Study of hybrid photovoltaic thermal systems

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Abstract. Sun is the primary source of renewable energy. It is abundant, inexhaustible and clean. It plays a very important role in the present energy crisis. Solar energy can be harnessed by hybrid photovoltaic thermal system to generate power and heat. These devices generate thermal and electrical energy simultaneously. Hybrid photovoltaic thermal systems have high efficiency. There is ample scope in this area as much work remains to be done. The hybrid system has huge potential in India where the availability of solar energy is spread throughout the country. The paper focusses on the study of hybrid photovoltaic thermal systems.

Keywords: Photovoltaic thermal; Hybrid solar; PVT performance.

1. Introduction
Climate change, global warming and environmental pollution have forced the world to look for clean energy technology. These problems can be solved by using renewable energy from sun and wind. All renewable power sources have their primary source in Sun. The motivating fact is that solar insolation rate received by earth is greater than the demand of fossil fuels. The earth intercepts about $1.8 \times 10^{11}$ MW power from sun. This is greater than the present rate of all energy consumption. [1][2] Solar power is abundant, and its conversion is also less costly. Different methods for collecting solar energy in the usable form are being developed. Some methods focus on the use of solar PV, whereas others on thermal conversion. Solar PV works on energy of electrons excited by solar photons. Solar thermal depends on energy of water heated by sunlight. This hot water can be used for heating or electricity generation. [3][4][5] Solar cell converts only a fraction of solar energy (14-20\%) to electricity through photovoltaic effect. Remaining energy is dissipated as heat energy. The efficiency of silicon solar cell decreases 0.45 \% per °C. Panel temperature can reach 70 °C in hot summer days. This means panels will produce up to 20 \% less power compared to their rated power capacity at 25 °C. To overcome this, hybrid solar technology was developed. A hybrid solar concentrator system captures this waste energy and thus removes the waste heat from solar module. This also increases the efficiency of the combination remarkably. [6][7] The individual silicon cell has an efficiency of 25\% whereas efficiency of solar PVT system can reach up to 70\%. [8]

2. History of Solar PVT system
The history of solar PV began in 1839 after the breakthrough discovery of photovoltaic effect by Alexandre-Edmond Becquerel, a French physicist. Solar cells are made up of silicon which captures the photons emitted by sun and generate voltages. [9] The photoconductivity of selenium was then discovered in 1873 by English electrical engineer Willoughby Smith. The first solar cell was designed in New York by Charles Fritts. It was done by coating selenium with a thin cover of gold. The efficiency of solar cell at the time of invention was mere 1\% compared to the efficiency of modern solar cells at 20\%. Silicon was found to be more efficient than selenium in 1953 by Bell Laboratories. And in this way production of solar cells took off commercially. The demand for solar power increased as the oil prices rose in 1970. This led to more research in the area and further reduction of cost. [10] The history of solar
thermal dates to 1839. There are records of solar heating in United States. Captain John Ericsson invented solar power engine in 1864. Solar Stirling Engine was driven by a parabolic concentrator. [11] In 1913, the first parabolic trough system was made for generating steam in Maadi, Egypt. The studies in PVT technology started in 1970. PVT technology has become an attractive energy solution for buildings as they require less space and provide more efficiency. [12] Hybrid PVT systems combine both the above idea.

Figure 1. Solar thermal collector system

3. Hybrid solar PVT system
Hybrid photovoltaic solar concentrator is a combination of solar cell and solar thermal collector. The model of hybrid solar thermal collector system is shown in Fig. 1 above. The cold water is supplied from household to the hybrid collector where it gets heated from the waste heat from the hybrid system. Combining thermal and photovoltaic system helps reducing space, on site electricity generation and thermal generation. The detailed view of PV collector is shown in Fig. 2. The cover glass is used for protection and minimizing heat loss. Eva encapsulant is used to protect PV layer from shock and vibration. Thermal insulation is also provided beneath the PV layer to reduce the heat loss from the surface. Fuentes et al. [13] founded that the combined efficiency of hybrid PV/T system can reach 80% during the day. Bhattarai et al. [14] analysed a hybrid solar PV/T collector and found that energy savings of hybrid PVT is more compared to conventional PV. Dupeyrat et al. [15] showed 79% thermal efficiency and 8.7% electrical efficiency for hybrid solar PVT. The electrical efficiency of solar cells was found to be 15% for 90% of solar insolation absorbed. Remaining was rejected as heat. [16] The study on liquid type PVT systems were first done between 1978-1981. [17] Lovvik and Bergene [18] studied the effect of cooling on solar cell. Temperature in the range of 60 – 80 °C were found common for solar cell and cooling resulted in increased electrical efficiency of about 10-30%.

