A transmissive, spectrum-splitting concentrating photovoltaic module for hybrid photovoltaic-solar thermal energy conversion

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Abstract: A spectrum splitting, transmissive concentrating photovoltaic (tCPV) module is proposed and designed for a hybrid photovoltaic-solar thermal (PV/T) system. By utilizing III-V triple junction solar cells with bandgaps of 2.1eV/1.7eV/1.4eV, ultraviolet (UV) and visible light will be absorbed and converted to electricity, while infrared (IR) light will pass through and be captured by a solar thermal receiver and stored as heat. The stored thermal energy may be dispatched as electricity or process heat, as needed. According to the numerical analysis, the tCPV module can perform with overall power conversion efficiency exceeding 43.5% for above bandgap (in-band) light under a standard AM1.5D solar spectrum, under an average concentration ratio of 400 suns. Passive and active cooling methods, keeping cells below 110°C, are also investigated and discussed, indicating that a transparent active cooling design could improve the CPV module efficiency by around 1% (absolute), relative to a passive design, by reducing the maximum cell working temperature by around 16°C. Furthermore, cost analysis shows that installation cost of around \$1.9/W – \$2.2/W could be reached for the tCPV based PV/T system, which shows a competitive economic advantage compared to a more conventional PV with battery system.

I. INTRODUCTION

As a promising renewable energy, solar power has gained increasing attention from worldwide researchers during recent years. From photovoltaic (PV) solar cells to concentrating solar thermal (a.k.a. concentrating solar power – CSP), various solar technologies have been applied in order to most efficiently utilize the sun as an energy resource [1]. Combining photoelectric and solar thermal conversion processes via hybrid PV and solar thermal (PV/T) systems is a promising way to optimally utilize the full solar spectrum to generate electricity and heat energy with very high efficiency [2-4]. The PV cells, typically the most expensive component in the system, could be utilized in a much more economical way by employing concentrating approaches to reduce the PV area required to convert a given amount of solar power to electricity, gaining improved efficiency in the process [5]. Regular PV/T systems

without concentrating approaches generate a relatively low working temperature (typically less than 60°C) and have been widely investigated [6-8], while concentrating PV (CPV) - solar thermal (CPV/T) systems face challenges from several aspects, including a need to maintain reasonably low cell temperatures (typically <110°C) and non-uniform irradiance [6]. Studies have been done on CPV/T systems to investigate a variety of applications and effects, e.g. solar cooling [9-10], spectrum splitting [11-17] and thermoelectric conversion [18-20], etc. Moreover, studies also show that the PV cell could act as heat absorber in a hybrid CPV/T system for commercial use [21-25]. Higher operating temperature CPV modules have also been investigated to allow the system to operate at higher temperature [26]. Influence of irradiance and temperature on CPV cells is also studied for obtaining the optimal parameters of CPV module [27]. In many cases, efficiency and performance is limited by either a) inefficient spectrum splitting or b) a mismatch between the need to keep cell temperatures low (for efficiency and reliability purposes) and thermal output temperatures high [8, 23] (for maximizing thermal exergy and meeting the needs of higher temperature applications).

Here we propose a transmissive, spectrum splitting concentrating photovoltaic (tCPV) module specifically for use in a hybrid concentrating photovoltaic-solar thermal (CPV/T) system. By utilizing III-V triple junction solar cells in the tCPV module, with lowest bandgap around 1.4 eV, ultraviolet (UV) and visible light is directly absorbed and converted to electricity, while infrared (IR) light will pass through the cells and module to be captured by a solar thermal receiver and stored as heat. This spectrum splitting approach is angle insensitive and very high efficiency relative to other spectrum splitting approaches [6, 31]. The tCPV module can be kept below 110°C, where cells optimally perform, while the cavity thermal receiver can heat the heat transfer fluid (HTF) to greater than 570°C. The tCPV module shows an overall energy conversion efficiency of around 43.5% for the above bandgap (defined as in-band) light, while transmitting below bandgap (defined as out-of-band) light with approximately 75% transmission efficiency. The whole system is anticipated to have a minimal installation cost of \$1.9/W, which is expected to be competitive in the PV plus energy storage market. In addition, the thermal output, which can be tuned from 100°C to 570°C depending on need, can also be used in industrial process heat markets, such as solar heating and cooling, desalinization, enhanced oil recovery, refining, food processing, and more.

