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Energy Co-Generation in Photovoltaic Thermal-Collector (PVT) System: A Significant Increase in Efficiency

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Abstract – *The main obstacle of using the earth's enormous solar energy potential is its low conversion efficiency. The conversion efficiency from solar irradiation to electricity by the photovoltaic (PV) cell is around 5–20%. The remaining energy that falls on the PV surface becomes waste and increases the PV surface temperature. In this experimental work, we have modified a solar Photovoltaic (PV) system into a Photovoltaic-thermal collector (PVT) co-generation system and examined the effects on its performance. A coolant (water) has been circulated underneath the PV surface to extract heat and keep the PV surface temperature low. In the modified system, a glass cover was also placed on the top of the PVT to minimize the heat loss. This study found that electrical efficiency of the PV decreases linearly with surface temperature. In the modified PVT, when heat is extracted from the PV surface, the total efficiency increased to a significant level (i.e. 82%). The top loss of the PVT system was minimised effectively by putting a transparent glass cover on the PVT top. Although the top cover glass of PVT costs about 1% of electrical efficiency due to the glass's transmission factor, it significantly increases thermal efficiency i.e. from 48 % to 75%. The overall efficiency (electrical and thermal) of the co-generation system is much higher than the standalone PV or solar collector system.*

Keywords: Photovoltaic, Thermal collector, Co-generation, Coolant, Electrical efficiency

1.0 INTRODUCTION

The world's energy demand is increasing day by day due to growing population, industrialization and economic growth [1]. If the current trend continues, the world conventional fossil fuel reserve will be completely exhausted by 2080 or even before [2].The conventional fossil fuel also causes environmental degradation on the earth. Currently the renewable energy has drawn a great attention of the researchers due to its environmental friendly characteristics and renewability nature. Among the renewable energy sources, the solar energy is very promising considering its big potential and widespread availability.

The conversion efficiency for electricity generation from solar source is very low (at best 25% of the updated photovoltaic cells) [3]. The major part of the solar radiation falls on the PV surface is not converted to electricity rather gone wastage as heat [4].This is because, only photons of light with energy equal to or greater than the band gap of the PV promote the electrons into electricity. Moreover, with the increasing of the temperature in the cell further

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affects the electrical conversion efficiency. Keeping the electrical efficiency to a good level, the PV cell should maintain a reasonably low temperature. There are many techniques to cool down the PV surface with different heat extraction media and their configurations. One technique to lowering the PV surface temperature is the extraction of heat from the cell surface with circulation of proper coolant. Several researches have been done about the temperature effect on photovoltaic system [5,6,7]. Huang et al. [8] modified and tested 3 types of solar PVT collector with different heat transfer configurations and coolants. Study [9] examined the performance of PVT co-generation by placing the three alternative modes for the water heat exchanger inside the air channel and found around 55% thermal efficiency. Despite the potential benefit for heat extraction from PV system, there is a clear lack of emphasis on energy co-generation from the PV systems and this approach is yet to flourish in practical applications [10–13]. Further site-specific work should be carried out to enhance the motivation of adapting PVT over PV system. We have modified a PV into a photovoltaic-thermal collector (PVT) co-generation system and investigate its efficiencies with various configurations. This experimental study aims to examine how efficiently a PVT co-generation system converts solar energy into useful heat and electricity. This study will help to enhance the PVT co-generation for various households and small-scale heat and electricity demands.

2.0 THEORETICAL OVERVIEW

2.1 Influence of surface temperature on PV performance

As the temperature increases, the band gap of the intrinsic semiconductor shrinks, and the open circuit voltage (V_{oc}) decreases. PV cell therefore have negative temperature coefficient (β) for open circuit voltage [14]. As temperature increases, again the band gap of the intrinsic semiconductor shrinks meaning more incident energy is absorbed because a greater percentage of the incident light has enough energy to raise charge carriers from the valence band to the conduction band and thus short circuit current (I_{sc}) increases. Therefore, the short circuit current (I_{sc}) have positive temperature co-efficient (α). The open circuit voltage, short circuit current and maximum power can be obtained as Eqs. 1-3.

$$V_{oc} = V_0\left(1+\beta\Delta T\right) \tag{1}$$

$$I_{sc} = I_0\left(1+\alpha\Delta T\right) \tag{2}$$

$$P_{max} = I_{sc}V_{oc} = I_0V_0\left\{1+\left(\alpha+\beta\right)\Delta T+\alpha\beta\Delta T^2\right)\right\} \approx P_0\left\{1+\left(\alpha+\beta\right)\Delta T\right\} \tag{3}$$

where, I_0 is the short circuit current (A) at reference temperature 25 °C, V_o is the open circuit voltage (V) at reference temperature, P_{max} is the theoretical maximum power (W).

