Experimental validation of a novel light-splitting technique for retrofitting CSP plants by hybridizing with CPV

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Abstract

Photovoltaic (PV) solar power generation is expanding rapidly relative to Concentrating Solar Power (CSP) due to a faster decline in solar PV panel costs after manufacturing commenced in east Asia in the 1990s. One remaining advantage of CSP is thermal energy storage (TES) which allows for smoothing output and timed dispatch of power at utility scales, whereas PV power, which currently has lower investment and levelized costs, is dependent on battery storage that has not yet matured at a large scale. There are potential advantages in hybridizing the two technologies if the low investment cost and higher areal basis yield of PV can be combined with CSP's robust and scalable storage. Under the Advanced Research Projects Agency-Energy (ARPA-E) FOCUS program, our team developed a novel approach to achieve CSP-PV hybridization through an add-on package that can retrofit existing parabolic trough collector (PTC) plants with secondary spectrum-splitting optics and a concentrating PV (CPV) receiver. The dichroic filter transmits UV and IR solar irradiance to the standard evacuated tube heat collection element (HCE) while wavelengths that are optimally utilized by PV are reflected down to an actively cooled flow through CPV receiver. The fraction of solar energy remaining available for storage can be tuned between 20-100% through configuration of the extension and optical properties of the filter. An experimental section of a standard RP3 mirror parabolic trough and HCE outfitted with the upgrade demonstrates the proof-of-concept for the approach and validates key technical and economic performance targets. The results of these experiments are relevant to operators of CSP plants as a means of enhancing output and return on investment.

Keywords: Solar, CSP, PV, Thermal, Storage, Hybrid, Retrofit, Parabolic Trough, Dichroic filter, CPV

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1. Introduction

Solar thermal, also known as concentrating solar power (CSP), and solar photovoltaic (PV) generation are competing approaches to viably and economically supply utility scale energy converted from sunlight. In the past decade market forces, technology and volume manufacturing in east Asia have resulted in PV power surpassing CSP in installed capacity and bankability, with PV projects competing for power purchase agreements (PPAs) at prices competitive with traditional sources (Bleich & Guimaraes, 2016). As penetration of grid-scale solar generation has increased since the 1980s, the phasing of daytime supply against 24-hour demand has led to an increased awareness of the value of energy storage in promoting and maintaining grid stability (Castillo & Gayme, 2014). CSP historically has been coupled with an economical grid-scale storage solution by capturing solar energy as heat, pre-conversion to electricity, in thermal energy storage (TES) typically using molten

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salts and other phase change materials (PCMs). Photovoltaics directly convert sunlight to electricity and therefore require batteries for energy storage. Due to nascence of technology for grid-scale battery deployment both the absolute and relative capacity of battery storage to solar generation lags for PV in comparison with CSP (Orosz, 2015). Whereas PV and CSP generation are technologically disparate conversion methods, there is a means of fusing the technologies to pair the advantages of PV's low investment costs with CSP's mature and scaleable thermal batteries. This paper describes an approach for separating the solar spectrum via the addition of an optical filter to the standard parabolic trough collector (PTC) CSP architecture and equipping the PTC with a secondary, linear, actively-cooled concentrating photovoltaic (CPV) receiver.

2. Spectrum Splitting Secondary Optics

Under the Advanced Research Projects Agency-Energy (ARPA-E) FOCUS program, several concepts for spectrum-splitting hybrid solar thermal and photovoltaic power are under investigation with the rationale of coupling with TES to promote grid stability. The conversion of photons into electricity is only marginally wavelength dependent for CSP technology; to a first order approximation the spectral response of optical and thermal elements in solar thermal conversion is flat. Approximately 70% of a photon's energy can be expected to be concentrated and captured as heat and from there conversion to electricity by endoreversible thermodynamic means is typically around 30% for a 390ºC steam Rankine cycle, for a combined efficiency of around 22% for a well matched solar field and power block (Lovegrove & Stein, 2012). Photovoltaics conversely have a distinctive spectral response due to the bandgap of the semi-conductor junction: longer wavelength photons below the bandgap energy (E_g) threshold fail to promote an electron into the conduction band, while high energy photons excite electrons into overshooting and relaxing back towards the band gap. Over 70% of the solar spectrum in a single junction PV cell is lost in heating up the device, however the quantum efficiency of conversion at the band gap approaches 90% and falls off from there towards higher wavelengths (Green, 1982). This suggests a simple logical framework for comparison of PV and CSP efficiency on the basis of spectral determinants: for any wavelength a photon would be optimally directed to PV where the quantum efficiency of the PV cell exceeds a baseline of 22%, and elsewhere directed to CSP. Calculating this in turn specifies the band edges for a dichroic filter interposed in the flux line of a PTC with transmission and reflection bands capable of splitting sunlight and directing photons of differing energies to their respective optimal targets. Following this procedure we specify a spectral response for an optical coating on borosilicate glass facets for reflecting (mainly visible and near IR) light downwards to a CPV receiver using single junction c-Si cells (E_g of 1.1 eV). The as-built performance of the filter at normal incidence is shown in Figure 1.

