Experimental Performance of a Hybrid PV/T Collector

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Abstract

Solar PV/T systems generate both electricity and thermal energy from the same collector area. While flat plate PV/T collectors have been traditionally utilized in residential applications, minichannel geometries allows for larger contact area between the heat transfer fluid and the absorber, reducing thermal resistance and producing higher outlet temperatures. In this article, a novel low-cost high efficiency solar PV/T collector is experimentally characterized which generates both electricity and thermal energy for space and water heating up to 60 °C. The collector utilizes nonimaging optics for solar concentration, aluminum minichannels for efficient thermal collection, and commercially-available solar cells for electricity production. A reflector around the bottom-half of the glass tube enclosure provides optical access to both sides of the minichannel absorber for efficient utilization of the entire surface area. A 20-tube array of collectors has been extensively tested outdoors. For a 5.5 kWh/m^2/day solar resource, we expect the solar PVT collector to generate 226 kWh of electricity and 603 kWh (20 therms) of heat each year for domestic hot water and space heating. By doing so each square meter of collector will reduce natural gas consumption (locally and at natural-gas fired power plants) by 1280 kWh (44 therms) and eliminate 184 kg of CO_2 emissions each year. At an estimated mass-production cost of $81 per square meter, a module will cost $0.54 per Watt (note: 2018 residential PV modules cost $0.47). The extra $0.07 per Watt can be attributed to the 400 Watts of thermal generation, which is essentially free. At a comparable cost as residential PV, it is likely the PVT collector could enjoy similar adoption and market penetration. In doing so it would make use of significant heat generating capacity of distributed rooftop PV systems, resulting in energy savings and emissions reductions. Over a 20 year lifetime, the estimated investment cost for GHG savings is approximately $22/metric ton of avoided CO_2.

Keywords: Minichannels, heat pipe, PV/T collector.

1. Introduction

California currently has more than 8,000 MW[1] of distributed photovoltaic generating capacity deployed on rooftops across the state. These technologies convert sunlight into electricity with efficiencies approaching 20%, with the remainder either reflected (~5%) or lost as waste heat (~75%). At a ratio of more than 3:1 (heat to electricity), there is a significant opportunity for recovery and reuse. For example, more than 150 TWh (5 billion therms) are consumed by the residential[2] and commercial[3] sectors in California each year for space and water heating below 60 °C. This is a large market space and source of emissions, about 80% of which is provided by high quality fossil fuels (natural gas, propane, and fuel oils) with combustion temperatures above 1000 °C. The temperatures needed for space and water heating, however, are readily achieved by existing solar collectors; in fact, it is not uncommon for PV modules to reach these temperatures just sitting outdoors. Therefore, it should be technically possible for a large portion of this market to be supplied by distributed and renewable solar systems.

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[1] https://www.californiadgstats.ca.gov/

[2] KEMA, Inc. 2010. 2009 California Residential Appliance Saturation Study. California Energy Commission. Publication number: CEC- 200-2010-004-ES

[3] Itron, Inc. 2006. 2006 California Commercial End-Use Survey. California Energy Commission. Publication number: CEC-400-2006-005

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Solar hybrid photovoltaic / thermal (PVT) solar collectors generate electricity while simultaneously providing thermal energy for hot water or space heating needs. These are enabling technologies of distributed zero-net-energy buildings, which reduce fossil fuel consumption on-site and at power plants and reduce loads on both the electric and natural gas grids. In addition, they offer several benefits over side-by-side PV + thermal systems. By recovering waste heat, there is increased production from the same collector area and an improvement in space efficiency. Where once two systems needed to be installed, now only a single system needs to be installed, reducing total installation time and cost. Furthermore, since installation costs are amortized over the electric *and* thermal generation of the collector, PVT technologies promise faster returns on investment.

