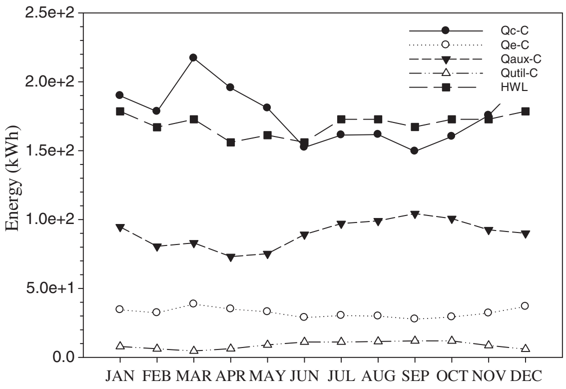

Figure 9. Monthly energy flow of c-Si photovoltaic-thermal system at optimum flow rate.

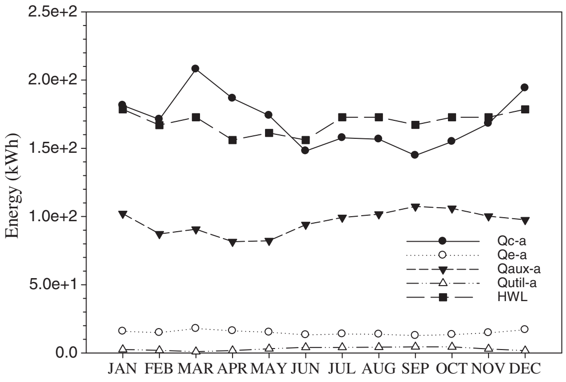

Figure 10. Monthly energy flow of a-Si photovoltaic-thermal system at optimum flow rate.

3.3. Solar contribution of the system

The simulation results shown in Figure 13 are the solar contributions or solar fractions with respect to hot water output from the systems. The figure shows the solar fraction, which determines the percentage of thermal energy load covered by solar energy and can be calculated by the following equation:

$$f = \frac{Q_{load} - Q_{aux}}{Q_{load}} \tag{1}$$

Table II. Energy output of photovoltaic-thermal collectors at optimum water flow rate.

	Qc [GJ]	Qe [GJ]	Qc with glass cover [GJ]	Qe with glass cover [GJ]	% of thermal energy increasing	% of electrical energy decreasing
a-Si PVT	4.69	0.66	7.36	0.64	36.5	3.0
mc-Si PVT	4.51	1.18	7.17	1.12	36.6	5.1
c-Si PVT	4.67	1.48	7.0	1.40	33.3	5.4

PVT, photovoltaic-thermal; GJ, 1 x 10^9.

Figure 13 shows the solar fraction for all types of PVT systems. It can be seen that the monthly distribution of the solar fraction for Bangkok is broadly similar to the distribution of ambient temperature rather than the distribution of solar radiation. The maximum solar fraction occurs during summer period (April–May). The average solar fractions for all types of PVT system are 46.8%, 43.3%, and 44.8% for c-Si PVT, a-Si PVT, and mc-Si PVT systems, respectively. It can be seen that the values of solar fraction depend on aperture area of PVT collector rather than the used types of PV cells.

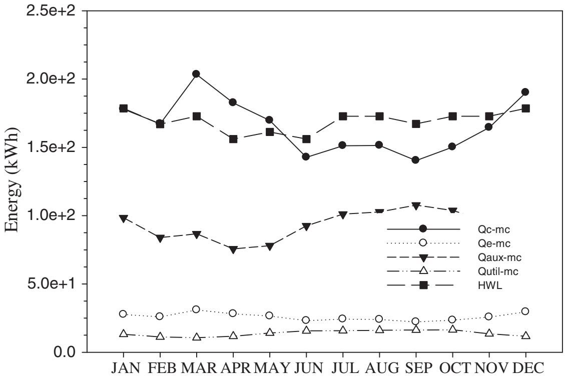

Figure 11. Monthly energy flow of mc-Si photovoltaic-thermal system at optimum flow rate.

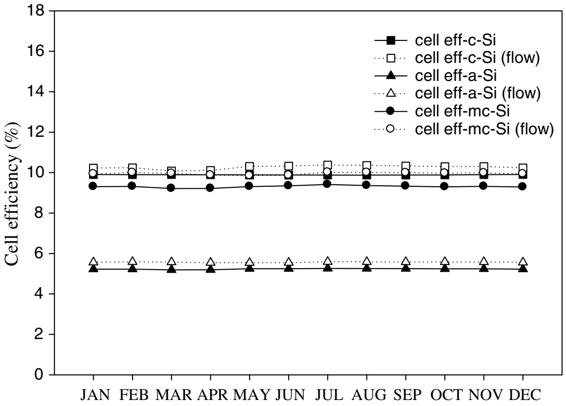

Figure 12. Variation of monthly electrical cell efficiency of normal photovoltaic and photovoltaic-thermal collectors.

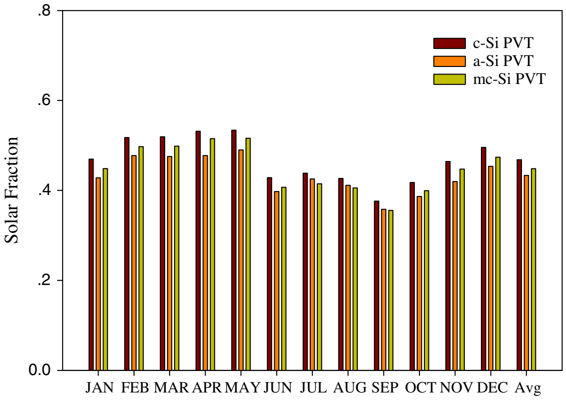

Figure 13. Solar contribution.