2.2 Energy Balance of a PVT co-generation system

The Energy performance of a PVT co-generation system can be evaluated by the energy balance Eq. 4 [15-17].

$$Energy\ output = Energy\ input - \left(Energy\ losses + Energy\ stored\right) \tag{4}$$

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2.3 PVT total efficiency

The total efficiency of a solar PVT system can be expressed as in Eqs. 5- 8.

$$\eta_{tot} = \frac{q_u + q_e}{IA_c} \tag{5}$$

$$q_u = A_c[I\ (\tau\alpha)_e - U_L(t_p - t_a)] - A_c I\ (\tau\alpha)_e[\eta_{e,ref} - \mu(t_p - t_{ref})] \tag{6}$$

$$q_e = A_c I\ (\tau\alpha)_e[\eta_{e,ref} - \mu(t_p - t_{ref})] \tag{7}$$

$$\eta_{tot} = [A_c[\ I(\tau\alpha)_e - U_L(t_p - t_a)]/I.A_c] = [(\tau\alpha)_e - U_L(t_p - t_a)/I] \tag{8}$$

Where, q_u is the extracted thermal energy (Wh/h), q_e is the extracted electrical energy (Wh/h), I is the solar radiation on collector surface (Wh/m^{2}h), τ is the solar transmittance of the collector cover glass, α is solar absorptance of the collector absorber plate surface, μ is PV efficiency temperature coefficient (K^{-1}), $\eta_{e,ref}$ is electrical efficiency at reference temperature 25 ºC, t_p is average absorber surface temperature (K), U_L is overall heat transfer coefficient (W/m^2.K), t_a is Ambient air temperature (K), A_c is the absorber effective area (m^2). Properly insulated PVT water collector normally has U_L value about 3.6 W/m^2.K [18].

3.0 MATERIALS AND METHOD

3.1 PVT co-generation system

A PVT system was built by putting a polycrystalline Si solar array onto a black plastic water heat exchanger with the water passage (Figure 1a). The PV array was consisted of two PV solar modules with 36 polycrystalline Si solar cell each. Plastic heat exchanger with water passage (Figure 1b) was put on the back of the PV module such a way that water can flow from top of the system to the bottom by the force of gravity. The PV-plastic heat exchanger assembly was put into an aluminium box whose inside was insulated by mineral wool. Heat losses from the PVT bottom and each side have been minimised by this insulation. A tempered glass sheet has been put on the top of the aluminium box for minimising the heat losses from the top of the PVT. Adhesive tape was used for fixing the glass cover with the top of the PVT to make it air-tight between PV surface and the glass cover thus heat losses from the top side of the PVT was minimised.

The construction details were as follows: Number of PV modules used were 2, PV area for each module was 639 x 652 mm^2, total PV surface area (A_{pv}) was 1278 x 652 mm^2, PV model (KC50), PV cell manufacturer- NAPS, Finland, the thicknesses of heat exchanger was 2 mm and bottom & side insulation were 100 mm and 300 mm thick respectively made of mineral glass wool.

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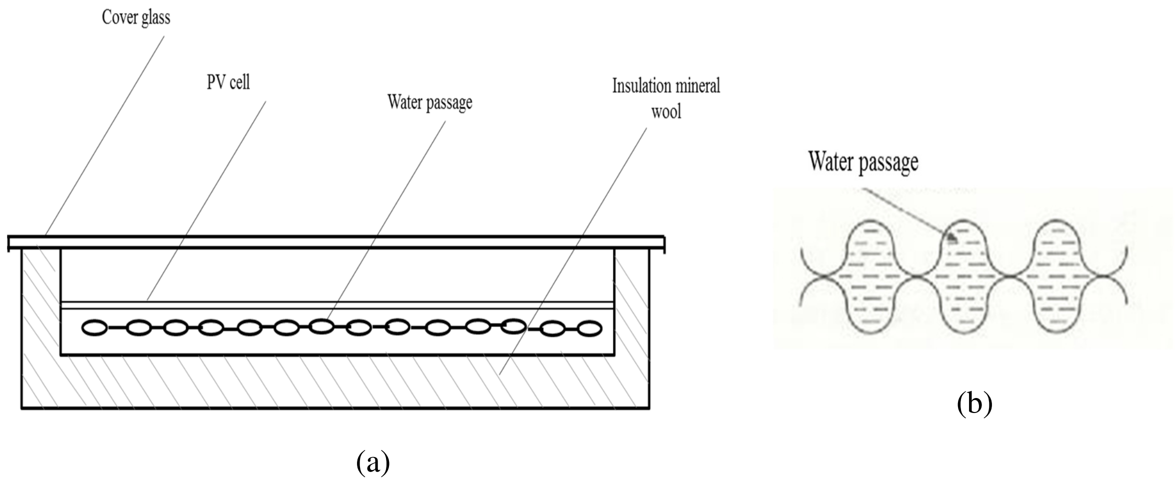

