Development of a roof mounted PV system to a PV/T air system

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Abstract

Photovoltaic systems are increasingly being used in residential buildings. The absorbed heat of PV panels is normally dissipated to the ambient air via a natural convection and radiation. This paper will describe how to convert a PV system to a PV/T system, to make it possible to utilize PV modules thermal energy for different applications as well as increasing the electrical efficiency of the panels. This paper focuses on the design development of an existing roof mounted PV system of a house in Sydney to a PV/T air system including a PV/T air collector and an air handling system from the collector back end to bedrooms of the house. Thermal and electrical energy output of the new system is examined in this study. Additionally a payback period analysis is conducted to evaluate the economic benefit of such a PV/T system.

1.   Introduction

Recently, installation of PV systems has increased on residential buildings. A PV module absorbs heat from the sun and converts a small portion of solar radiation to electricity. However, a large fraction of absorbed heat is dissipated to the ambient. Photovoltaic thermal (PV/T) collectors are being utilized to recover heat from PV modules. Many studies investigated building integrated PV/T system. Bazilian, (2002) worked on building integrated photovoltaic thermal systems in Sydney and reported an outlet air temperature of 20- 25℃ at midday of a winter day. Also the author stated that the thermal output of this system could not offset the heat loss of the whole building. Chen et al., (2010) evaluated a PV/T air system linked to a ventilated concrete slab of a house. With a low air mass flow rate of 0.0056 kg/s.m^2, their system could supply an outlet air temperature of 40℃. Bambrook, (2011) designed and constructed a PV/T air system and investigated coupling this to a low energy house. The author reported that the thermal output of a PV/T air system could be enough for heating demand of a well-insulated house with thermal mass in Sydney. Previous studies mainly focused on the design and the investigation of the thermal output of PV/T air collectors. There is a lack of information for the development evaluation of a roof mounted PV system to a PV/T air system.

This paper investigates the thermal and electrical output of a developed PV/T air system in Sydney from 1st of May to the end of September. A PV/T air system includes a PV/T air collector and an air handling system linked to bedrooms of a house with the thermal mass. It is assumed that the building needs to be heated during the above mentioned time period. In addition, hourly heat load of the bedrooms is calculated and compared with the corresponded PV/T air system thermal output. Eventually by estimating the cost of this development and system power consumption an economic analysis is carried out to evaluate the benefit of this development.

2. Essential Practical Measures to Develop a PV System to a PV/T Air System

Figure 1 shows a generic PV/T air collector includes PV array on top and an air duct or plenum underneath the PV array.
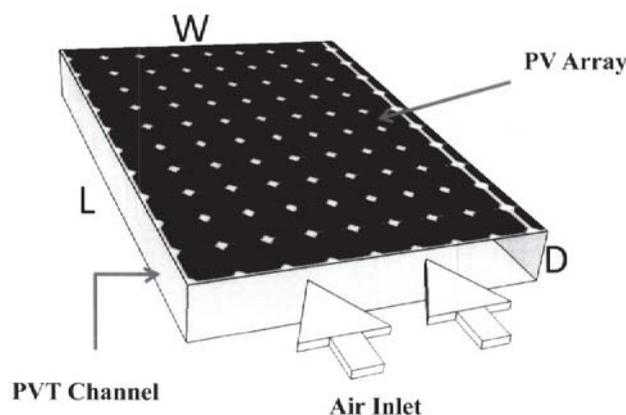
Figure 1. PV/T air collector

In addition, usually for a roof mounted PV system there is an air gap between a PV module and the roof materials. This is because of pitched roof styles (for example corrugated roof type) or using some rails for the installation of PV panels. Simply by performing the following practical measures a roof mounted PV system can be developed to a PV/T air system:

1. Enclose the air gap between a PV panel and a pitched roof. It is notable that there should be an opening in the air gap enclosure. This gives us an air plenum (duct) underneath a PV array which has an air intake opening. Also a sparse mesh can be installed on the opening.
2. Install bulk insulation on the inner surface of the roof. This increases the thermal resistance between roof materials to the roof space.
3. Penetrate part of the pitched roof underneath the PV panel in order to make an air outlet for the air plenum. This penetration is used for linking the above mentioned plenum to an air distribution system is located within the roof space of the house.
4. Supply and install an air handling system including ducts, a fan, a filter, fittings and grills. This system is to be connected to the above mentioned penetration and deliver the warm air to the bedrooms. Figure 2 shows an example of air distribution system connected to a PV/T air collector.
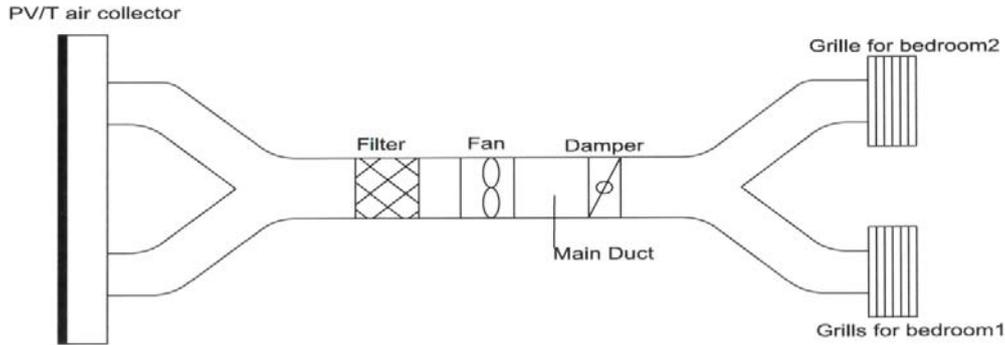
Figure 2. Air distribution system connected to PV/T air collector

Considering the system shown in the Figure 2, as the fan is switched on a sunny winter day, the warm air is delivered to the building.

3. Steady State Model of a PV/T Air Collector

Many steady state models and thermal circuits have been reported for different solar thermal or PV/T collectors (for example see Kalogirou, (2009), Bambrook, (2011), Duffie and Beckman, (2013)). Figure 3 shows the equivalent thermal circuit model for PV/T air collector presented by (Bambrook, 2011).
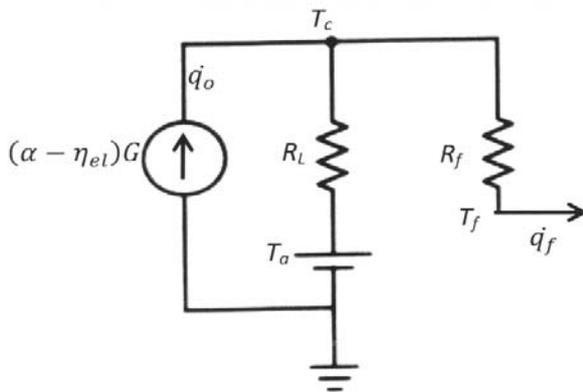
R_L	total thermal loss resistance from the top of the PV module to the ambient
R_f	combined radiative and convective thermal resistance from the PV module to the air in the duct
$\dot{q}_o$	overall rate of heat transferred from the collector to air in duct and ambient
$\dot{q}_f$	rate of heat transferred from the collector to the air in duct
T_c	PV temperature
T_a	ambient temperature
T_f	output fluid temperature

Figure 3. Equivalent thermal circuit of PV/T collector (Bambrook, 2011)

Considering the above model the temperature rise of the outlet air above the ambient temperature (ΔT), the rate of heat and electrical output per unit area ($\dot{Q}_f$), ($\dot{W}_{PV}$) were calculated by (Bambrook, 2011) as follows:

$$\Delta T = [(\alpha - \eta_{el})GR_L + T_a - T_{in}](1 - \exp(-\frac{A_c}{\dot{m}c_p\,R_o})) \qquad (1)$$

$$\dot{Q}_f = \frac{\dot{m}c_p}{A_c}\left[(\alpha - \eta_{el})GR_L + T_a - T_{in}\right]\left(1 - \exp(-\frac{A_c}{\dot{m}c_p\,R_o})\right) \quad (2)$$

$$\dot{W}_{PV} = G\left\{\eta_{ref}\left[1 + \beta_{ref}(\tilde{T}_c - T_{STC})\right]\right\} \quad (3)$$

where $\dot{m}$, $\eta_{el}, c_p, \alpha, G, A_c, \eta_{ref}, \beta_{ref}, \tilde{T}_c, T_{STC}, R_o, T_{in}$ are the air mass flow, the electrical efficiency, the specific heat of the air, the PV absorptivity, the solar irradiance, the collector area, the PV efficiency under standard test, the temperature coefficient, the average temperature of the solar cell, the standard test condition temperature, the overall thermal resistance and the inlet fluid temperature respectively. Also R_o is combination of R_L and R_f.