Fig. 1. (a) Schematic diagram of the tCPV-based PV/T system. (b) 3D model of the PV/T system. (c) 3D cross-sectional view of the tCPV module integrated with the thermal receiver. (d) Planar view of the tCPV module. (e) Cross-sectional view of the tCPV module.

The hybrid system is principally composed of the photovoltaic sub-system and the solar thermal sub-system, as illustrated in Fig. 1(a). The photovoltaic (PV) part, which contains the concentrator and the multi-junction solar cells, will only absorb incoming photons whose energy is above the lowest bandgap of the solar cells (consisting mainly of UV and visible light) and directly generate variable electric power. The solar thermal part, which contains the thermal receiver, the thermal storage, and the HTF system, will capture the transmitted photons with energy lower than the lowest solar cell bandgap (consisting mainly of IR light) and convert them to dispatchable thermal power. This thermal power may be converted to electricity by a suitable heat engine or used directly for process heat applications. By this means the transmissive PV sub-system splits the solar spectrum and utilizes it in two different sub-systems. The multi-junction solar cells in the PV sub-system most efficiently convert high energy photons to electricity, as the V_{oc} -bandgap offset (W_{oc}) is somewhat independent of bandgap [32]. The thermal system is less sensitive to incoming photon energy and is more efficient at utilizing IR photons.

The specific design of the whole system can be seen in the 3-D CAD drawing shown in Fig. 1(b). The core part of the system at the top, as marked with a red solid line, is the PV module with thermal receiver. The heat will be conducted from the thermal

receiver to the thermal energy storage (TES) tank through a HTF piping system. A parabolic dish is used to concentrate the incident light onto the transmissive PV and thermal receiver, in order to dramatically increase illumination intensity on the solar cells, enhancing efficiency and reducing cell cost. A simple, low-cost, and effective bellows-based actuator is implemented as the two-axis solar tracking system, which allows the system to receive maximum irradiation throughout the day and with changing season [28]. Figure 1(c) shows the details of the receiver. The transmissive concentrating photovoltaic (tCPV) module is placed directly in front of the thermal receiver along the optical axis of the concentrator. With this design, the concentrated solar light will be first absorbed by the tCPV module, with most of the remaining light passing through the module and reaching the thermal receiver. Due to the high concentration ratio (~ 500 suns on average at the tCPV), the temperature of the cells becomes much higher than ambient temperature, resulting in a reduction in cell conversion efficiency. A radial metallic fin heat sink is applied around the tCPV module, allowing for passive cooling without blocking transmitted light. By implementing the metal fin heat sink, the heat can be conducted out of the tCPV and spread into the air via convection to reduce the module temperature.

The tCPV module consists of 49 triple-junction cells grown on GaAs substrates, which distribute in a 7×7 array, as shown in Fig.1(d). The size of each cell is $5.5\text{mm} \times 5.5\text{mm}$, and there is a 1mm gap between neighbouring cells. The cell array is placed on a round sapphire substrate with 4cm radius and 5mm thickness. Another 5mm thick sapphire wafer is placed above the cells as a superstrate, and silicone encapsulant is used to fill in the space between the sapphire and the PV cells as a sealing material, as Fig. 1(e) shows. We utilize sapphire instead of traditional glass as the superstrate and substrate because of its relatively high thermal conductivity and optical transparency. Heat from the cells is extracted laterally through the sapphire to the encircling radial heat sink. The triple-junction solar cells may retain their GaAs substrate, resulting in a total thickness of around $450\mu\text{m}$. However, the design also allows for the use of epitaxial lift-off (ELO) multi-junction solar cells with thickness of $\sim 10\mu\text{m}$, providing enhanced optical transmission of IR light with potentially higher efficiency and lower cost. In order to minimize cell temperature rise during operation, only a thin layer of the relatively low thermal conductivity encapsulant is left on the top surface and bottom surface of the cells, which is approximately $20\mu\text{m}$ thick.

