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OPTIMIZATION OF PHOTOVOLTAIC / THERMAL COLLECTORS

Joseph McCabe, P.E.
Energy Ideas
13 B Main Street
Winters, CA 95694
energyi@mccabe.net

ABSTRACT

Recent designs in the Solar Decathlon have incorporated solar electric modules with heat capture. Zero Energy Buildings (ZEB) solicitations through the National Renewable Energy Laboratory (NREL) have recently awarded photovoltaic / thermal (PV/T) projects incorporating air and fluid based heat transfer mediums. This paper introduces the PV/T collector with a quick history of four different research and development projects starting with the Massachusetts Institute of Technology (MIT) in 1978. Suggestions for engineering design and performance guidelines are provided. A demonstration of a zero glazed thin film amorphous silicon photovoltaic module with air as the fluid transfer medium, captured off the backside, is presented. The paper provides suggestions on applications and appropriate environments for various PV/T collector types.

INTRODUCTION

Energy systems employing solar are continually becoming more effective and practical. One solar energy design incorporates solar electric modules with heat capture. Heat capture can be used to heat domestic water, or can heat the inside of buildings during cold months. The National Renewable Energy Laboratory (NREL) is supporting projects such as these. The PV/T collector combines electrical and thermal production in one collection surface. The primary benefits of combining PV modules with solar heat collection are:

- An area covered with PV/T panels produces more electrical and thermal energy than a corresponding area covered half with conventional PV-panels and half with conventional thermal collectors. This is particularly useful when the amount of space on a roof is limited.
- PV/T panels provide architectural uniformity on a roof, in contrast to a combination of separate PV and thermal systems.
- The average PV temperature in a PV/T collector might be lower than a conventional PV-laminate, thereby increasing its electrical performance. [1]
- Some installation labor, balance of systems costs and transaction costs can be reduced by one type of system installation.
- PV/T systems can remove heat from the building shell, which can have whole building energy benefits.

The drawbacks of PV/T collectors include the possibility of reduced performance compared to the optimized collector for either electrical or thermal production. Furthermore, additional layers of glass, or glazing, also cause additional performance reductions.

NOMENCLATURE

η_T =	Thermal Efficiency
η_{th} =	Experimental derived Thermal Efficiency
η_{el} =	Electrical conversion efficiency of PV
$\eta_{(pv\ in\ pvt)}$ =	Efficiency of PV in a PV/T collector
$\eta_{pv\ stc}$=	Standard Test Condition PV efficiency
$\eta_{(pvt)}$ =	Efficiency of PV/T collector including both thermal and electrical energy
F_R =	Collector heat removal factor
α =	Absorber plate absorptance
τ =	Transmittance
$(\tau\alpha)$ =	Transmission absorption product of cover and absorber
C_p =	Heat capacity of fluid (J kg^{-1} C^{-1})
I =	Irradiation (W) area is overall collector surface
I_m =	Current at maximum power point (A)
V_m =	Voltage at maximum power point (V)
U_L =	Collector overall heat loss coefficient (W C^{-1}) area is overall collector surface
T_a =	Ambient air temperature (^oC)
T_o =	Outlet temperature (^oC)
T_i =	Inlet temperature (^oC)
T_{cell} =	Cell Temperature (^oC)
MCF =	Module cooling factor (~30 for a passively cooled module in free air, ~45 for BIPV)
m* =	Mass flow rate of heat transfer fluid (kg s^{-1})

1. Design / Performance Guidelines for PV/T Systems

It has been shown that PV/T collectors harvest less heat when the PV is producing power [1], therefore thermal performance should be measured under PV load. In addition to the thermal evaluation, we look at the performance of the PV at design temperatures for the PV/T collectors. Combining these energy production goals, we optimize the photovoltaic collector for electrical and thermal harvest, longevity, and safety.

1.1 Thermal Evaluation

We start with the delightful Hottel-Whillier equation [2]:

$$\eta_T = F_R(\tau\alpha) - F_R U_L \frac{T_i - T_a}{I} \qquad (1)$$

This equation is an expression of the collector thermal efficiency as a linear decreasing function of the parameter (T_i – T_a) / I.

