

Separating the heat from the gap

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Summary

Increasing the conversion efficiency incident solar energy to electricity is a key goal in the solar R&D community. In this issue of Joule, a conceptual hybrid photovoltaic/thermal (PV/T) receiver design is reported by the research groups of Evelyn Wang and Gang Chen. High exergetic efficiency is achieved by absorbing below-bandgap and excessively high-energy photons as thermal energy, while allowing photons at the PV's bandgap to pass through to the underlying cell.

Main Text

One need go no further than the first paragraph of any article on solar energy technology to confront the mind-boggling scale of the available energy resource. The deployment of solar technology has experienced incredible growth in the past decade. This deployment has been dominated by single-junction silicon photovoltaic (PV) technology. These devices are characterized by a single bandgap which is unable to convert a significant fraction of the incident solar spectrum. The Shockley-Queisser efficiency limit for single band-gap silicon PV devices is 32.2%, accounting both thermal losses of photons below and greatly above the bandgap and radiative recombination losses, and deployed systems experience a much lower conversion efficiency. Besides conversion efficiency, another barrier to ever increasing solar penetration is the lack of cost-effective grid-scale electricity storage technologies, since storage is necessary for solar electricity to be available overnight or during extended periods of clouds.

Another approach to solar energy conversion to electricity is via concentrated solar power (CSP), where the incident solar energy is concentrated and used to heat a storable high-temperature working fluid which is then used to drive a heat engine. Increases in system efficiencies are therefore achieved by increasing the collector temperature. CSP based on conventional molten salts has been limited by the vapor pressure of the molten salts to temperatures around 600°C. Recent work has focused on developing molten metal systems due to their high energy densities and compatibility with collector temperatures in excess of 1350°C.² These high temperatures potentially allow for a higher exergetic efficiency but cause many challenge for overall plant design and longevity.³ Hybrid approaches, on the other hand, offer the possibility of achieving high exergetic efficiency while maintaining the thermal system and a lower temperature.

Hybrid photovoltaic/thermal (PV/T) systems offer the prospect of utilizing cost-effective single-junction PV cells for direct conversion of photons with energies at or just above the material's bandgap, while collecting the remaining solar energy in high-temperature working fluid for dispatchable energy when the PV cell is not directly irradiated.⁴ One approach to actualizing this vision is single- and multi-junction PV topping cycles operated at high concentrations and temperatures where the waste heat is then

stored, and later utilized in a Rankine bottoming cycle.⁵ This approach suffers from competing interests associated with optimizing the thermal and photovoltaic subsystems—increasing cell temperature to boost efficiency of the Rankine cycle decreases the PV cell efficiency and material choices available. Another approach is to utilize a parallel hybrid collector scheme, where the solar spectrum is split into wavelengths best suited for utilization in a PV cell or to be thermalized dependent on the bandgap(s) of the PV material.⁶

In 2013, the United States Department of Energy (DOE) Advanced Research Projects Agency – Energy (ARPA-E) released a Funding Opportunity Announcement (FOA) with the intention to fund transformative technologies to enable hybrid PV/T technologies.⁷ The Full-spectrum Optimized Conversion and Utilization of Sunlight (FOCUS) program took the approach of maximizing the *exergetic* efficiency of hybrid PV/T solar collector technology. The exergy of a unit of energy is defined as the amount of useful work that can be extracted from it. The exergy of one joule of electricity is one joule, because electricity is a form of work, while the exergy content of some unit of heat, Q , is defined as $Q(1 - T_C/T_H)$ where T_H is the temperature of the heat and T_C is the temperature of the available cold environment, the parenthetical term is the Carnot efficiency limit of a heat engine operating between the two temperatures. So, while collected thermal energy has value as a stored dispatchable resource, an efficiency penalty is paid due to the exergy destroyed (entropy generated) by collecting the heat from the sun (approximately 5777K) at a temperature lower than the sun.⁸ For a CSP system at 600°C, the exergetic value of a collected joule of energy is 0.656 joules.

In this issue of Joule, Weinstein et al. detail a conceptual design for a parallel hybrid PV/T collector dubbed the Hybrid Electric And Thermal Solar (HEATS) receiver.⁹ The team uses a spectrum splitting approach where incident concentrated solar radiation is passed through a light pipe which allows mid-energy photons of specified wavelengths to pass through to the PV module. Low energy photons, less than the PV's bandgap, and high energy photons above some specified energy are thermalized in the lightpipe and transferred to a thermal working fluid. A key to the successful application of the HEATS module is keeping the light pipe thermally insulated from the environment to avoid unnecessary losses, and crucially from the PV module, in order to maintain high PV conversion efficiency. Because the parts requiring insulation also constitute the optical path into and through the receiver, an aerogel with high optical transparency and low thermal conductivity is employed as the insulator. See figure 1 for a rendering of the HEATS concept.