Figure 2. Detailed view of PV collector

4. Application of Hybrid PVT
Solar hybrid PVT liquid collectors have been used for domestic hot water application. Hybrid PVTs have been also integrated with buildings. Chow et al. [19] concluded that building integration for PVT is more popular than
that of water application. A 20 kWp PVT with air as thermal fluid is located at Mantaro Library in Spain. Concordia University, Montreal also developed a PVT system with 24.5 kW and 75 kW electrical and thermal power respectively. Beijing Olympic village also installed a PVT system with 10 kW and 20 kW of electrical and thermal power generation respectively. Fang et al. [20] concluded that the integration of hybrid PVTs with building is going to be most focussed area in the world. Global solar thermal capacity grew from $89 \times 10^6$ m$^2$ (2000) to $675 \times 10^6$ m$^2$ (2017) in China. 3.78 $\times 10^6$ kg of oil and 1.2 $\times 10^9$ kg of CO$_2$ was saved due to this. Denmark, Sweden, Austria, Greece and Spain have large scale solar thermal plants since 1980. China has also recently installed a large no. of such systems.

4.1 Applications of Hybrid Photovoltaic Thermal Systems:
The major application of Hybrid PVT system is found in building integration. These systems can be used for pool water heating (25 – 35 ºC), space heating (up to 60 ºC) and domestic hot water. [21] Space heating and DHW constitute for nearly 50 % of heat demand. The hybrid systems also allow for the most efficient utilization of roof space. The total installation cost is also lesser when compared to individual installation of solar thermal unit and solar PV unit separately.

i. Building integrated photovoltaic thermal – BIPVT capacity has increased due to increase in grid connected photovoltaics. BIPVT is generally mounted on rooftop of building. The orientation of BIPVT should be such that solar insolation can be accessed. Irradiance and PV module temperature are important parameters for such system.

ii. Power generation – Hybrid PVT system can be used for power generation. Also, it was found that PVT plant is capable to produce more power than conventional plant. But the cost would be more. [22]

iii. Agriculture – PV pumps are most suitable application when plenty of sunshine is available. Hybrid PVT collector system with air can be also used for agriculture purpose or crop drying. Fierich et al. [23] experimentally studied a solar drier equipped with solar PV/T air collector. The hybrid PVT drier shortened the drying time and increased the efficiency. Barnawal and Tiwari [24] performed grape drying using hybrid photovoltaic greenhouse drier at solar energy park, New Delhi.

iv. Street lights – Hybrid system can be used for lighting streets, yards, compounds and industrial roads.

v. Concentrating PVT – These systems have been used in hospitals and schools. Swedish manufacturer Absolicon installed concentrating PVTs in a private hospital in Harnosand for power. The Cogenra building installation at the university of Arizona Tech Park supplies 191 kW and 36 kW thermal and electric power respectively. [25]

vi. Solar distillation – The overall thermal efficiency of hybrid solar PVT still designed Kumar and Tiwari [26] was found to be 20 % more than the conventional solar still. The electrical efficiency of the former was also found to be higher. Pounraj et al. [27] found 38% efficiency rise for Peltier based hybrid PVT active solar still as compared to conventional PV still.