II. CPV Cell Design

Figure 2(a) shows the structure of the triple-junction solar cells used in this tCPV module, with top subcell (C1), middle subcell (C2), and bottom subcell (C3). Each subcell includes a window layer, emitter layer, base layer, and back surface field (BSF) layer. Tunnel junctions (TJ12 and TJ23), which produce effective potential barriers for minority-carriers, are utilized between subcells and designed for high injection levels

(high concentration). Another polarity reversing tunnel junction (PR TJ) is used after C3 [33]. This enables the use of a n-type GaAs:Si growth substrate with carrier concentration of $0.8\text{-}3 \times 10^{17} \text{ cm}^{-3}$, chosen to minimize absorption of transmitted out-of-band photons while maintaining sufficient conductivity for carrier collection at the back electrodes. Even though the absorption of the GaAs substrate is relatively low in the out-of-band, IR region, this absorption can be negated with the incorporation of an ELO process in the cell fabrication, which will dramatically reduce the total cell thickness (from $\sim 450 \mu\text{m}$ to $\sim 10 \mu\text{m}$). This will save materials costs, reduce IR absorption, and potentially enhance cell performance, along with some increase in the difficulty of cell fabrication and module assembly. Both the front and back contacts are designed to minimize shadowing of transmitted light and also minimize resistive losses in current collection; the grid fingers and busbar on each side are co-aligned to further reduce transmission losses.

Fig. 2. (a) Structure of the CPV tandem cell (not to scale). (b) Inband efficiency map vs. different bandgap of subcell2 and 3, with subcell1 bandgap fixed at 1.42 eV. (c) IV curves of individual subcells and the tandem cell.

The materials and bandgap selection of each subcell are: AlGaInP for C1 with bandgap of 2.1eV, InAlGaAs for C2 with bandgap of 1.67eV, and GaAs for C3 with bandgap of 1.42eV. The choice of material and alloy composition for each subcell is mainly determined by the requirements for lattice-matching and current-matching, with the goal of maximum conversion efficiency for in-band light. Fig. 2(b) shows the

calculated power conversion efficiency of the triple-junction solar cells versus the bandgap of the top cell (E_{g1}) and middle cell (E_{g2}), where the bottom cell bandgap (E_{g3}) is fixed at 1.42eV (corresponding with GaAs). The bandgap selection for the bottom cell (1.42eV) is much higher than a conventional multijunction solar cell, such as a Germanium based one (~ 0.67 eV) [32]. This choice is made for two reasons: 1) to enhance the efficiency of the CPV cells by only converting high energy photons in the cells, with V_{oc} a larger fraction of the bandgap; and 2) to enhance the fraction of energy transmitted to the solar thermal receiver. By utilizing a higher bandgap GaAs bottom cell, at least 50% of the incident light can be transmitted to the solar thermal receiver for generating dispatchable electricity. Note that the efficiency plotted in Fig. 2b is for conversion of in-band light only and also does not include ohmic or reflection losses. By adjusting the bandgaps of each subcell, the performance of the tandem solar cell may be optimized for maximum in-band power conversion efficiency.

The calculated IV curves of the tandem solar cell and each subcell are illustrated in Fig.2 (c). These curves are produced by a detailed device model that incorporates specific design details and feedback from experimental performance assessed by our partners at Spectrolab, Inc.. For the data plotted here, the concentration ratio is set to be 500 suns and the cell working temperature is 25°C. The short-circuit current density J_{sc} of the three subcells C1, C2, and C3 are 4.82A/cm², 4.78A/cm² and 4.78A/cm², respectively, which are close to each other, indicating a good current match between each junction in our design. The J_{sc} of the tandem cell is 4.78A/cm², while the open-circuit voltage V_{oc} reaches 4.23V, as the sum of those for each subcell. The fill factor (FF) of C1, C2 and C3 are 86.5%, 87.8% and 89.4%, resulting in a FF of 86.3% for the whole device.

III. CPV Module Design

In order to investigate the performance of the whole tCPV system, Finite Element Method (FEM) modelling is employed using COMSOL Multiphysics. The model combines ray optics with thermal analysis simultaneously for a full understanding of the feedback between optical and thermal performance. A 1m² round parabolic dish is employed as concentrator, with focal length of 0.68 m and rim angle of 45 degrees. Corrections for finite source diameter and dish surface roughness are applied to make the simulation more accurate. A maximum disc angle of 4.8mrad and surface roughness of 2.55 mrad is set in the model to compensate for the angular distribution of incoming sunlight and surface/shape error of the dish, respectively. An empirical power law is also applied for the limb darkening model. The total number of rays is set to be 2×10^5 .