While technically feasible, solar PVT systems have had trouble penetrating the market because their capital costs are too expensive to justify the additional heat generation compared to standalone PV panels ($\$0.47/W_{DC}$, (Ran, et al., 2018)). A price survey conducted in 2018 revealed an average flat plate PV/T module price of approximately $\$350/m^2$ or $\$2/W_{DC}$ (De Keizer, et al., 2018). Without innovations combining the two technologies (PV and thermal), the capital costs are high and payback times can reach 14 years (Tse, et al., 2016). What is really needed is an efficient and low-cost solar PVT collector with a similar price point as PV to access the market and capitalize on this distributed heat generating potential.

To achieve such a target, a new solar PVT collector which utilizes nonimaging optics for solar concentration, aluminum minichannels for thermal collection (Sharma, et al., 2011), and commercially-available solar cells for electricity production has been proposed. The PVT collector incorporates a nonimaging optical design to provide optical access to both sides of the heat transfer element. Since both sides are utilized, no insulation or back sheet material is needed and the collector requires only half as much material as a flat plate collector. Expensive copper tubing is replaced with an aluminum minichannel (Hota, et al., 2018) (made low-cost by the automotive and LED industries) for efficient collection of thermal energy (Hota, et al., 2019). The ability to utilize solar cells in a less expensive package, and at the same time provide additional heat is key to lowering the levelized cost of energy from the system and reducing the payback time. At an expected module cost near the same price point as residential PV, it is likely this collector could see greater market penetration, allowing end users to capitalize significant heat generating capacity of distributed rooftop PV systems.

2. Collector geometry

The hybrid PV/T collector (Figure.1) uses strips of narrow PV cells attached to a heat transfer element. Both minichannel and heat pipe absorbers were used in two different configurations of the collector. The outer glass tube is 2 m long with an outer diameter of 70 mm. The PV cells were attached to the absorber using a thermally-conducting and electrically-isolating silicone tape. The collector is filled with Argon gas for reducing convection losses between the absorber and the glass. A silver reflector coating applied on the bottom-half of the glass tube reflects sunlight to the backside of the absorber, thereby improving spatial utilization of the absorber. The minichannel tube has four ports of width 7.2 mm and aspect ratio 4.5 (height 1.6 mm). The fluid flows into and out of the minichannel from the top. The heat pipes use acetone as the internal phase change working fluid. The width of the minichannel was 33 mm while that of heat pipe was 31mm. The active absorber length inside the tube for both configurations was 1.83 m long. In accordance to this mode of fluid flow in the minichannel tube, minichannel will be interchangeably labelled as flow through tube to avoid confusion. The optical simulation indicated a horizontal configuration to have optimal performance. Further details can be found in (Brinkley, et al., 2018).

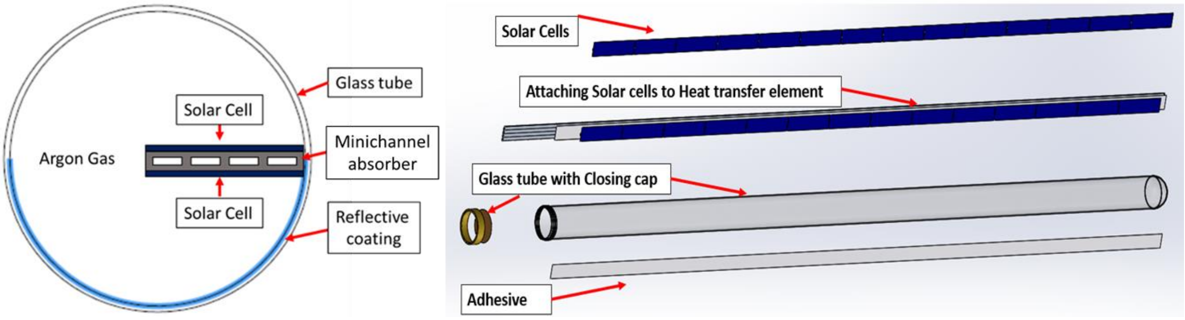

Figure 1: (left) Cross-section of PVT collector, (right) components of the hybrid PV/T collector

Sunpower Maxeon Gen II cells were used as the electric component of the PV/T collector, selected for their high efficiency, robustness of their inter-digited back contacts, and durability. The commercial cells come in sizes of 125 mm X 125 mm. In order to apply them on the 33 mm wide absorber tubes, each cell was cut into three strips of width 30 mm each. A total of 13 cells were applied to each side of the absorber, interconnected by sets of tabbing wire. Both sides (top and bottom) were then wired in parallel to each other.