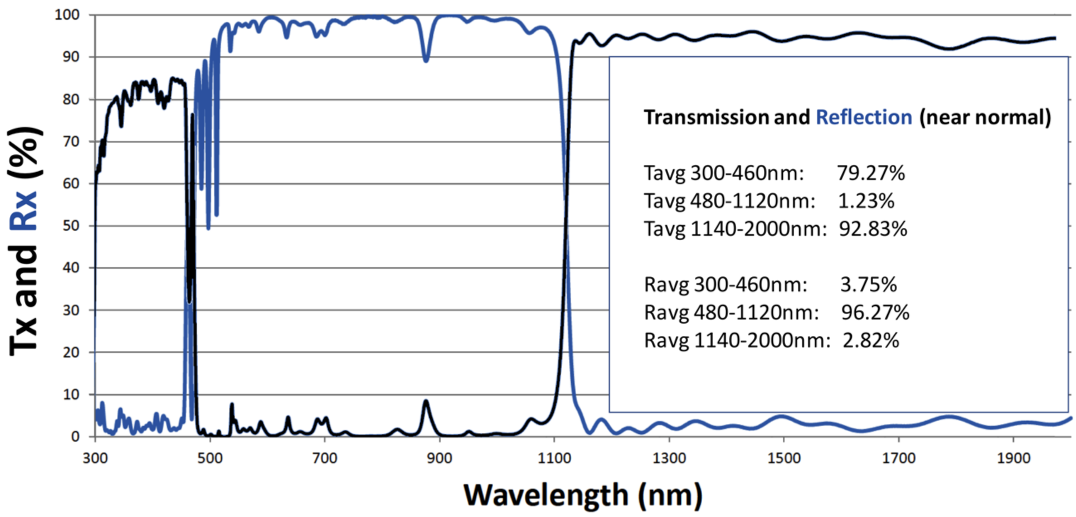

Figure 1. Spectral response of a dichroic filter for separating light into bands optimized for PV (blue) and CSP (black) receivers

It should be noted that efficiency is not necessarily the only determinant of the filter design. The selection of the band edges for reflection to the CPV receiver is subject to tuning as part of an optimization strategy considering component and system level efficiency and economic impacts - which may be site specific relating to the Rankine power cycle specifications and the physical properties of any connected thermal energy storage (TES) system. The retrofit can be flexibly adapted, by means of the dichroic filter spectral response and physical placement, to redirect design specific amounts and wavelengths of the solar spectrum within wide ranges.

3. CSP-CPV Retrofit Prototype

3.1. Design approach and component performance validation

To evaluate the potential for solar thermal and photovoltaic hybridization ("Retrosol") our team modelled and considered both ground-up designs and approaches that add filter and CPV components to an existing CSP platform (Matthew Orosz, Zweibaum, Lance, Ruiz, & Morad, 2016). The latter strategy has the economic advantage of requiring minimal investment since the primary optical and thermal infrastructure is already present, and the deployment of specialized concentrating PV panels is minor in extent relative to the solar field aperture due to the 50-100 concentration factor. Techno-economic dynamic modelling of a retrofit to a case study CSP plant in Bythe, CA indicates a potential increase in power output of 30% (O'Hern, et. al., 2017). To validate the concept and the previously developed performance models we designed a prototype for on-sun testing consisting of a standard inner set of RP3 mirrors (featured in many parabolic trough plant designs) focusing on a standard 70mm evacuated heat collection element (HCE) at a characteristic focal length of 1.7m – essentially a copy of the typical parabolic trough collector (PTC). The main components and design features are illustrated in Figure 2.