Three great design features can be obtained from the graphic representation of this equation. First the optical qualities of the collector are being represented by the y-intercept component when graphed, the $F_R\tau\alpha$. Second, the x-axis intercept, or when the difference between the ambient air and inlet temperature is greatest, represents the stagnation temperature of the collector. Lastly, the slope of the performance curve is represented by F_RU_L. The slope is representative of the thermal losses of the collector. A steeper slope indicates higher thermal losses.

We experimentally test the efficiency of a thermal collector using the relationship of the output of energy over the input of energy:

$$\eta_{th} = \dot{m}c_p(T_o - T_i) / I \qquad (2)$$

Setting the first two formulas equal to each other, $F_R\tau\alpha$, F_RU_L and the stagnation temperature can be determined by testing various collector temperatures with constant flow and insloation. Inlet and outlet temperatures, mass flow along with insolation are easily measured and plotted for various (T_i – T_a) / I.

Solar Ratings Certification Corporation (SRCC) provides procedural testing of collectors. SRCC is a standard testing procedure for solar thermal collectors and systems [3]. SRCC attempts to keep radiation and collector flow consistent so that thermal performance curves can be compared across different manufacturers.

1.2 Photovoltaic Evaluation

PV operates at known power outputs for various intensities of incoming solar radiation and cell temperatures. The efficiency is the product of the current and voltage divided by the insolation (I) received by the collector surface:

$$\eta_{el} = I_m V_m / I \qquad (3)$$

In PV cells the voltage varies with the cell temperature. Different PV technologies have different temperature correction factors.

PV modules are rated at a specific intensity of incoming solar radiation and cell operating temperature, typically 1,000 watts per square meter and 25°C respectively for standard test conditions (STC). For constant solar radiation, operating cell temperature is the critical component of expected energy production in a PV/T. If a PV module is hot, it puts out less electricity compared to when it is cold. Cell temperature can be estimated by using a module-cooling factor:

$$T_{cell} = (MCF * (I / 1{,}000) + T_a) \qquad (4)$$

For I = 1,000 watts per square meter

$$T_{cell} = (MCF + T_a) \qquad (5)$$

The PV electrical efficiency is corrected for temperature by:

$$\eta_{(pv\ in\ pvt)} = \eta_{pv\ stc} * (1 + [PV_{tc} * (25^{\circ}C - T_{cell})]) \qquad (6)$$

η_{stc}= Standard Test Condition PV efficiency
MCF = module cooling factor (~30 for a passively cooled module in free air, ~45 for BIPV)
PV_{tc} = PV Temperature correction / degree C (0.005 for crystal, 0.002 for a-Si)
I = Insolation in Watts / square meter
T_a= Temperature ambient in °C

For example, using a 12% efficient polycrystalline silicon BIPV module with an ambient temperature of 28°C and 1,000 watts per square meter of irradiance will have a cell operating temperature (45 * 1,000 / 1,000) + 28 = 73°C, and an efficiency corrected for temperature of 0.12 * (1 + 0.005 * (25 – 73)) = 0.0912 or 9.12% efficient. A 120-watt rated module would only produce 91.2 watts due to this temperature condition.

Using this same example, but reducing the cell temperature from 73°C to 50°C due to thermal harvest of a PV/T collector, will produce more electricity. Here we see a temperature correction of 0.12 * (1 + 0.005 * (25 – 50)) = .105 or 10.5%. The same 120-watt module would produce 105 watts, or 13.8 more watts because of the more favorable temperature of the cells. In addition, ~50°C liquid or air can be utilized.

1.3 Thermal and PV Energy Performance Combined

Normally, cell temperature is similar to the stagnation temperature and demonstrates the potential for harvesting thermal energy. A PV/T lowers the cell temperature by removing heat from the module, more than would have been removed passively. If the cell temperature is the same as the PV/T collector thermal operating temperature (cell temperature is slightly higher), remembering that the thermal performance was determined with the PV under load, we can combine the two performance functions into one PV/T performance formula:

$$\eta_{(pvt)} = F_r\tau\alpha - F_r\, U_L(T_i - T_a)/I + \eta_{pv\ stc} * (1 + [PV_{tc} * (25^{\circ}C - (MCF * (I / 1{,}000) + T_{amb}))]) \qquad (7)$$

The total energy produced is the insolation in watts * PV/T efficiency.