The cells were then characterized sequentially during the cutting process under outdoor conditions. Solar measurements were made by a reference cell and the IV curves taken using a Keithley 2460 SourceMeter. A 20.1% efficiency measured in the uncut cell was reduced to about 18.7% in the cut cells. We believe some areas of the cells were deactivated due to the cutting process, which isolated some of the back contact regions as their contacts were cut.

3. Single tube PV/T test performance

IV curve testing was performed on the tubes during and after assembly. The IV curves of bare top and bottom strips (taken outside, on-sun, and without a glass tube) are shown in Figure 3 (left). Both strips have nearly identical on-sun IV curves with maximum power point efficiencies of about 18.3%. The IV curves from a finished collector are shown in Figure 3 (right). The top strip inside the PVT collector (blue) is reduced compared to a bare strip due to the transmission loss through the glass tube. The bottom strip inside the PVT collector (green), however, is reduced 2/3 of the top strip which is more than expected from just an additional reflection loss. This may be due to uneven illumination of the solar cells (for example via shading from one of the absorbers supports) which may be current limiting the entire strip. When the two strips are wired in parallel in the PVT collector (red) the resulting IV curve is the sum of the top and bottom strips as expected.

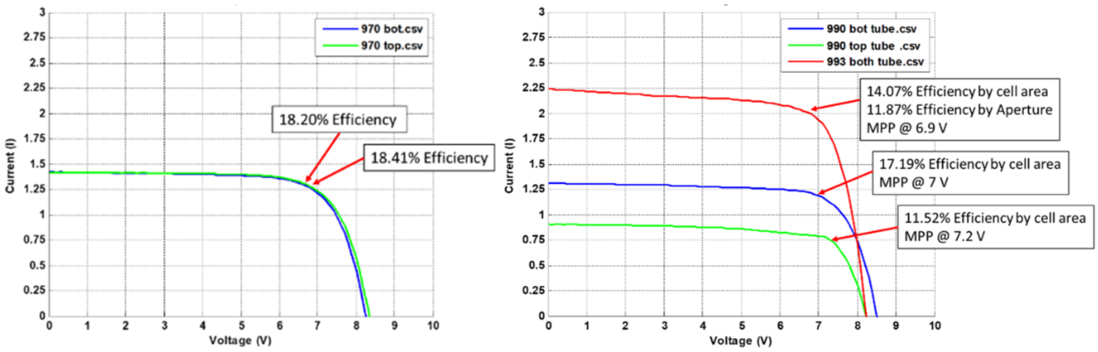

Figure 2 – (left) bare strips exposed to sunlight, (right) strips inside a solar PVT collector.

4. Collector Array

Twenty fully working PVT collector tubes were then assembled into an array and mounted on an outdoor test platform at the UC Merced Castle Research Facility in Atwater, CA (37.37°, -120.58°). Two collector arrays were made of 10 flow through minichannel tubes and 10 heat pipe tubes. The arrays were individually tested for thermal and electrical performance.