Fig. 3. (a) Ray tracing analysis, (b) intensity distribution (in suns) and (c) temperature (in °C) from tCPV FEM model. (d) Cell in-band efficiency vs. temperature and concentration ratio. (e) All in parallel cell interconnection method and cross sectional view (not to scale).

In this model, the tCPV module is placed just in front of the thermal receiver, and the thermal receiver front opening is placed at the focal point of the dish, as shown in Fig.3 (a). The structure and materials for the tCPV module are set as shown in Fig. 1, while the thermal receiver material is set to be stainless steel with a highly absorbing internal surface (i.e. Pyromark black paint). The optical and thermal properties of all the materials are quoted from literature [29]. The metallic heat sink is not built into the module in order to simplify the calculation; however, the equivalent boundary conditions are applied on the circumference of the aluminium frame, using a heat transfer coefficient h_{eq} of 3400W/K/m^2 , which represents the predicted thermal resistance of the heat sink (equivalent thermal resistance of the heat sink $R_{eq}=1/h_{eq}$). The remaining surfaces of tCPV module are set with a heat transfer coefficient of 2W/K/m^2 , which represents natural convection with minimal surrounding airflow. Surface to surface radiation is also considered between the tCPV module and the thermal receiver, setting the inner surface of the receiver as a diffuse surface with emissivity of 0.87. The ambient temperature is 30°C .

In the tCPV module, the optical intensity distribution on individual cells has a high correlation with cell temperature, as the temperature will increase when the concentration ratio goes up, and both will impact the power conversion efficiency of the solar cells. In particular, due to the transmissive nature of our module design, cell cooling is a particular challenge. Therefore it is critical to systematically investigate the optical and thermal performance of the module. Here the ray optics module and the thermal module in COMSOL are coherently implemented: the absorbed heat energy in each individual cell is obtained from the ray optics module output, which is then used in the thermal module to simulate the thermal performance of the system. Specifically, the heat generated in a CPV cell is calculated as follows:

$$W_{heat} = W_{absorb} - W_{electricity} \quad (1)$$

Where W_{absorb} is the energy that each cell absorbs, which is calculated as:

$$W_{absorb} = \int_{300nm}^{2500nm} S_{cell} A(\lambda) D_{AM1.5D}(\lambda) d\lambda \quad (2)$$

Where S_{cell} is the cell area, $D_{AM1.5D}(\lambda)$ is the solar power density under the AM1.5 Direct spectrum, and $A(\lambda)$ is the calculated absorbance of the CPV cell derived from the optical properties of each layer (as shown in the Supplemental Materials). $W_{electricity}$ is the output electrical power from the CPV cell, which is defined by:

$$W_{electricity} = \eta_{inband} \int_{300nm}^{873nm(1.42eV)} S_{cell} A(\lambda) D_{AM1.5D}(\lambda) d\lambda \quad (3)$$

Where η_{inband} is the modified power conversion efficiency of the CPV cells specifically for in-band light, or light with energy above the bandgap of the bottom subcell C3 (1.42eV). Similarly, the out-of-band light is defined as light with energy below this 1.42 eV bandgap.

Also, there are spaces left between the CPV cells in the array (as shown in Fig 1d), which allows some of the in-band light to pass through to reach the thermal receiver without being absorbed by the CPV cells; this light is referred to as bypass light. The optical bypass ratio (OBP) of the tCPV module is defined to evaluate the fraction of bypass light as:

$$OBP = 1 - \frac{W_{CPV_inband}}{W_{total_inband}} \quad (4)$$

Where W_{CPV_inband} is the total energy of the in-band part of the incident light illuminating the CPV cells, and W_{total_inband} is the total energy of the in-band light incident on the entire module. This bypass ratio allows for a tunable dispatchability fraction in system design, controlling the total fraction of incoming solar energy that is converted and stored as heat. Also, incorporating bypass into the tCPV design helps to mitigate cell temperature rise in the CPV module and also leaves space for wiring between cells. The transmissive, hybrid nature of our design allows us to avoid losses

associated with light that misses CPV cells, typically a major loss mechanism in conventional dense array CPV module designs.