Figure 1: Cross-section view of a PVT (a) collector and (b) water passage

3.2 Circulation of coolant water

The PVT was placed on the roof top of Mechanical Engineering building (59.3° N, 18.07° E) at Royal Institute of Technology (KTH), Sweden with 45º inclination to the floor. The solar Pyranometer was placed in such a position that its face was parallel with the PVT surface thus it measures the solar radiation with the same angle as the radiation falls on the PV surface. A thermometer sensor was placed on the centre of the PV surface and temperature was measured. Two PV module were connected in series and their electrical performance such as open circuit voltage, short circuit current, and electrical power with variable loads were measured by using multi-function VA meter.

Voltage output of the solar Pyranometer was measured by a voltmeter with mV range. A plastic tank of 20 litre water containing capacity was placed on 2 meter height from the floor. The outlet of the water container was connected with the inlet of the PVT water passage. The outlet of the PVT water passage was open. The level of water in the water tank was maintained in a certain level by supplying new water from water tap thus achieved constant water flow through the water passage. Thermometer sensors were placed in the inlet and outlet of the PVT water passage and instantaneous temperature was measured in regular interval.

4.0 RESULTS AND DISCUSSION

The electrical efficiency of the PVT system was found decreased linearly as increased the surface temperature. The slop of the T_{pv} Vs η_e curve (Figure 2) was negative, i.e. $(\alpha+\beta)$ of Eq.3 is negative, that means, electrical power goes down with increasing the surface temperature. While the PV cell used as conventional lone system i.e. water was not flowing through the water passage, the average electrical efficiency was found 7.33%. The average electrical efficiency of the PVT co-generation system while water was circulated for extracting heat from the PV surface were found 7.62 % without glass cover and 6.66% with glass cover (Figure 3).

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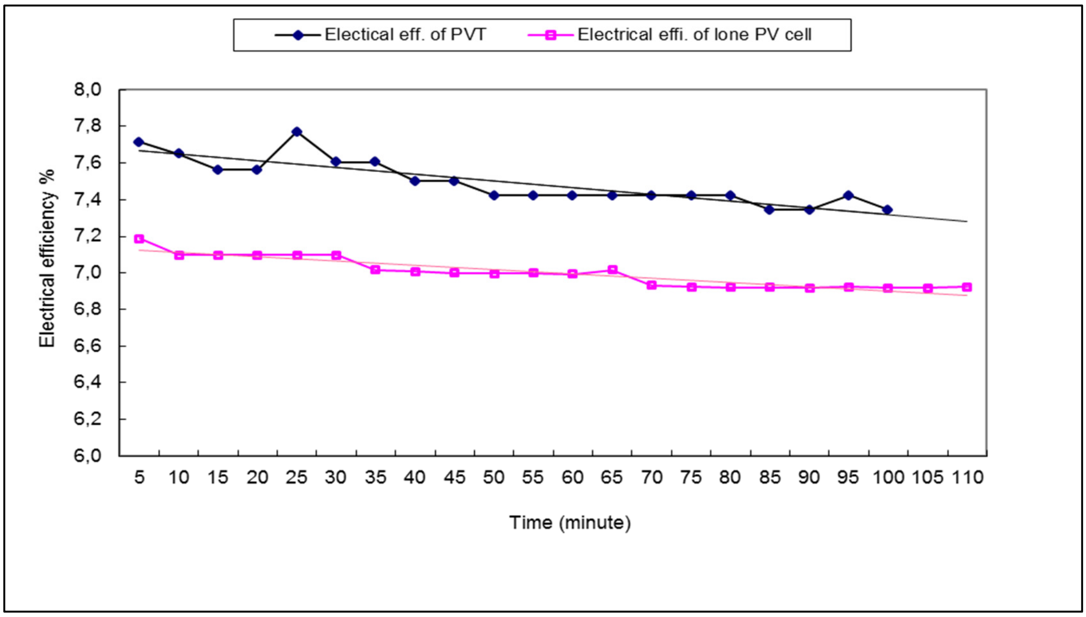