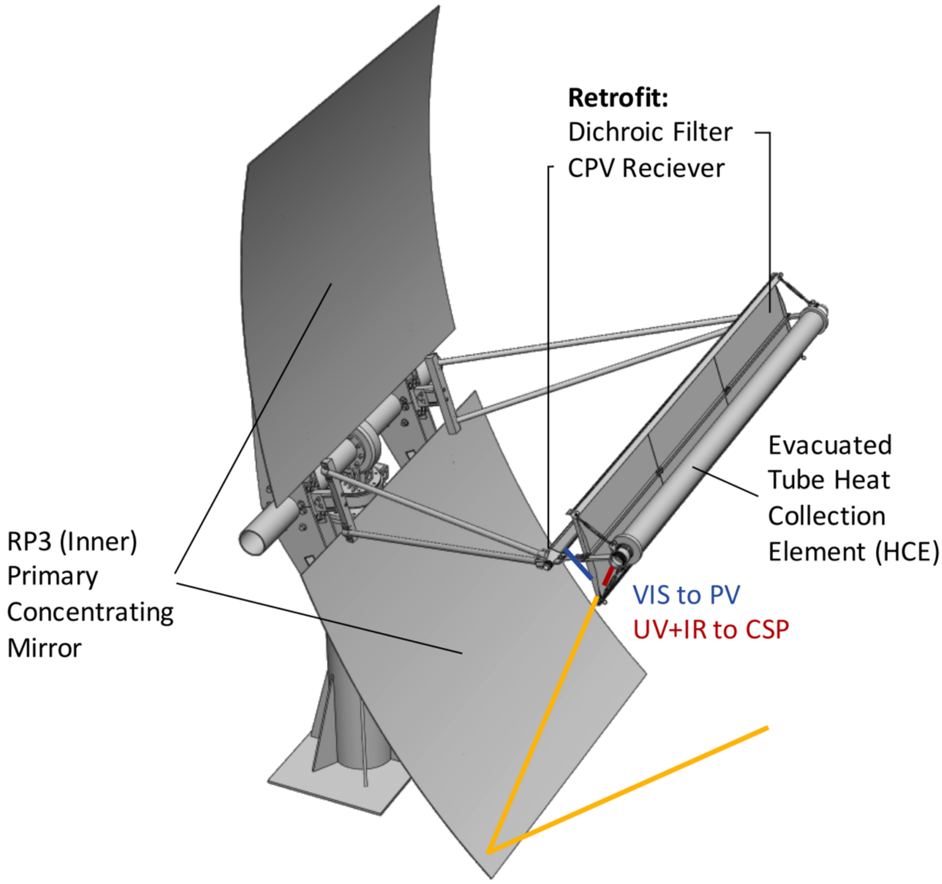

Figure 2. Prototype hybrid CSP-CPV collector using standard PTC architecture and adding dichroic filter and PV receiver as a bolt-on retrofit.

The rationale behind the design of the prototype for Retrosol is to combine the ability to experiment and collect research data with a platform that is reasonably similar to the operational Parabolic Trough Collector (PTC) power plants that would be candidates to retrofit with CPV. While PTCs are linear concentrators, there are some losses associated with walk off at the edge of the collectors that are insignificant at the length scales of 100m or longer assemblies common in CSP plants. For a single set of RP3 inner mirrors, this effect is significant and we therefore mount the PTC on an Azimuth-Zenith two-axis tracking platform such that the aperture is always normal to the sun. The use of RP3 mirrors as a primary reflector is consistent with the standard practice in PTC plants and the prototype features inner RP3 segments, a typical Schott-like Heat Collection Element (HCE), and a torque tube and arm design which is a combination of support structure that is in use in commercial plants (alongside space frame support structures). Whereas the typical PTC plant uses both inner and outer mirror segments and a single axis tracking layout, in order to operate at a reasonable scale for experimentation the prototype features only inner mirrors and uses a dual axis slewing drive for Azimuth-Zenith tracking to avoid dealing with walk-off effects on a small aperture of ~5m^2. This approach enables the project to achieve its R&D goals while demonstrating the appearance and geometry familiar to the CSP industry which can be leveraged during technology-to-market outreach. Conceptual design of the prototype following these principles has resulted in detailed part and assembly design and fabrication with installation at the North Campus facility of the University of

Tulsa, Oklahoma, USA.

Testing is achieved through I-V measurement of CPV receiver output and heat gain the HCE is measured as mass flow times heat capacity and temperature difference across the focal line.

3.2 Wind Load Analysis

In order to take appropriate steps towards a prototype design that would be compliant with relevant standards regarding safety and wind loading the team developed specifications using IEC 62817: Design Qualifications for Solar Trackers as a reference (IEC 2014). These included that the prototype structure should survive a 40 m/s (90 mph) wind and be operable in a 10m/s (22mph) wind. For this purpose a deflection of 1mm and 5mm are applied for operable and survival respectively. Wind loading is estimated using CFD flow simulation and deformation of the structure under the calculated static load is performed using finite element analysis.