The modelled concentration ratio and related temperature distribution on the CPV cell arrays are illustrated in Figs. 3(b) and (c). As is shown, the concentration ratio on the cells varies from ~50 to ~580 suns, with an average of 380 suns, while the temperature goes from ~60 to ~100°C with an average of 82°C. The OBP here is 43%. The concentration profile is close to a Gaussian distribution, decreasing from centre to edge, with minor deviations from a Gaussian distribution due to the surface roughness and shape error of the dish. The temperature of the CPV cells has a similarly shaped distribution, as would be expected. Notice that the cell at the centre shows much lower irradiance; this is because of the shadowing on the dish from the module itself.

The increasing intensity of the irradiance dramatically enlarges the photocurrent of the CPV, due to the increasing number of the absorbed photons, while higher temperature will mainly reduce the output voltage as the bandgap is decreasing [27], as Fig. S1 shows (see supplemental materials). We optimize the design of our tCPV module to take into account the effect of variable illumination intensity and temperature on CPV performance. The plot of calculated power conversion efficiency of individual CPV cells at different concentration ratio and temperature is given in Fig. 3(d). It is clear that given a constant concentration ratio, the temperature increase from 40°C to 140°C causes the CPV efficiency to gradually decrease, due to a corresponding decrease of voltage output (see Fig. S1); on the other hand, as the concentration ratio increases from 100 to 1300 suns (for given constant temperature), the efficiency rises up to a maximum then goes down, indicating that the optimized concentration ratio is around 300-500 suns for achieving a maximized efficiency. This variation trend is explained as follows: although the photocurrent is increasing nearly linearly as the concentration ratio increases, the electrical loss due to the electrode resistance and series resistance of the cell is boosted as a function of the square of the photocurrent. Thus, for higher concentration ratio, the electrical loss becomes excessively large and hampers performance, resulting in a reduction in power conversion efficiency. Even if the CPV cells are carefully designed for higher concentrations (e.g 800 suns), a similar trend results, with optimized efficiency around 400-500 suns, due to series resistance in the cells that cannot be reduced.

As the I_{sc} of the CPV cells is highly variable (ranging from 2A to 5A) due to the non-uniform intensity distribution (see Fig.3b and Fig.S1), while the variability of V_{oc} is much smaller (ranging from 3.4V to 3.5V), a non-conventional method is employed to connect all the CPV cells. All cells are wired in parallel instead of in series or in series/parallel combinations, taking advantage of this low variability in voltage in order to reduce electrical mismatch losses when interconnecting cells, as shown in Fig. 3(e). This takes advantage of the convenient outcome of this intensity and temperature distribution, where cells with higher illumination are boosted in voltage, offsetting their corresponding decrease in voltage due to higher temperature (and vice versa).

The 49 cell array is set in 7 groups by rows, and every 7 cells in the same row are electrically wired in parallel. Each row is connected to a 3V-to-12V DC-DC convertor [30]. The outputs of 7 DC-DC convertors are then connected in parallel and finally linked to a 12V-to-110V DC-AC inverter to connect the output power to the grid. This all-in-parallel cell interconnection method dramatically decreases electrical losses due to current mismatch between cells due to non-uniform illumination, and it also minimizes power losses that occur when focal spot wandering happens, as shown in Fig. S2. Although a non-imaging optical primary concentrator or advanced secondary optical approaches can also be utilized in this system to decrease illumination non-uniformity, system cost would notably increase and spot wandering issues may still exist. Nevertheless, the all-in-parallel connection method, in combination with our desire for spilled light to reach the thermal receiver, solves these issues without significantly increasing the system cost. The cell interconnection approach is sketched in Fig. 3(e) (figure on the right). Micro channels are fabricated on both the top and bottom sapphire substrate via laser etching and copper interconnects are deposited in the channels by inkjet printing and electrodeposition; the cell assembly is realized by indium bonding cells to these copper interconnects and followed by filling the module with silicone encapsulant for sealing, as the figure shows.