1.4 Physics

PV Cells are designed to absorb solar wavelengths that can produce electricity, and not absorb wavelengths that create heat. They are also designed to emit as much heat, or long wave radiation as possible. The photovoltaic collector is designed to thermally conduct, convect, and radiate heat away from PV surfaces. These features help to keep the cells cool because PV produces more electricity when cooler. PV modules emit heat, solar thermal system absorb heat.

In order to be as safe as possible, PV/T surfaces need to be electrically isolated from the fluid heat transfer medium. However, PV/T collectors attempt to conduct as much thermal energy away from the cell as possible. These two goals, electrical isolation and thermal conductivity, are physically opposed.

At higher temperatures, PV cells produce less voltage (and slightly more current). The type of PV technology determines the temperature correction factor. Both single and poly crystalline silicon temperature correction factor are typically 4.5% to 5% per 10°C. Thin film amorphous silicon is typically 2% per 10°C. Other thin film technologies can vary from 0% to 5% per 10°C. A cell operating at glazed thermal collector temperatures can have electrical losses as high as 35% compared to an unglazed version. Society puts a high value on electrical energy, so these losses due to elevated operating temperatures are economically significant.

1.5 Other Design Considerations

1.5.1 Stabler-Wronski

Amorphous silicon PV performs 10 to 15% less than originally manufactured after a few hundred hours of soaking in the sun. This is called light induced degradation or Stabler-

Wronski degradation after the discoverers. Manufacturers account for this when selling modules, and show performance according to the degraded levels. Interestingly for PV/T, this degradation can be annealed by heating the modules. In essence, a module can be re-annealed repeatedly to reduce the light induced degradation. The good news for PV/T design is that elevated temperatures might help re-anneal light induced degradation in amorphous silicon PV materials.

1.5.2 Stagnation Temperature

Thermal collectors are often in stagnation condition. This occurs when the heat transfer fluid is not moving in the collector, stagnant, and the collector heats up to a maximum condition.

From the Hottel-Whillier equation when efficiency = 0, stagnation temperature is:

$$T_i = \tau\alpha I / U_L + T_a \qquad (8)$$

Consider situations where reflected solar radiation, inadvertent concentrations of sunlight, which might increase the stagnation temperatures.

1.5.2 Thermal Shock

What happens when a thermal collector is in stagnation condition and cold fluids are introduced? Thermal shock has the potential to destroy a thermal collector. This is more problematic when expensive PV materials are included. Losses could be substantial if mechanical connections or electrical safety is compromised by thermal shock. SRCC has recommended this protocol for testing thermal shock:

At one time during the test sequence the unfilled collector shall be exposed to full sun, not less than 950 W/m², for one hour. While the collector is still so exposed, liquid shall be circulated through the collector for five minutes at a flow rate of approximately 17 ml/s per square meter of collector. The temperature of the entering liquid shall be 24°C ±5°C during the test [3].

1.5.4 Glazing

Additional glazing can increase temperatures of the collection surface. This is advantageous for thermal energy harvest. However, additional glazing increases solar radiation transmission losses to the collection surface and can increase reflection losses. Electrical production can be reduced 10% or more for each additional glazing.

2 History of the PV/T Collector

Optical analysis of PV/T collectors, using single crystal silicon PV cells dominated the research in the late 1970's. In 1978 Ed Kern (et al) showed at least 22% of the solar spectrum available for thermal energy collection exists at wavelengths, which cannot contribute to the PV output. In addition, it was also shown that these PV cell designs had back surface metallization (typically aluminum) that reflected the wavelengths for thermal back toward the sky, reducing the wavelengths absorption. Approximately 20 to 25% of the solar spectrum was being reflected back out of a typical silicon solar cell due to the highly reflective metal backing placed on the cell as an electrical contact. It was suggested that the cells be designed with a grid for electrical contact, similar to the front of cells. This reduced the fill factor (a theoretical measurement of performance) substantially. [4] Newer bifacial cells may be an opportunity for investigation due to the small surface area grids on both sides of the cells.