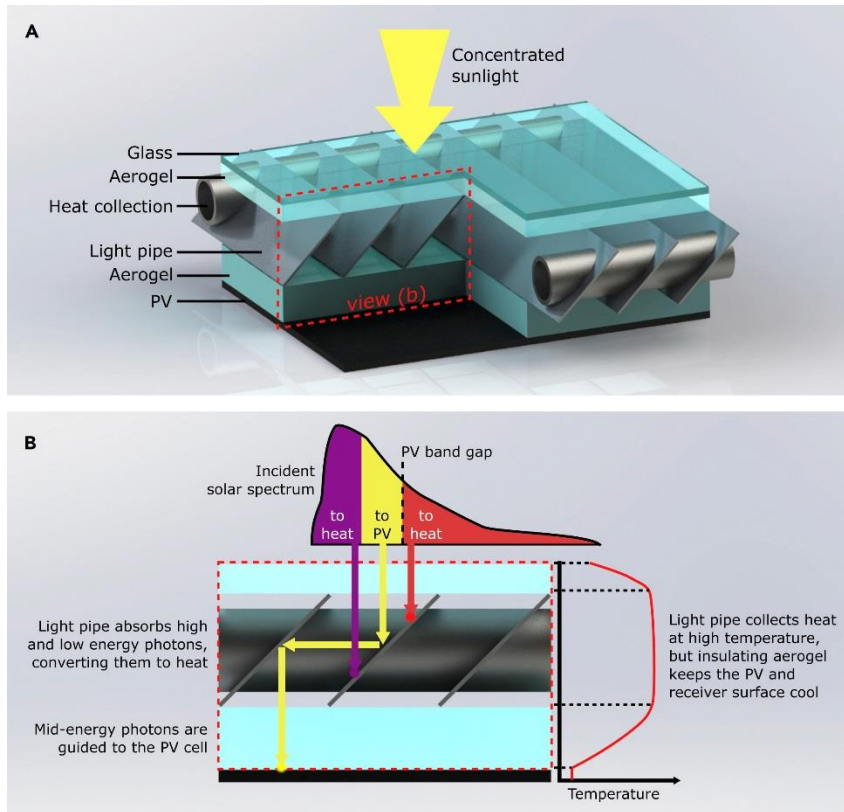


Figure 1- Hybrid Electric and Thermal Solar Receiver Design adapted from Weinstein et al. (2018).⁹ (A) Rendering of receiver concept with cutaway section to see internal receiver structure. (B) The spectrally selective light pipe (SSLP) absorbs high- and low-energy photons as thermal energy while directing mid-energy photons to the PV cell on the other side. Transparent aerogel on each side of the SSLP allow the SSLP to operate at high temperature while the PV cell and glass cover remain at low temperature.

In order to characterize the device performance, the team reports an exergetic solar collector efficiency defined as:

$$\eta_{elec} = \frac{P + Q_h \left(1 - \sqrt{\frac{T_C}{T_H}} \right)}{Q_{solar}}$$

where P is the electrical power output of the PV cell, Q_h is the heat delivered by the collector to storage or a heat engine operating between the high temperature T_H and low temperature T_C , and Q_{solar} is the incident solar radiation on the collector. Here, the team uses the stricter endoreversible efficiency rather than the Carnot efficiency to calculate the maximum useful work that can be extracted from the stored heat. The team also reports the fraction of exergy collected as thermal energy as the dispatchability ratio. With an idealized model, the team predicts η_{elec} to be 35.2% with a dispatchability ratio of 44.2% for a thermal collector temperature of 775K. With measured component performance values for systems with thermal collector temperature of 700K, the model predicts an efficiency of 26.8% and dispatchability of 81% for silicon PV, and an efficiency of 28.5% and dispatchability of 76% for gallium arsenide PV.

Exergetic maximization of a solar collector is a necessary but insufficient design parameter when the goal of a solar installation is to ultimately provide electricity (or another form of useful work) as the only product. Techno-economic optimization must also be performed where capital cost of the proposed system is taken into consideration, and some value is given to the dispatchable thermal fraction of the energy collected. The ARPA-E FOCUS team expands on this point in Branz et al. (2015).⁸ Further, an economic value can be assigned to the availability of high temperature process heat given that there exists a local thermal amenity market such as industrial steam, which could potentially give higher return on investment for collection and storage of thermal energy in a hybrid system.¹⁰

Balancing the thermodynamic and techno-economic optimization in designing the next generation of solar collector technologies poses a great opportunity to increase the value of a new solar installation by adding the ability to provide dispatchable electricity generation or local thermal amenities. Weinstein et al. have laid out a compelling design, based off rigorous thermodynamic analysis, for the next generation of parallel solar PV/T collectors.

Declaration of interests

The author declares no competing interests.

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