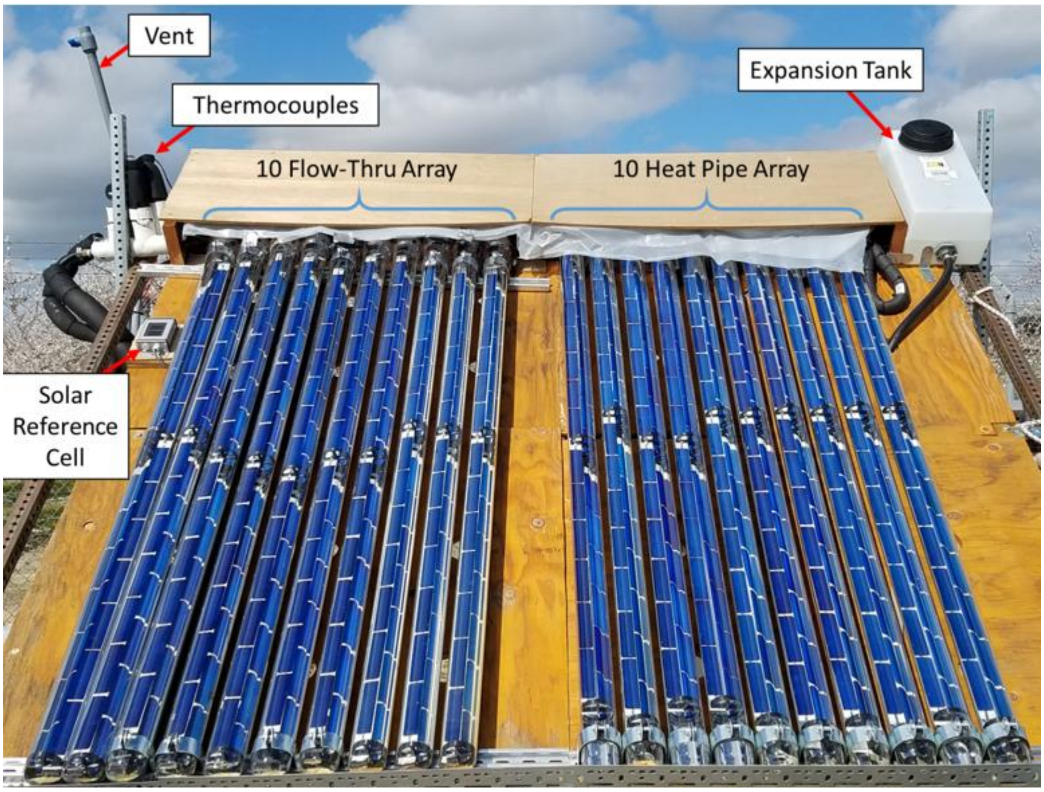

Figure 3: PV/T array. (L): Flow through minichannel based absorber; (R): Heat pipe based absorber

Figure.3 shows the collector assembly. Flow through tubes were connected in parallel to reduce the pressure drop in the system. The condenser sections of the heat pipes were sandwiched between two manifolds to extract heat from both sides of the heat pipe. Electrical data is measured by MPPT tracker while the fluid temperature is monitored at the inlet and the outlet by thermocouples connected to a data logger device. A reference cell is used to read the solar irradiance.

Outdoor test results were gathered between February-June of 2019. Both open loop and closed loop tests were performed to obtain data for working temperatures between 20°C - 60°C. The output variables were continuously monitored for the working test conditions mentioned below in Table. 1.

Table 1: Test conditions for the performance analysis

Test Parameter	Standard test condition
Duration of test	30 minutes
T_{in}	Must not vary by more than ±1 °C during course of test
$\dot{m}$	Must not vary by more than ±8 g/s during course of test
GTI	Must be ≥ 800 W/m^2 during course of test
GTI	Must not vary by more than ±50 W/m^2 during course of test

The measured variables were used for computing electrical and thermal efficiency given as:

$$\eta_{th} = \frac{Q_{thermal}}{Q_{solar}} = \frac{\dot{m}C_p(T_{out}-T_{in})}{AG} \qquad \text{eq (1)}$$

$$\eta_{elec} = \frac{Q_{electric}}{Q_{solar}} = \frac{\mathrm{IV}}{AG} \qquad \text{eq (2)}$$

The flow rate ($\dot{m}$) and temperatures were measured using an Omega gear-type flow meter and J-type thermocouples connected to a DAQ system. The specific heat capacity of water (C_p) was considered constant (4.183 kJ/kg-K). The current (I) and the voltage (V) were measured by the MPPT tracker. The denominator in equations 1 and 2 represent the absorber area (A) and the GTI (G) observed by the reference cell.