In 1983 Brown University was also interested in increasing anti-reflection, because of low solar absorptance of PV cells. Polished silicon wafer with anti-reflection coating had an absorptance of only 0.75 – 0.80, as compared to 0.95 for a good thermal collector surface. Similar to Kern's work, it was shown that the ohmic contacts on the light-receiving surface are good optical reflectors. [5]

The main reason PV/T were not being accepted in the 70's and 80's was because crystalline cells had high losses of electrical performance at high temperatures.

2.1 PowerTherm

PowerTherm is a zero glazed amorphous silicon PV/T using liquid heat transfer off the backside, investigated by PowerLight of Berkley California. The PV cells are made by United Solar Systems of Auburn Hills Michigan. Heat capture materials are similar to EPDM, a standard material used in pool heating solar thermal collectors as shown in Figure-1.

Harter makes a zero glazed pool heater with a thermal performance equation Y = -12.2X + 0.67. The EPDM has an absorptivity of .97 and an emmisivity of 0.90 - 0.92. This gives a good comparison of zero glazed commercially available solar thermal only products.

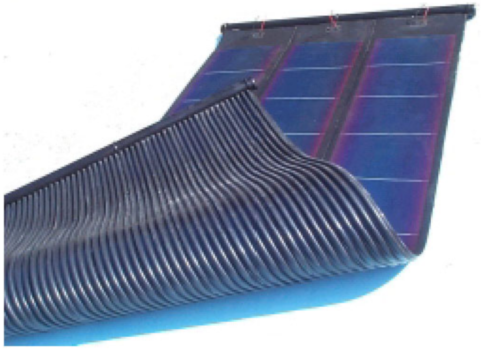

Figure-1: PowerRoll - embodiment of thin film PV integrated with EPDM solar thermal collector (Photo courtesy of PowerLight).

PowerTherm was demonstrated to have a thermal performance equation $Y = -4.8X + 0.58$. Note that apparently this data was collected from a horizontal array, so incidence angle differences probably account for some of the different $F_R\tau\alpha$ (intercept) values. Also, the collectors were installed on an insulated roof in Sonoma California, versus an open rack mount, thus convective losses from the system would be less than observed at the Florida Solar Energy Center (FSEC) SRCC testing, resulting in a lower F_RU_L value for all the collectors. SRCC procedures were not exactly followed in the demonstration.

PowerLight reports that the technical and economic goals for their project were achieved. PowerLight also reports a decision not to manufacture this product until further improvements in the manufacturing process are realized. [6]

2.2 Solar Decathlon 2002

Solar Decathlon 2002 was a successful demonstration of building efficiency combined with renewable generation held on the Washington DC Mall in 2002. Crowder College received a sixth place award, in part due to their PV/T collector. Working in collaboration with British Petroleum (BP) Solar, Watts Radiant (radiant floor company), and a roofing company, the team designed a hybrid system that combines solar thermal and PV. Crowder College concentrated on building integration using lower efficiency thin film amorphous silicon. In a diary entry, they wrote, "We knew that the panels we chose would not compare to the higher efficiency multi- or single-crystalline panels but, simply put, our BP Millennia panels could take the heat. Our BIPV-T (Building Integrated Photovoltaic-Thermal) panels require an electric panel that can withstand temperatures at or exceeding 200ºF. As a fringe benefit, these panels are beautiful, looking like smoked glass on the roof of our house." Figure-2 shows the PV trailer that powered the construction site. The collectors near the ladder are PV/T. [7]

Figure-2 Crowder College 2002 Solar Decathlon home entry.

2.3 Phototherm

Phototherm is a glazed PV/T collector using liquid as the heat transfer, which attempts to institutionalize the PV/T collector as an energy production solution. In 2003, Solar Design Associates published results from their testing of United Solar's thin film triple junction amorphous silicon PV combined with Sun Earth's flat plate solar collector.