The above model did not take into account the impact of the sky temperature. Considering the effect of sky temperature on the radiative heat transfer from collector to the ambient an effective air temperature (T_{eff}) is to be replaced with the ambient temperature on the model. (Figure 4)
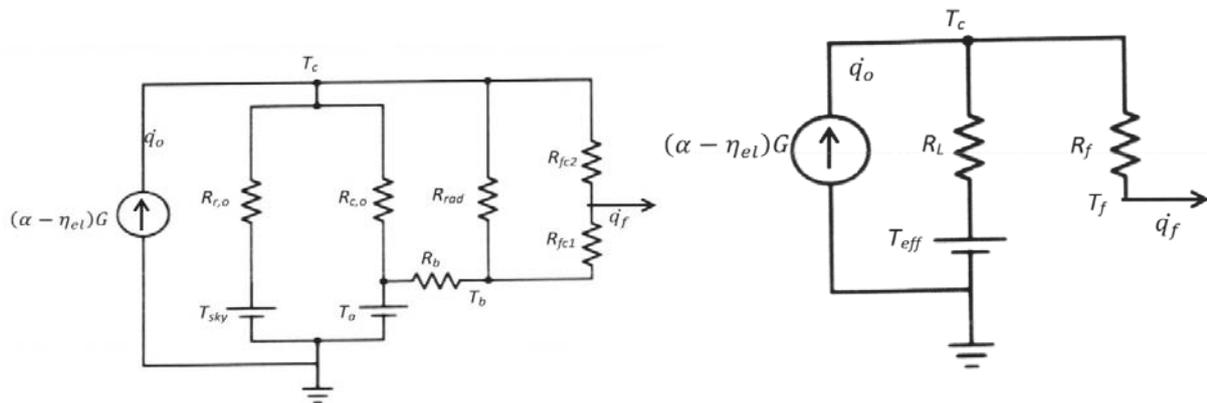
Figure 4. Evolution of equivalent thermal circuit of PV/T collector considering sky temperature

T_{eff} is the combination of the sky temperature (T_{sky}) and the ambient temperature and given by:

$$T_{eff} = \frac{T_{sky}R_{c,o} + T_a\,R_{r,o}}{R_{c,o} + R_{r,o}} \quad (4)$$

$R_{r,o}$ and $R_{c,o}$ are the radiative and convective thermal resistance from the top of the PV module to the ambient. $R_{f_{c1}}$ and $R_{f_{c2}}$ are the convective thermal resistances from the PV and the back of duct to the air respectively, and R_{rad} is the radiative thermal resistance from the PV array to the air in duct. R_b is the thermal resistance from the collector to the roof is infinite because of assuming high levels of the insulation at the back of the collector.

As a result of this evolution, equations for (ΔT), ($\dot{Q}_f$) and ($\tilde{T}_c$) equations are modified as follows:

$$\Delta T = \left[T_{eff} - T_a + (\alpha - \eta_{el})GR_L\right](1 - exp^{\left(\frac{-A_c}{\dot{m}C_pR_o}\right)}) \quad (5)$$

$$\dot{Q}_f = \frac{\dot{m}C_p}{A}\left[T_{eff} - T_a + (\alpha - \eta_{el})GR_L\right]\left(1 - exp^{\left(\frac{-A_c}{\dot{m}C_pR_o}\right)}\right) \quad (6)$$

$$\tilde{T}_c = T_a + [T_{eff} - T_a + (\alpha - \eta_{el})GR_L][1 - (\frac{R_L}{R_o})F''] \quad (7)$$

$$\dot{W}_{PV} = \eta_{el}G \qquad (8)$$

where F'' is the flow factor which is given by (Duffie and Beckman, 2013):

$$F'' = \frac{\dot{m}c_p R_o}{A_c}\left[1 - \exp(-\frac{A_c}{\dot{m}c_p R_o})\right] \qquad (9)$$

4. Calculation and Comparison of bedrooms heat demand and the developed PV/T air system output

In this study it is assumed that the PV module is an unglazed crystalline PV which has an air gap of 40mm above the roofing materials. Table. 1 shows all assumptions for the physical parameters and PV dimensions. It is also assumed that the supply air temperature of the developed PV/T air system is being kept constant at 25℃ by the variation of the air flow rate passing through the system. TMY2 weather data for Sydney is used for defining the ambient air temperature, the sky temperature, the wind speed and solar irradiation at different hours between 1st of May to the end of September. It is assumed that the building needs to be heated during the above mentioned time period. Then, using Eq(4) to Eq(7) and performing iterative calculation, the air mass flow rate values ($\dot{m}$), the average temperature of the solar cell ($\tilde{T}_c$), rate of heat and electrical output from the developed PV/T air system are determined at different hours.