As high temperature cell operation decreases the performance of the CPV module, it is critical to implement cooling methods to ensure that the system is working at an acceptable temperature. In particular, our tCPV module must utilize highly transparent cooling methods. The maximum cell temperature is dependent on various parameters. High OBP results in relatively lower temperature because less energy is absorbed by the CPV cells, as shown in Fig. 4(a). As the OBP increases from 41% to 51%, the maximum module and cell temperature decreases by around 15°C from 102°C to 87°C, and the average cell temperature drops by around 9°C from 76°C to 67°C. The heat sink acts as the passive cooling system to dissipate the heat from cells, and its performance could be also improved to reduce the system temperature. Fig. 4(b) shows the relationship between the maximum/average cell temperature and the equivalent heat transfer coefficient of the heat sink h_{eq} . The maximum cell temperature is dramatically decreased by increasing h_{eq} , which may be realized by changing the geometry and materials of the heat sink. Nevertheless, the system temperature no longer sharply decreases, but rather only changes slightly, when h_{eq} increases up to 10,000W/m²/K, with peak temperature around 92°C for the maximum and 61°C for the average cell. With high enough h_{eq} , the thermal conductivity of the encapsulant and the sapphire become the dominant limitations to heat transfer.

Fig. 4. (a) Optical bypass vs. maximum/average temperature of the module. (b) Equivalent heat transfer coefficient h of the heat sink vs. maximum/average temperature of the module. (c) Schematic structure of CPV module with active cooling system. (d) Temperature distribution for passive/active cooling approaches. (e) Cooling performance vs. velocity of coolant of active cooling system.

Upgrading the heat sink to improve its performance or increasing the thickness of the top/bottom superstrate/substrate layers are possible approaches to obtain lower peak module temperature, albeit, with significant increase in module cost. Another acceptable way is to use active cooling instead of passive cooling. Fig. 4(c) shows the 3D model for the tCPV module with active cooling; from the figure it can be seen that 7 micro-channels are located at the back side the CPV module, using water as the coolant. The dimensions of each channel are 5.5mm wide by 100 μ m thick by 6cm long. The cells are sandwiched between a top glass layer and a bottom sapphire layer. The channels are etched into a glass layer located below this sapphire layer, with the location of the channels aligned exactly underneath the cells. Two manifolds at the sides of the module guide cooling fluid into and out of the channels. A small pump is placed behind the thermal receiver to keep the coolant flowing, and a forced-air radiator is implemented to reduce the coolant temperature. The pump and the radiator are powered by the CPV system itself. Compared to the passive cooling, the active cooling method decreases the module temperature even further and improves its

performance accordingly. Fig. 4(d) shows the comparison of the temperature distribution on the tCPV array using each cooling method. The active cooling method clearly performs at a much lower temperature than passive cooling, now with 84°C for the maximum temperature and 71°C for the average. Also, the temperature distribution is more uniform for the cells at the corners, as the coolant flows and extracts heat more uniformly along the row. The performance of active cooling may also be adjusted by changing the flow velocity of the coolant. By changing the pressure of the pump, the velocity of the coolant is varied, which results in different module temperatures, as shown in Fig. 4(e). The maximum module temperature drops from 91°C to 84°C when the mean velocity of the coolant increases from 0.5m/s to 1m/s, with the same trend in the average temperature. Thus, our designs show that either passive or active cooling may be implemented with tCPV with high transparency and cooling performance. Peak module temperature is shown to be significantly decreased by employing the active cooling approach.

Table 1 summarizes the calculated performance of the tCPV module. Different types of losses are listed, including optical losses at anti-reflection coatings (ARC) in the module, and electrical losses including the wiring resistance loss, circuit mismatch loss, and losses in the DC-DC converters [30]. A current/voltage output of 12.68A/12V for passive cooling or 12.94A/12V for active cooling is finally obtained from the module, which gives total power output of 152.16W for passive cooling or 155.28W for active cooling, for a concentrating dish aperture area of 1 m². For the overall efficiency of the tCPV module, the calculation shows that the in-band efficiency η_{inband} is 42.65% for the passive cooling design and 43.53% for the active cooling design.

Table 1 Photovoltaic performance of the tCPV module

Optical loss		Passive cooling	Active cooling
Reflection & Absorption	3%	Output Current	12.97A
Electrical loss		Output Voltage	12V
Wiring	1%	Output Power	155.61W
Mismatch	0.5%	Avg Cell Efficiency (inband)	48.2%
DC-DC	7%	Module Efficiency (inband)	42.7%
			43.5%

IV. Cost Analysis

Compared to active cooling, the passive cooling strategy still has several advantages, including enhanced reliability for long life-time applications (e.g 30 years or more) and no parasitic power demands. On the other hand, active cooling not only has better

cooling performance, but it also considerably reduces the module cost to enlarge the performance cost-ratio of the module. This is because most of the heat is conducted from the tCPV cells to the coolant through a thin bottom sapphire layer in the active cooling scenario, thus allowing the top sapphire substrate to be replaced by traditional glass and the thickness of the bottom sapphire to be reduced from 5mm to 1mm or less, which will significantly reduce the usage of costly sapphire materials.