Figure 3 Phototherm PV/T on Left, SunEarth Empire thermal collector on right. (Photo courtesy of NREL and Solar Design Associates)

Solar Design Associates reports that τ, the minimum transmissivity of the glazing given by the manufacturer as 0.91 and α is the absorptivity of the collector given by the manufacturer as 0.70. At least two factors affected the performance of the PV/T collector during the simulation. These are the very high emittance (0.89 vs. 0.12 for the standard collector) and lower than typical plate absorptance (0.70 vs. 0.95 for the standard collector). [8]

2.4 Winters California PV/T

A fully Underwriters Laboratory (UL) approved PV/T collector was installed in the spring of 2002 in Winters California. This collector uses United Solar System amorphous silicon PV modules (PVL-58). Air is used as the heat transfer fluid. A 1.2 kW PVUSA Test Condition (PTC) rated collector was installed on top of upside-down standing seam metal roofing. At the time, the 16-guage metal was required for UL approval and the shortest laminate USSC made was 9' 6". This was the first manufactured PVL-58, challenging United Solar to make a module that was 8 feet in length to match the building industry's 4' X 8' dimensions like most plywood and drywall (Actual dimensions became 4'-2" X 8'-4"). The system installation attempts to be more aesthetically pleasing, more geometrically valuable, produce more thermal and more electric energy for the home than previously available PV/T solutions.

Figure-4 Installation of first 4' wide module. (Photo by Energy Ideas)

Figure-5 Completed Winters PV/T array. (Photo by Energy Ideas)

Figure-6 Detail of Winters PV/T collector. (Photo by Energy Ideas)

We combined three PVL-58 peel-and-stick laminates, attached them to the bottom three standing seam metal pans. This produces a 150 watt PTC, 75 pound lightweight, low profile, nominal 4' X 8' PV/T array. The Winters PV/T system has 8 of these arrays. By inverting a typical standing seam metal roof, placing the PV on the flat side and using the standing seam as the legs, we were able to produce a 1-1/2" high plenum where air can circulate underneath the modules to collect heat.

In Figure-4, the vent pipes shown were relocated; the holes were used as inlet and outlet of air for thermal harvest. The Figure-6 detail shows a grip-edge providing additional hold down for the "peel and stick" laminate. The grip edge has been riveted to the upside-down standing seam pan. A black L bracket supports the top and bottom, here shown with a hole for electrical wiring outlet. The black L roof bracket is bolted to the roof by a hanger bolt and sealed. An additional sheet metal screw holds down the bottom of the laminate. Self-tapping sheet metal screws (not shown) hold the roof bracket to the modules. The grip edge holds the laminate without any actual mechanical attachment; the metal and the modules needed to expand and contract, while the module needed to be secured from any uplift wind forces.

As one solar engineer named Bill Brooks said about the system, it is an "…attractive low profile roof-mounted array" [9].

Testing of the air temperatures available off the backside of the collectors is typically 20^{o}C to 40^{o}C higher than ambient air. Using a data acquisition, we were able to track the attic air temperature (shown as Temperature1), the outside air temperature just above the roof (shown as temp_probe1), and the airstreams being harvested off the backside of the PV/T collector (shown as temp_prob2). The graphs in Figure 7 - 12 demonstrate the various conditions available.

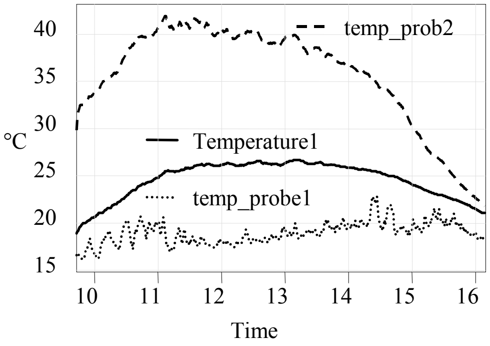

Figure-7 On December 7th, 2003 at the beginning of the testing the PV produced about 700 watts AC at 9:45 AM, and there was a slight breeze. The PV was producing 740 watts AC at 10 AM, 770 watts AC at 10:15, and 10:30 AM, and 520 watts AC at 2 PM. The testing ended at 4 PM with 20 watts AC. A total of 4,371 watt hours AC electricity was produced for this low sun winter day. It is important to notice the high temperature air available from the 23.8 square meter PV/T collector on this winter day.

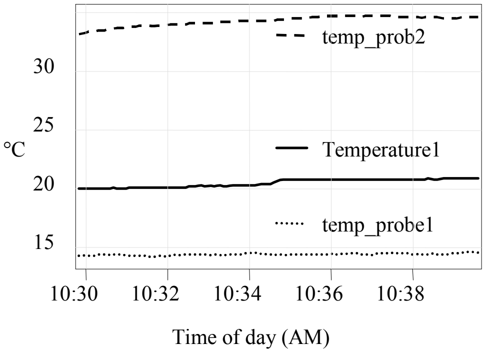

Figure-8 Here is a short sample on a sunny day, very windy, blustery, February 2nd, 2003.