Table 1. Assumed physical parameter and PV dimension values for this study

| Parameter	Value	Parameter	Value
PV absorption coefficient (α)	0.8	PV array area (A_c)	13.6m^2
PV efficiency under standard condition (η_{ref}) (Luque and Hegedus, (2003))	0.12	PV array width	3.4m
Temperature coefficient(β_{ref}) (Luque and Hegedus,(2003))	0.005/K	Average Density (ρ)	1.18 kg/m^3
Specific heat of the air (C$_p$) (Cengel, (2006))	1.005kJ/kg. ℃	Outlet fluid temperature(T_f)	25℃

As it mentioned previously, it is assumed that the air output of this PV/T air system is delivered to the bedrooms of a house during the day. The internal walls are single brick, external walls are double brick and the ceilings of the bedrooms have bulk insulation (R-value = 4 m^{2}K/W). Therefore the heat delivered to the bedrooms is stored in the brick walls during the day and the heat is then available to warm the bedrooms through the night. Using Accurate sustainability software (Accurate Sustainability, 2013), the peak heat demand ($\dot{Q}_h$) of the bedrooms at the

coldest day in June was calculated ($\dot{Q}_h$=2.4 kW at 7am on June 8th) by considering TMY2 weather data for Sydney and a heating set point temperature (T_{set}) of 18℃ for bedrooms. The peak heat demand for bedrooms is equal to 2.4 kW at 7 am on June 8th. Assuming steady state heat flow through building components and considering minimum air temperature (T_{min-a}) at the coldest day of June, the thermal resistance ($R_{bedroom}$) of bedrooms is calculated by:

$$R_{bedroom} = \frac{(T_{set} - T_{min-a})}{\dot{Q}_h} \qquad (10)$$

In this study it is assumed that thermal resistance of bedrooms remain constant as bedrooms are surrounded by vegetation and consequently the solar heat gain can be neglected during the winter. Eventually taking into account a heating set point temperature (T_{set}) of 18℃ for 24 hours in bedrooms, hourly heat demand of bedrooms is calculated and compared with the corresponded PV/T air system thermal output. Considering colder climate for the above house the heat demand of bedrooms is increased.

Figure 5 shows the results for the developed PV/T air system from 1st - 9th of June. It can be seen that thermal output of the system (Q_{th-PVT}) and the electrical output of the system (W_{el-PVT}) are dependent on solar irradiance (G), the ambient temperature and the wind speed. The value of Q_{th-PVT}, increases as a result of a decrease in the value of wind speed, and an increase in the value of G and the ambient temperature. Furthermore, the electrical output of the system (W_{el-PVT}) is improved based on an increase in G and the wind speed and a decrease in the ambient temperature. Comparing the results between 1st and 7th of June it is indicated that the ambient air temperature impacts on the outputs. Additionally, when the results for 6th of June are compared against outputs for 8th of June, it can be seen that the variations in the wind velocity changes the electrical and thermal output of the system. It is interesting that by converting a PV system to a PV/T air system sometimes a significant amount of heat could be generated. Also, it is indicated that the electrical output of a PV/T air system is slightly higher than a standard PV system at the same condition.
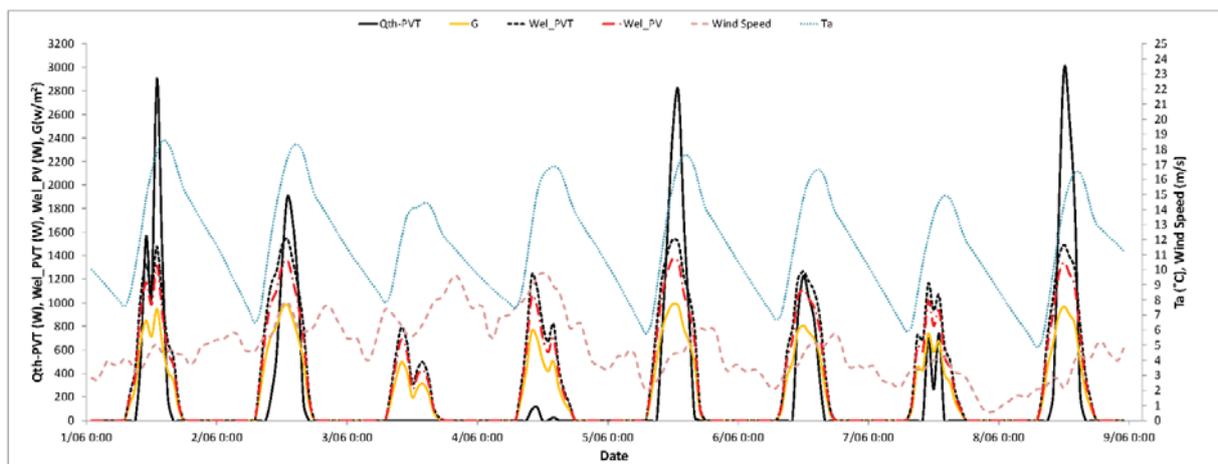