5. Performance of Hybrid Solar PVT
Based on working fluid, there are two main types of hybrid collector. These are water-based and air-based hybrid collectors. Air has some advantage over water since it does not freeze and there is no damage if leakage occurs. But the heat capacity and conductivity of air is lower. PVT air collectors are generally used in buildings. The overall performance of the hybrid system is the sum of thermal efficiency and electrical efficiency. [28]

$$\eta_{PVT} = \eta_{th} + \eta_{PV}$$  \hspace{1cm} (1)

5.1 Thermal Performance

5.1.1 Solar module temperature

$$t_{m0} = t_{amb} + (NOCT - 20) \times \frac{G}{800}$$ \hspace{1cm} (2)

where NOCT the temperature of module in an environment with solar irradiation of 800 W/m$^2$, 20ºC ambient temperature and wind speed of 1 m/s. The heat can be removed from the cell by different modes of heat transfer. The heat removed can be utilized for different purposes. The thermal efficiency of hybrid system and other parameters can be obtained as:

$$\eta_{th} = \frac{m \times c_p \times (t_{out} - t_{in})}{a_{PV} \times G}$$ \hspace{1cm} (3)

The loss of heat from the reservoir to the surrounding is:

$$Q_{loss} = \int U_t (t_{in} - t_{amb}) \, dt$$ \hspace{1cm} (4)
5.2 Electrical efficiency
The electrical efficiency is given as:
\[
\eta_{el} = \left( \frac{P}{P_{max}} \right) \frac{I_{sc} V_{oc}}{G S}
\]  
(5)

\[
f' = \frac{P_{max}}{I_{sc} V_{oc}}
\]
(6)

The energy conversion efficiency of the PVT system is:
\[
\eta_{PVT} = \frac{w+q}{\eta} = \eta_{el} + \eta_{th}
\]
(7)

5.3 Energy saving efficiency
The energy-saving efficiency of the pvt system is given by
\[
E_{sa} = \frac{\eta_{el}}{\eta_{power}} + \eta_{th}
\]
(8)

6. Losses in solar thermal system
Losses in solar thermal system are mainly optical and thermal. The solar thermal system efficiency keeps changing due to changing solar and weather condition. [30]

i. Cosine loss – These losses occur due solar radiation not being perpendicular to reflector.

ii. Shading and blocking – Losses within the system due to blockage by individual elements

iii. Reflectance – The reflector does not allow all the incident light to pass through it

iv. Cleanliness – Dirt and dust from atmosphere accumulate on the surface of reflector and decrease efficiency.

v. Incident angle modifier (IAM) – Optical parameters generally degrade with increase in incident angle.

vi. End losses – Some part of receiver does not receive radiation from solar collector.

vii. Intercept – These losses occur due to geometrical inaccuracies.

viii. Shielding by bellows – These losses occur due to bellows shielding.

ix. Transmittance of glass – These losses are depending on the nature of glass material.

x. Absorbance of receiver – The receiver surface coating absorbs some radiation.

xi. Thermal losses – This is caused by convection and radiation.

xii. Thermal losses due to piping – These losses occur due to conduction and convection.

7. Conclusion
There has been huge research in the field of hybrid system since 1970. Hybrid PVT system transforms solar insolation into usable heat and power. The hybrid system is a combination of solar PV and thermal collector. Solar PV converts solar energy into electric power whereas thermal collector removes waster heat from the solar PV. This results in the increase in the efficiency of the hybrid system. The electrical efficiency of solar PV is about 10% without cooling. The conversion efficiency of hybrid PVT systems can reach up to 80 %. The hybrid system can be very useful for developing country like India which has huge potential of solar energy spread throughout the country.
Nomenclature

- $\eta_{el}$: electrical efficiency
- $\eta_{power}$: efficiency of electrical power generation
- $t_{out}$: outlet temperature of collector (°C)
- $t_{in}$: inlet temperature of collector (°C)
- $c_p$: specific heat (J/kg/K)
- $\eta_{th}$: thermal efficiency
- IAM: incident angle modifier
- NOCT: nominal operating temperature (°C)
- SRE: standard reference environment
- $U_l$: overall heat transfer coefficient of reservoir (W/m²K)
- $q$: heat (J)
- $E_{sa}$: energy saving efficiency
- $s$: surface area of the unit (m²)
- $G$: solar irradiance (W/m²)
- $U_{oc}$: open circuit voltage (V)
- $\eta_{PV}$: photovoltaic efficiency
- eva: Ethylene-vinyl acetate

Subscripts
- el: electrical
- out: outlet
- in: inlet
- th: thermal
- mo: module
- amb: ambient
- max: maximum
- avg: average
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