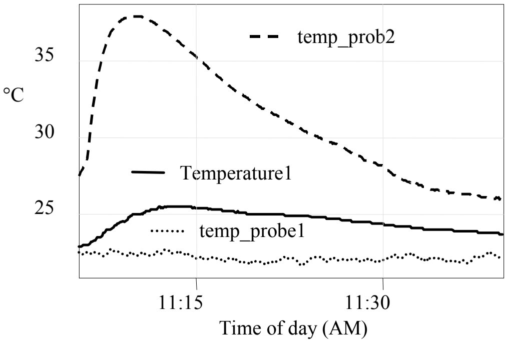

Figure-9 The PV output was 500 watts AC at 11 AM on this 9th of November 2003. The ramp up of the thermal energy is because the fan had just been turned on. The fan was off for first few seconds, so the roof and PV/T temperatures were about the same, at 23 C. Then fan was started, and the PV/T airstreams temperature rose. There was a slight outside breeze. Then clouds rolled in. PV electrical production was reduced down to 94 watts AC, the fan was turned off, and data collection ended.

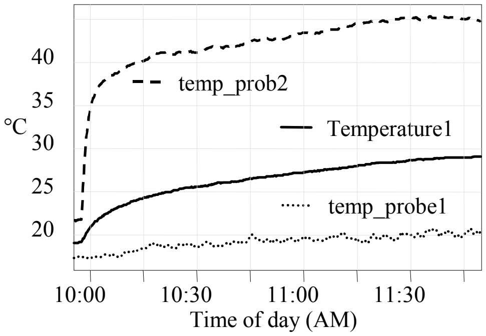

Figure-10 On November 11th, 2003 the fan was turned on just before 10 AM, the PV was producing 750 watts AC. It was quite sunny slightly breezy. The PV system produced 815 watts AC at 10:30 AM. Recording ended a little before noon, with 45°C available air.

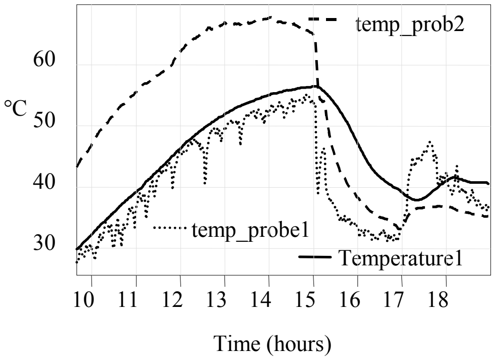

Figure-11 On July 6th, 2003 we tested cooling of the PV/ T system. Water was sprayed on the collector at 3 PM, and then turned off at 4:30 PM. The graph shows the rapid cooling of the PV/T, the attic, and the roof ambient air temperatures. The PV electrical production rose 15% due to the washing of the modules and from the cooling.

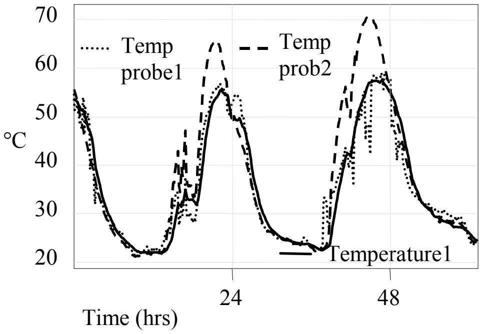

Figure-12 On the 19th of July we sprayed the modules at 10:10 and 10:40 AM for 5 minutes, then again at 11:10 AM for a half an hour. It was partly cloudy. Cooling produced 10% more electricity from the recently cleaned modules. A comparison of temperatures can be seen in the July 20th data, which had no water spraying.

The Winters PV/T system demonstrates the potential for an extra surface on the roof to be used to cool the roof and attic space, providing ducted-space energy savings. However, it should be noted, that the Winters design does not benefit from any re-annealing of Stabeler-Wronski degradation because the modules do not reach elevated temperatures. The system has no potential for thermal shock and no stagnation temperature worries because there is no glazing. Electricity is electrically isolated from the air heat transfer and thus completely adheres to established UL safety testing.