5. Results

An example test day is shown in Figure 5, during which the minichannel array was undergoing testing. As the elevation and the azimuth changed, the incident solar radiation increased with time and then decreased during the sunset. The ambient temperature increased with time. Flow was maintained at almost a constant 90 g/s which allows for enough residence *t*ime to generate a measurable temperature difference while maintaining laminar flow in the minichannels.

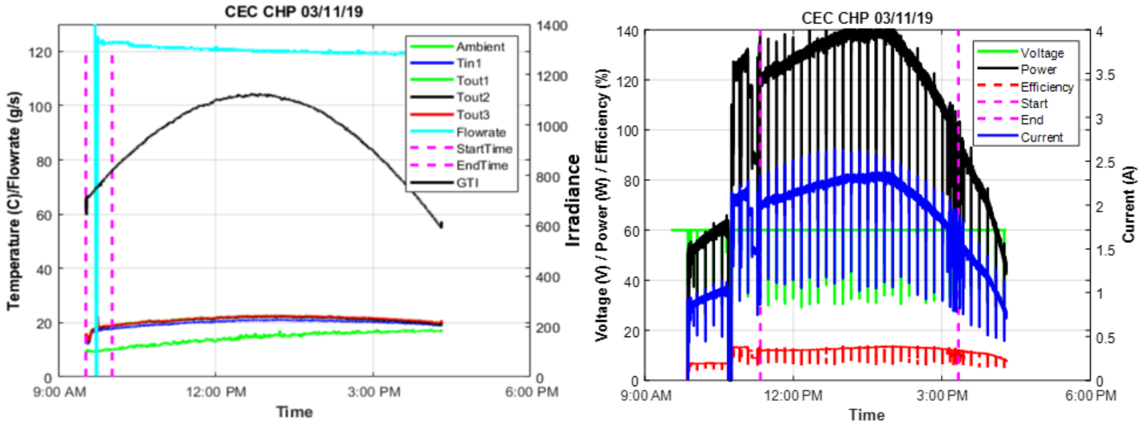

Figure 5: Thermal and electric data monitoring on a clear sunny day. (L): Thermal data; (R): Electrical data

Figure. 5 (L) shows the data monitored through the day on a clear sunny day on March 11th of 2019. The image on the left shows the global tilt irradiance (GTI) on the plane of the collector aperture, fluid (water) flow rate, fluid inlet and outlet temperatures and the ambient temperature. The start and end portion indicate the frame where steady state can be expected in terms of performance. Figure. 5 (R) shows the corresponding electrical measurements of the voltage and current recorded by the data logger. For all the 10 tubes, the electrical efficiency was around 12% average within the portion of interest.

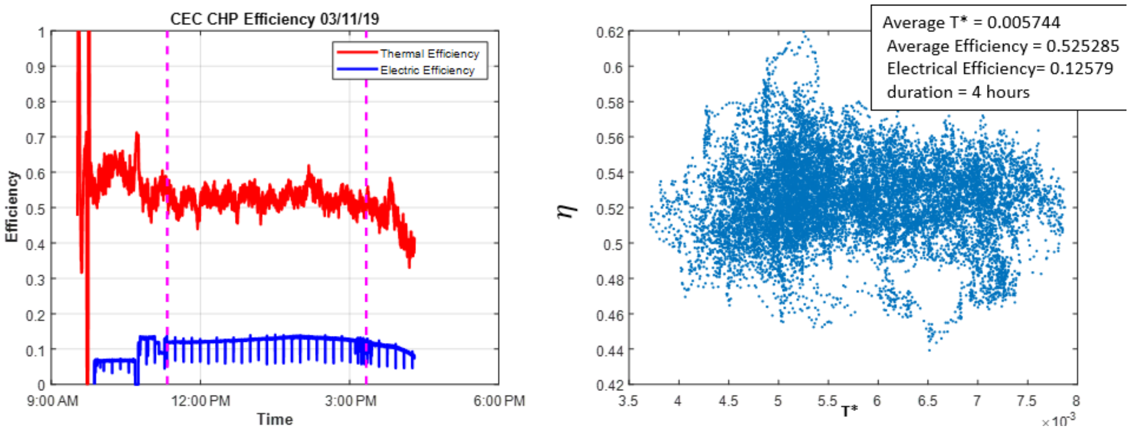

Figure 6: (L)Thermal and Electrical efficiency of the collector array; (R) Instantaneous thermal efficiency measured