3.4. Rate of energy reduction

To report the performance of PVT system to the end user, rate of primary energy reduction (%R) is a useful indicator to represent the reduction of primary energy. In Bangkok, the primary energy of over 95% of houses is electricity, which has been supplied by Metropolitan Electricity Authority, and the electricity has been used by mostly in household appliances such as lighting, home appliances, small boiling pot, shower, and so on. This is different to other countries such as Japan, where natural gas is the primary energy for hot water heating. It has been assumed that the heat production from a PVT system can be used in preheating hot water for applications such as cooking or bathing and these kinds of applications may be used to promote the PVT technology in the future. The expression of rate of energy reduction has been shown as follows:

$$C = \frac{E}{\eta_e} + \frac{Q_{aux,0}}{\eta_h} \tag{2}$$

$$M = \frac{Q_e}{\eta_e} + \frac{Q_{aux,o} - Q_{aux}}{\eta_h} \tag{3}$$

$$R = \frac{M}{C} \times 100 \tag{4}$$

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

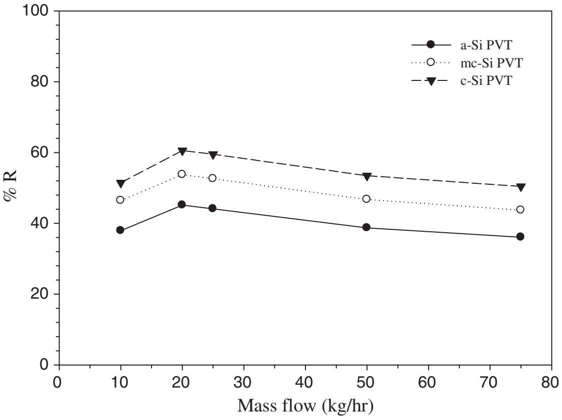

Figure 14. Rate of primary energy reduction with varying water mass flow rate.

Table III. Payback year of photovoltaic-thermal system.

	Qc [kWh/year]	Qe [kWh/year]	Net saving [THB/year]	System price [THB]	Payback [years]
a-Si PVT	2044	179	7229	46 400	6.4
mc-Si PVT	1991	311	7397	87 500	11.8
c-Si PVT	2126	388	8198	109 600	13.4

PVT, photovoltaic-thermal; THB, Thai Baht.

η_h [−]	System gas boiler efficiency (= 0.85)
η_e [−]	System power generation efficiency (= 0.4)
R [%]	Rate of primary energy reduction

Figure 14 shows the yearly rate of primary energy reduction with various water mass flow rates in the collector loop for all types of PVT systems. The results show that the rate of primary energy reduction was a maximum at the water flow rate of 20 kg/h and that the c-Si PVT system has a higher rate than the mc-Si one, which in turn was higher than the a-Si PVT panel.

3.5. Economic analysis

Economic analysis is another important tool for users to make their decisions to employ PVT systems. Typically, the economic analysis is presented in term of payback time. For this study, the payback times were calculated simply by the consideration of energy output and total costs (capital cost and yearly maintenance cost) of the PVT system. The capital and yearly maintenance costs have been investigated by the National Science and Technology Development Agency, Thailand in recent years.

Table III shows the net savings of PVT system in the Thai Baht currency. The results show that the fastest payback time is 6.4 years for the a-Si PVT system followed with 11.8 years for mc-Si PVT, and 13.4 years for c-Si PVT. The results were consistent with the solar fraction and rate of primary energy reduction that was reported.

Note: - Net saving cost is equal to total saving minus by yearly maintenance cost (2000 Thai Baht (THB)/year in this study)

- Electricity price provided by The Energy Policy and Planning Office (April 2011) is 2.98 THB/kWh, and the electricity was converted to heat by using an electric heater with conversion efficiency of 70%.
- The price of PV panels was the actual selling price provided by a vendor in Bangkok (2010).
- The costs of other system components including labor cost were estimated with approximate price in April 2011 in Bangkok.

4. CONCLUSION

The findings from the simulation of this study can be concluded as follows:

(i) The optimum of water flow rate for all types of PVT system is 20 kg/h. This means that PVT system can be used in the thermo-syphon mode, which can reduce the total system cost significantly and increase the attractiveness of the PVT technology. Additionally, the effect of water flowing can improve the electrical efficiency of PV cells for all types of PVT systems.

(ii) Fitting of a top glass cover increases the thermal energy output for all types of PVT systems significantly as it reduces the top convection loss, whereas electrical output only slightly decreases for the three types of PV cells due to the optical loss occurred at the top glass.

(iii) The solar contribution of the systems with respect to thermal energy is 43.3%, 44.8%, and 46.8% for a-Si PVT, mc-Si PVT, and c-Si PVT systems, respectively.

(iv) The rate of primary energy reduction [%R] is maximum at the water flow rate 20 kg/h for all types of PVT systems and the %R of c-Si PVT is higher than the one of other types of PVT. Additionally, the profile is similar to the energy output from the PVT systems.

(v) The a-Si PVT system has the fastest payback time which is 6.4 years followed by the mc-Si and c-Si PVT systems. This fast payback is relatively low when compared with the expected system lifetime.

The results presented in this paper can show that the PVT system is a very promising technology. However, it should be noted that the economic value of PVT systems depends on the price of PV panels used in the system and these prices are decreasing strongly at present. The authors recommend further work to continue to identify the advantages of the PVT approach.

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