An air PV/T can easily dump excess thermal if not needed. Additional research is needed to determine the fan (or liquid pump) energy vs. the extra watts produced by the PV.

Fan coils or heat pipes are readily available and easily installed, UL approved for safety.

3 Types of PV/T Collectors

Four types of collectors shown in Figure-13 include zero glazed and single glazed water and air PV/T.

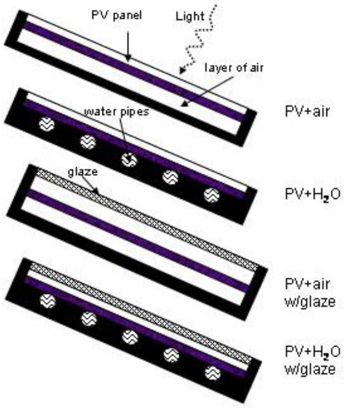

Figure-13 Types of PV/T, air and liquid collectors with and without glazing.

3.1 Example Thermal Performance

Liquid based polymer solar heat collectors with single crystal PV, both glazed and un-glazed, were recently tested by Bjørnar Sandnes and John Rekstad. The average values for the reported testing were $Y = -8.3X + 0.71$ for the glazed and $Y = -14.9X + 0.76$ for the un-glazed collectors. [10]

In another recent study by Tripanagnostopoulous (et al.), it was shown that an unglazed amorphous silicon with air as the heat transfer had a performance curve $Y=0.46 - 10.69$. [11]

Figure-14 shows these thermal performances, as well as other collectors mentioned in this paper. Liquid based performance curves can show conditions where the inlet temperature is lower than ambient. The air based amorphous silicon zero glazed example is the worst performer. However, as the Winters system demonstrates, it is the easiest to configure and install with existing UL safety certification. The $F_R U_L$ and $F_r \tau\alpha$ have not been shown for the Winters system, but are expected to be better than the Tripanagnostopoulous results because of the roofing deck being used instead of an open rack, and because of the advantageous optical results from the Powertherm testing of the United Solar System amorphous silicon PV modules

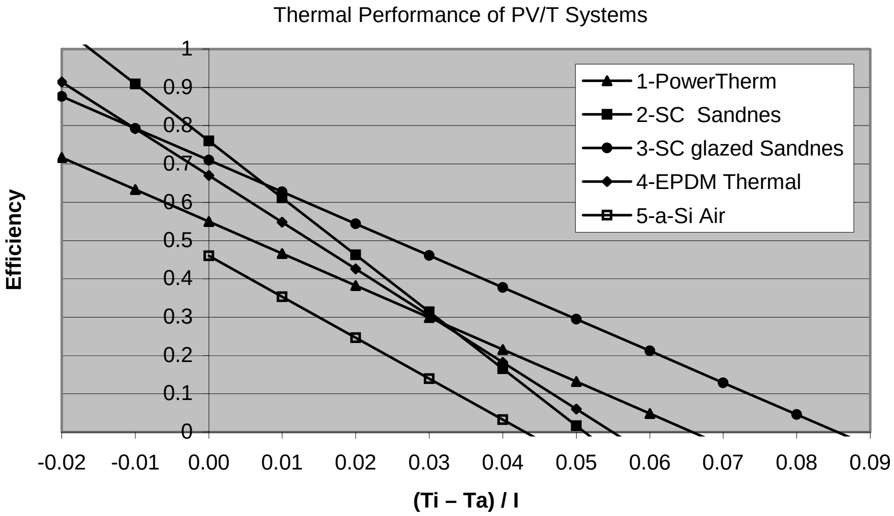

Figure-14 Thermal performance of various PV/T collectors (and one EPDM thermal collector).