Figure. 6 (L) shows the corresponding thermal and electrical efficiency obtained on the same day using equations 1 and 2. The thermal and electrical efficiencies were found to steady around 53% and around 12% respectively.

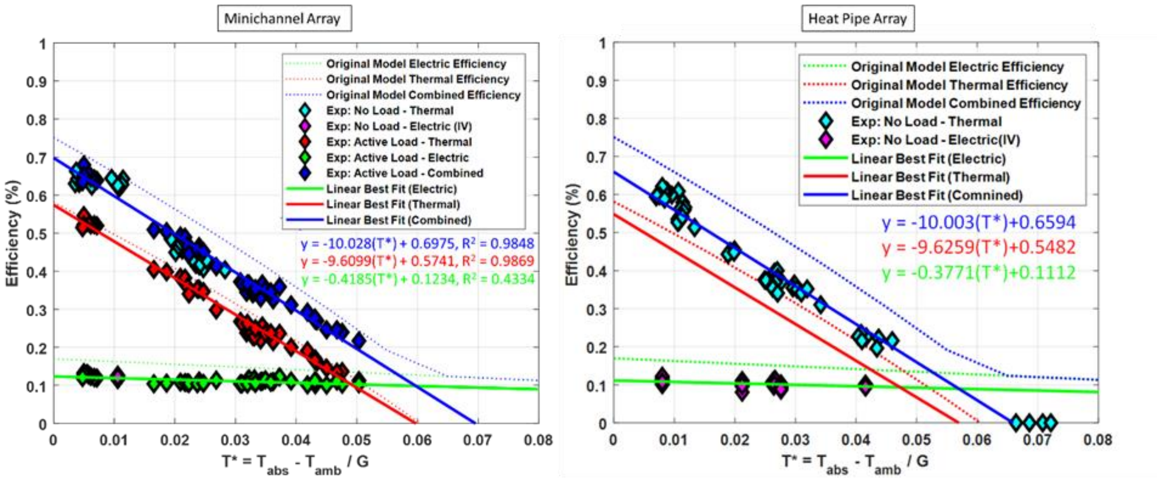

Figure 7: Performance of the PVT collector array. (L): minichannel; (R) heat pipe

After testing, the collector efficiency data which met the test criteria from Table 1 was consolidated as a function of temperature gradient T^* (Duffie, et al., 2013), where $T^* = \frac{T_{in}-T_{amb}}{G}$. The Fig 6 (R) shows the instantaneous steady state thermal efficiency measured according to eq (1) from 11 AM to 3 PM, whose bounds are represented by pink vertical lines in Fig. 6(L). The average efficiency of the points in that period is noted in the efficiency vs T* plot. The solar-to-thermal, solar-to-electric, and combined (solar-to-thermal+electric) efficiencies are plotted as a function of T* in Figure. 7. Linear trend lines for each system are shown in blue (cogeneration), red (thermal), and green (electrical) underneath their respective legends.

The prototype PVT collector has demonstrated 57% solar-to-thermal efficiency and 12% solar-to-electric efficiency by module area (15% solar-to-electric efficiency by cell area) when the PVT collector is operating near ambient conditions. At a reduced temperature of 0.04 (equivalent to 60 °C operation when the ambient temperature is 20 °C and the solar irradiance is 1000 W/m2), the PVT collector operates with 19% solar-to-thermal efficiency and 10.6% solar-to-electric efficiency by module area (13% by cell area). The results of experimental testing are quite well-grouped and well explained by the linear best-fits.