Figure 2: Electrical efficiency of PVT and lone PV cell

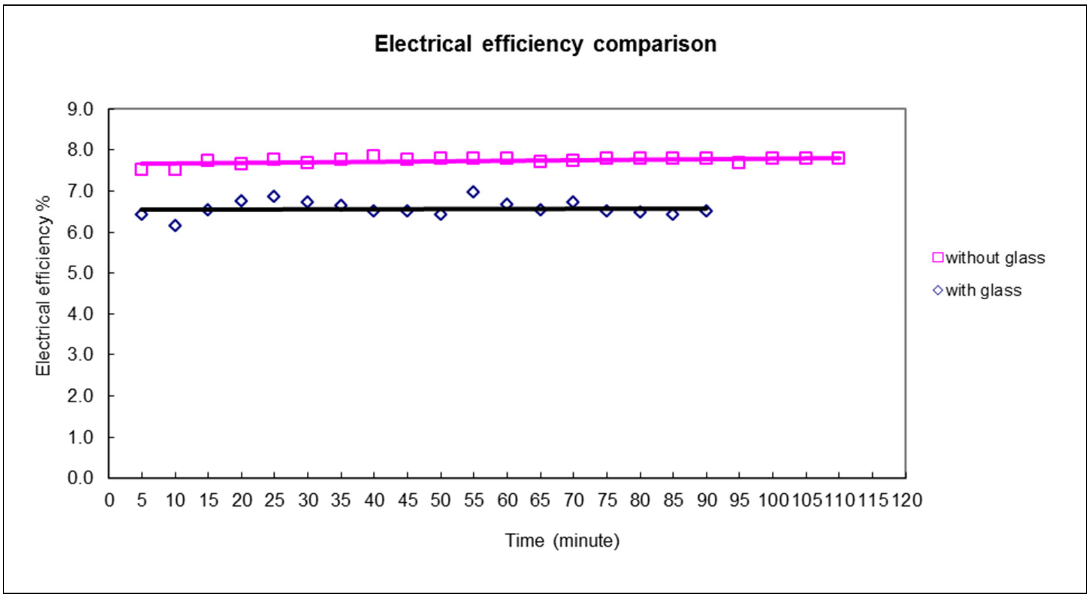

Figure 3: Electrical efficiency of the PVT with glass cover and without glass cover

Average thermal efficiency for the PVT was found 48% without using top glass cover and 75% with using top glass cover. Although thermal efficiency of the PVT increased significantly for using the top glass cover but it slightly costs the electrical efficiency. It is well recognised that electrical energy is high grade energy than heat energy in respect to the exergy value. So, for real comparison of the energy efficiency it needs to convert all the efficiencies to the same exergy value. I have determined the total thermal-equivalent efficiency ($\eta_{tot.te}$) by considering average efficiency of conventional thermal power plant (η_{ct}) according to the equation below.

$$\eta_{tot,te} = \eta_e / \eta_{ct} + \eta_t \tag{9}$$

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Total thermal-equivalent efficiency without using top glass cover was 70.97% and with using top glass cover was found 94.98 % (Figure 4).