Fig. 5. (a) Energy distribution of CPV module. (b) Cost comparison between the tCPV-based hybrid PV/T system and PV+battery system.

In order to evaluate the effectiveness of energy generation in the hybrid tCPV/T system, the resulting energy distribution of the incident radiation energy in the tCPV module is calculated, as shown in Fig. 5(a). This calculation assumes a bypass fraction of 42% of incident light on the module that passes between the subcells directly to the thermal receiver. It is shown that around 14% of the incident radiation energy is converted to electricity output through the module. For the rest, nearly 58% is transmitted to the thermal receiver, and nearly 15% of the original energy is converted to heat in the module, which is the main form of the losses. Other losses include 12% of incident light lost as optical reflection and minor heat generation outside the module (1%). The heat losses are mainly due to the heat generation in the PV cells and in the encapsulant, as well as the electrical resistance of all the electrodes/wires.

The total capital expenditure cost of the tCPV-based hybrid PV/T system (using the active tCPV cooling method) is also calculated and shown in Fig. 5(b), as compared to more conventional PV-plus-battery systems [34, 35]. The PV/T system costs are

calculated based on techno-economic analysis of the entire system bill of materials and manufacturing, at large scale production, plus indirect costs. The cost projection includes the CPV system, the solar thermal system (thermal receiver, HTF system, storage, and heat engine) and the shared parts between these two (the tracker, dish, plant and indirect costs). The hybrid PV/T system shows a capital cost for electricity generation of \$1.9/W at the low end (using our active cooling system and cells fabricated with a 50-wafer reuse ELO process) and \$2.2/W at the high end (using passive CPV cooling and without any ELO process used in cell fabrication), as shown in Fig. 5b. Our cost estimates for multijunction cells are derived from analysis by NREL's Strategic Energy Analysis Center [36]. Compared to our system, the more conventional PV-plus-battery system is anticipated to be more expensive (around \$2.36/W) based on projections for 2020 [35]. The PV in that PV-plus-battery system is projected to cost around \$1/W and the battery energy storage will cost even more (\$1.36/W) [34, 35]. Analysis of the levelized cost of electricity (LCOE) for our hybrid PV/T system shows LCOE of around 7 to 13 cents/kWh for the whole system, compared to 20 cents/kWh for PV-plus-batteries. Thus we expect that the tCPV based PV/T system has potentially significant competitive economic advantage compared to the PV with battery system in the competition to provide sustainable, scalable, dispatchable, and cost-effective electricity. We anticipate that for industrial process heat applications, our system cost will be even lower with the levelized cost of heat (LCOH) down to 0.9 cent/kWh, compared to natural gas LCOH of 7 cents/kWh, offering the possibility of use in a wide range of applications requiring electricity and heat.

Finally, we note that the tCPV module we propose here is not limited to one particular PV/T system design – it could be used for other spectrum splitting hybrid systems as well. The parameters of the module could be easily adjusted (e.g. bandgap selection, optical bypass ratio etc.) to meet various requirement of different systems. Indeed, this tCPV module could be widely utilized for solar energy conversion applications both in community and industrial scales.

V. CONCLUSION

In conclusion, we propose a transmissive concentrating photovoltaic (tCPV) module for hybrid photovoltaic and solar thermal (PV/T) energy conversion. Ultraviolet and visible light are absorbed and converted to electricity, while infrared (IR) light passes through and is captured by a solar thermal receiver and stored as heat. This heat may be used for generating dispatchable electricity or process heat, taking advantage of full-spectrum utilization of sunlight to enhance efficiency while sharing components and reducing cost. Numerical analysis shows that this tCPV module is expected to have an overall power conversion efficiency of 43.5% for in-band light under a standard AM1.5D solar spectrum. Active cooling and passive cooling methods that are also highly transparent to infrared light are designed and investigated, allowing the module to maintain a safe maximum operating temperature below 110°C.

Furthermore, cost analysis and market investigation show that our system is projected to have a competitive installation cost of \$1.9/W, which is around \$0.4/W lower than projections for a PV with battery system over the same time period.

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