6. Discussion, Environmental, and Techno-economic Analysis

While the thermal performance of the PVT prototypes matches our model quite well, the electric performance is about 75% of what we expected. We believe this is largely due to a low packing factor, with the cell area only covering about 80% of the module aperture area. Additionally, by cutting the cell into strips we are isolating and effectively deactivating portions of the inter-digited back contact. A quick area estimation shows this is on the order of ~93%. As a result we believe the solar-to-electric efficiency of future PVT collector models could be improved by (1) using cells designed to be cut into strips with no deactivated portions, (2) increasing the packing factor of the cells on the absorber to 95%. Additionally, an AR-coated glass tube would increase transmission from 92% to 96%, and with these changes we can reasonably expect a 16.8% solar-to-electric efficiency at ambient conditions and a 15% efficiency at a reduced temperature of 0.04.

A bottom up cost estimation was performed for the system, which yields a module cost of $81/m^2 under mass-production scenario. For the TEA and environmental analysis, we assume a 40% daily solar-to-thermal efficiency and a 15% daily solar-to-electric efficiency of the collector. Additionally, a performance ratio of 75% assumes only 75% of the generating capability of the PV and thermal streams are used as a conservative estimation and to account for cable, inverter, and PV losses as well as heat losses from the thermal system.

The total natural gas consumption avoided by the PVT collector (locally and at natural-gas fired power plants) is calculated as follows. The electrical generation component of the PVT collector is multiplied by 3 to estimate the amount of natural gas used at the power plant to generate an equivalent amount of electricity. It is then added to the kWh of thermal generation by the PVT collector for a total NG reduction in kWh/m^2/year. The total avoided

CO_2 emissions are determined using 0.18 kg CO_2 per kWh of natural gas and 0.331 kg CO_2 per kWh electric for California's electric grid. Multiplying these values by the kWh of heat generation and kWh of electric generation from the PVT collector yields a total kg of CO_2 avoided per m^2 per year.

For a solar resource of 5.5 kWh/m^2/day we would expect the PVT collector to generate 226 kWh$_e$/m^2/year and 603 kWh$_{th}$/m^2/year (20 therms). The resulting avoided natural gas reductions are on the order of 1280 kWh /m^2/year (44 therms) which saves 183.8 kg of CO_2 emissions. Over 20 years this accumulates to about 3.7 metric tons of CO_2 saved per square meter of collector. In this scenario the investment cost by module is $22/metric ton of avoided CO_2.

7. Conclusions

In this work, we demonstrate a proof of concept novel, low-cost, and high efficiency solar PVT collector which generates both electricity and heat for space and water heating up to 60 °C. The solar PVT collector utilizes nonimaging optics for solar concentration, aluminum minichannels for thermal collection, and commercially-available solar cells for electricity production, packaged in an inexpensive glass tube. A 20-tube array of collectors has been extensively tested outdoors and we are pleased to report the collector generates about 150 W$_{DC}$ electricity and 400 W$_{thermal}$ per square meter. For a 5.5 kWh/m^2/day solar resource, we expect the solar PVT collector to generate 226 kWh of electricity and 603 kWh (20 therms) of heat each year for domestic hot water and space heating. By doing so each square meter of collector will reduce natural gas consumption (locally and at natural-gas fired power plants) by 1280 kWh (44 therms) and eliminate 184 kg of CO_2 emissions each year. At an estimated mass-production cost of $81 per square meter, a module will cost $0.54 per Watt (note: 2018 residential PV modules cost $0.47). The extra $0.07 per Watt can be attributed to the 400 Watts of thermal generation, which is essentially free. At a comparable cost as residential PV, it is likely the PVT collector could enjoy similar adoption and market penetration. In doing so it would make use of significant heat generating capacity of distributed rooftop PV systems, resulting in energy savings and emissions reductions. Over a 20 year lifetime, the estimated investment cost for GHG savings is approximately $22/metric ton of avoided CO_2.

8. Acknowledgements

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