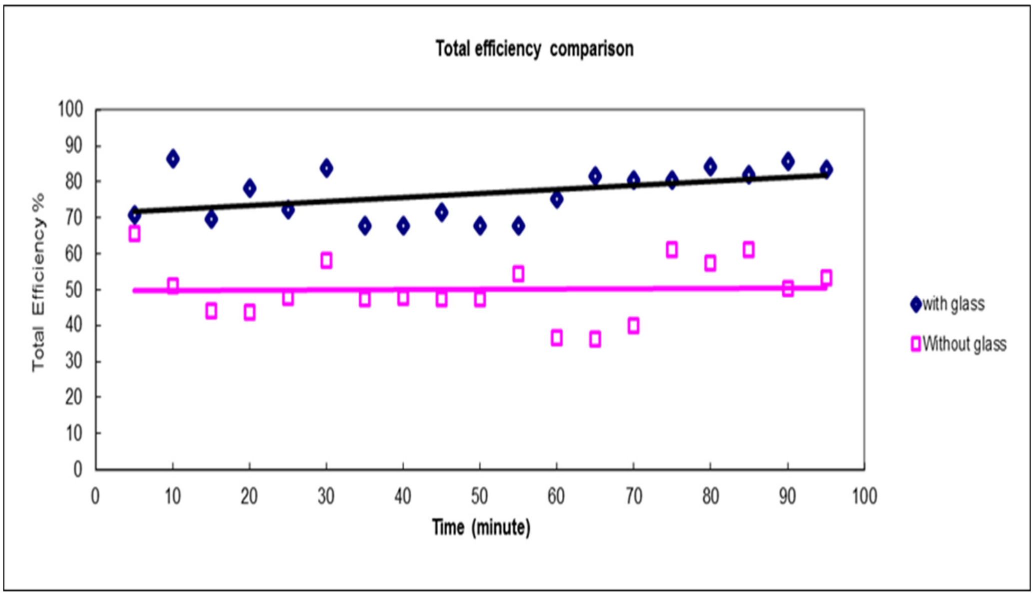

Figure 4: Total efficiencies of PVT with glass and without glass

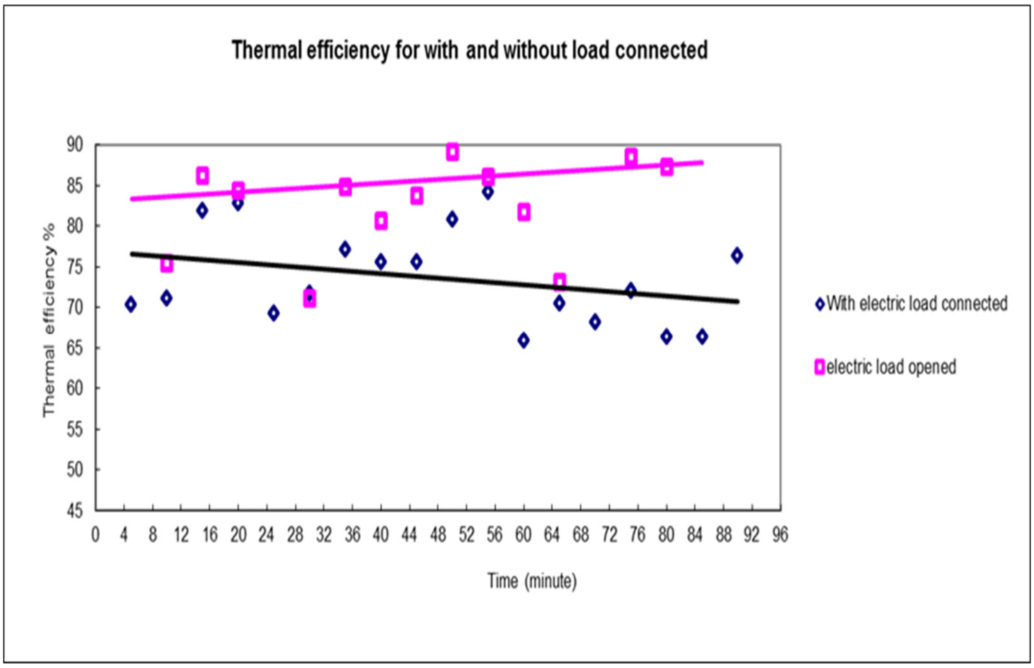

Figure 5: Thermal efficiency comparison for PVT with and without load connected

While electric power is not connected to any load, thermal efficiency of the top glazed PVT increased to 85.55% while it was 75.12 % with electrical load connected (Figure 5). From

Figure 5 it has been seen that thermal efficiency is higher when the electrical load is opened. When electrical load is not connected, the electricity dissipated again to PV surface as heat energy and thus increased the thermal efficiency.

All the above results were found while the inlet water temperature was maintained to a reasonably low level. In case of water recirculation through the water tank, the inlet temperature would increase, thus the results might not be same that of the fresh inlet water, because the total efficiency goes down with increasing of the water temperature [18]. All the measurements were taken with a certain (5 minutes) interval [19] but few data were discarded that corresponds to the solar radiation less than 500 W/m^2. Another backdrop was that though the PV generates electrical power instantly as the solar radiation falls, but water temperature cannot directly correspond to the solar radiation fall on the surface.

5.0 CONCLUSIONS

The objectives of this work were to experimentally examine the efficiency of the PV cell with varying the surface temperature and the electrical, thermal and total efficiencies of PVT (with and without glass cover) if heat extraction fluid (water) is passed to cool down the PV surface. This work found that the electrical efficiency of the PV cell is improved when heat extracting liquid is passed to cool down the surface. Though some little amount of electrical power costs for using the top glass cover, the overall thermal-equivalent efficiency were increased significantly. In sum up, PVT co-generation system not only increase the electrical efficiency but also provide extra heat energy that may be useful for low temperature hot water applications.

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