Figure 5. Developed PV/T air system outputs

Figure 6 presents the total heat and electricity generated and the total heat demand of the bedrooms ($Q_{h-demand}$) from 1st of May to the end of September. It is observed that 35% of total

heat demand of the bedrooms can be supplied. Also a significant amount of electrical energy can be generated. Considering a collector area of 13.6m^2 the heat and the electricity output are 72.6 kWh/m^2 and 77.96 kWh/m^2 respectively. While the total annual solar radiation is equal to 671.5 kWh/m^2. It is notable that the PV/T air system is not running as the outlet air temperature is less than the set point temperature (T_{set}) of 18°C.
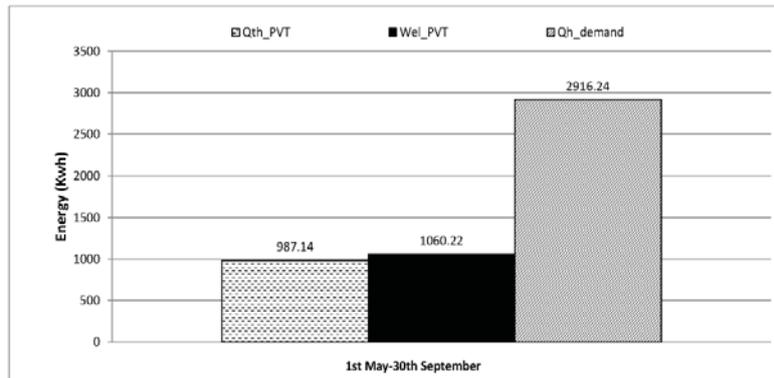
Figure 6. Total heat and electricity output of the developed system compared with total bedrooms heat demand

5. Economic Analysis

It is worthwhile to examine this development in terms of the cost. The following equation shows how a simple payback period can be calculated considering two different scenarios (Newman et al., 2008):

$$n = \frac{C}{S} \qquad (11)$$

where n, C, S are number of years, the additional capital cost and the additional saving respectively. The house currently has a PV system and electric heaters used for heating bedrooms. This is the first case scenario. The second case scenario is developing the first case to a PV/T air system. In addition, it is assumed that a fan with a variable speed controller is used for this system. Consequently the fan power consumption would be less than that additional electricity generated by this system development. On the other hand, Figure 5 shows that the additional electricity generated is not as significant as the heat generated. So the additional saving is defined by multiplying the annual heat and electricity generated by the electricity cost. There is no doubt that the electricity price varies based on the usage time and different countries policies. However, in this paper an average constant electricity cost of $0.3/kWh was taken into account based on the current price in Sydney. So it is expected to have an annual saving of $332 for a system with this specification. The Initial cost for this development includes one day labour cost, the equipment price as detailed in Table. 2. It is notable that these costs are based on the current market in Sydney and simply may varies for other cities.

Table 2. Details for the Prices of Initial Development

Item	Cost (AU$)
Equipment excluding PV system price (i.e. fan, flexible duct)	$1000
One day labour cost	$500
Total	$1500

Therefore the simple payback period is around 4.5 years. It is noticeable that if PV area increases the saving will be larger and consequently the payback period time will be smaller. Also, this payback period time changes based on the variation in the initial costs and the electricity price in different location across the world.

6.   Conclusions

This study focuses on the development of a roof mounted PV system on a house to a PV/T air system in Sydney. It is indicated that the system outputs vary based on the variation of ambient temperature, solar irradiance and wind speed. The thermal output of the system is compared to the head demand of the bedrooms. The results demonstrate that the developed PV/T air system is able to generate 35% of the bedrooms heat demand. In addition it is observed that the heat and electrical output of the developed system are 72.6 kWh/m^2 and 77.96 kWh/m^2 respectively. Further, an economic analysis is conducted for this development. The outcome shows a payback period of 4.5 years for this system converting. However, it is expected that payback period reduces for a larger PV array, a lower initial costs and a higher electricity cost.

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