4 Design Guidelines

1. Reduce electrical losses due to elevated cell temperatures.
2. If using amorphous silicon PV, investigate strategies to re-anneal light induced degradation.
3. In order to minimize thermal conduction losses the electrical isolator should be as thin as possible while providing crucial electrical isolation for safety.
4. Only use glazing in situations where thermal energy is valued over electrical energy; ensure stagnation temperatures of additional glazing can be withstood over time by photovoltaic materials.
5. Stagnation temperatures should never exceed PV materials thresholds for long-term material integrity. Include the potential for inadvertent reflection from buildings, cars, and parking lots when calculating stagnation temperatures.
6. Design should be fail-safe for thermal shock.
7. Various materials in a PV/T collector have absorption, reflection, transmistivity characteristics, which varying for different solar wavelengths. PV/T collectors should optimize the material selections for glazing (if higher temperatures thermal is desired), cell front, cell substrate and cell back surface treatments.
8. Electrical production benefits from the cooling effect of the PV cell from the thermal harvest.
9. The ultimate viability of the PV/T unit will be decided not merely by collector output, but by the ability of the PV/T system to match both the thermal and electrical loads of residences.
10. Specific site based hour by hour solar radiation should be used to determine the PV and thermal performance of a PV/T collector. The performance should be compared to the need (value) for the two forms of energy at the time of generation. Typically thermal energy is not needed in the summertime. Zero glazed collectors produce low-grade heat. It is challenging to utilize this heat in the summer and difficult to produce in the winter.
11. In the US, southwest states offer ideal weather conditions and demand conditions for electricity and low-grade thermal energy from PV/T collectors.
12. Design should address a market for the thermal energy from PV/T collectors, possibly pre-heating of outside air intake, similar to the transpired collector.

Conclusions

This paper has shown historical research and recent experimental examples of PV/T collectors. Various types of PV/T are explored with guidelines for designs. PV/T collectors have the potential to harvest both electrical and thermal energy from the same surface. Attention to detail, and optimization of the system to use the electrical and thermal energy when it is available is very important. Opportunities exist for PV/T collectors in locations that have good solar radiation, and a corresponding need for thermal energy throughout the year. A roof that has zero glazed PV/T collectors that feeds into a conventional solar-thermal-only glazed collector can be made architecturally attractive, and produces enormous amounts of electrical and thermal energy. Pre-heating outside make up air, and possibly heat pumps can benefit from heat and electricity from PV/T collectors.

REFERENCES

[1] Zondag, H. A., De Vries, D. W., Van Helden, W. G. J., Van Zolingen, R. J. C. and Van Steenhoven, A. A., 2002, "The Thermal And Electrical Yield Of A PV-Thermal Collector", Solar Energy Vol. 72, No. 2, pp. 113–128,

[2] Duffie J. A. and Beckman W. A. (1991). *Solar Engineering of Thermal Processes*, 2nd Edition, Wiley, New York.

[3] Solar Rating and Certification Corporation (SRCC), 1985 "Test Methods and Minimum Standards for Certifying Solar Collectors, FSEC-GP-5-80 (http://www.fsec.ucf.edu/solar/testcert/collectr/gp5std.htm)

[4] Kern, E. C., Pope, M.D., 1983, "Development and Evaluation of Solar Photovoltaic Sstems: Final Report, Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, Massachusetts, pp. 209-232

[5] Loferski, J.J. editor, 1982 , "Hybrid Solar Thermal-Photovoltaic Systems Demonstration-Phase I and II Brown University, Providence, Rhode Island DOE/CS/30205-T2 (DE84011814)

[6] Dinwoodie, T. L., Shugar, D., Ansley, J., 2002, "PowerTherm™: A Photovoltaic-Thermal Hybrid Commercial Roofing System", California Energy Commission P500-02-045F.

[7] Solar Decathlon website, Crowder College http://www.eere.energy.gov/solar_decathlon/crowder_d.html

[8] Munger, C. L. and Duffy, J. J., "Monitored Efficiency Of A Combined Photovoltaic And Thermal Solar Collector", 2003, American Solar Energy Society Conference 2003 Proceedings, Austin Texas.

[9] Brooks, B, 2002, "California PV Buydown Program: PV System Check Report", 6/13/02

[10] Sandnes, B., Rekstad, J., 2002, "A Photovoltaic/Thermal (Pv/T) Collector With A Polymer Absorber Plate. Experimental Study And Analytical Model", Solar Energy Vol. 72, No. 1, pp. 63–73

[11] Tripanagnostopoulos, Y., Nousia, Th., Souliotis, M., and Yianoulis, P., 2002, "Hybrid Photovoltaic/Thermal Solar Systems", Solar Energy Vol. 72, No. 3, pp. 217–2