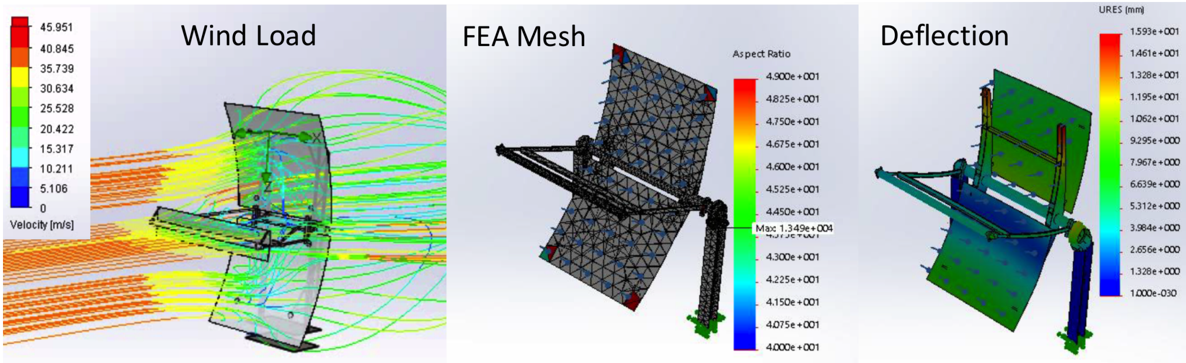

Figure 3 Design structural integrity and compliance with IEC 62817 uses simulated wind loading and finite element modeling

These analyses were used to investigate different mounting configurations and evaluate various design configurations for the mounting of the CPV receiver and dichroic filter. As a result of this process several changes were made to improve structural support of the receivers while also enabling them to be readily serviced and replaced in the field (an important consideration for operation and maintenance). This was a challenge due to the fact that there is a tradeoff between adding structure and shading the primary, and the fact that while the CPV receiver is intermediate between the torque tube and the HCE, a support that extends up from the torque tube supporting both CPV and HCE should be able to function while either one is removed. The updated configuration for mounting the CPV receiver meeting these requirements is shown below.

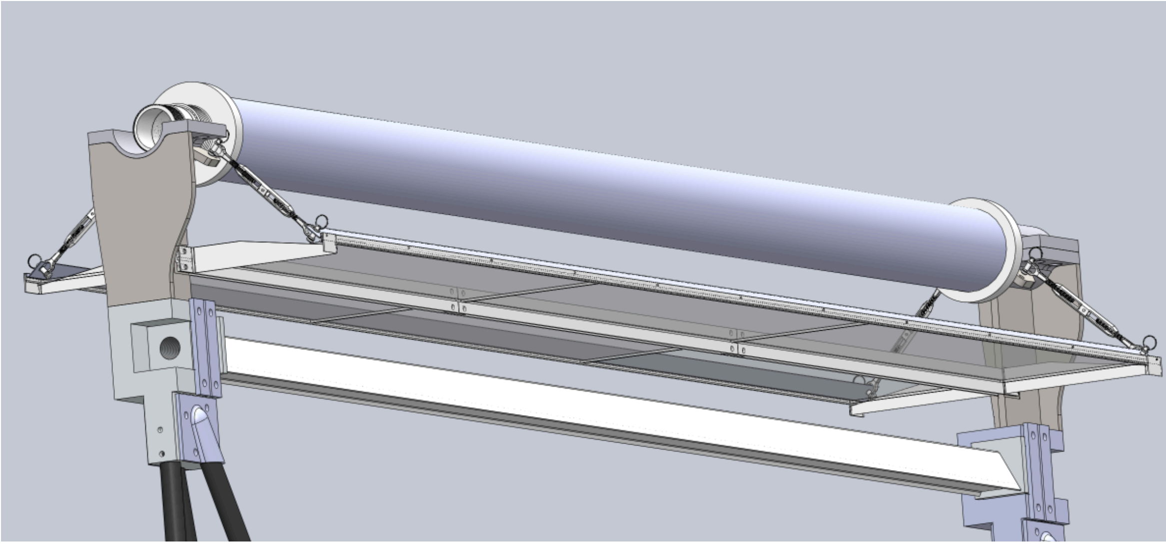

Figure 4 Updated mounting configuration with an HCE support that allows for the CPV receiver (shown beneath the HCE and dichroic secondary) to be removed for servicing from the side

3.3 CPV Receiver design

SunPower Maxeon back contact cells are deployed in the Retrosol CPV receiver as a low cost option that avoids the shading losses from dense front contacts (needed to convey increased current at concentration) of specialized concentrator cells. The solid copper substrate is suitable for managing the current generated at concentration. Because current increases nearly linearly with concentration and SunPower panels are nominally fused at 15A, the ~5A I_{mp} Maxeon cell nominally remains within its specifications if operated up to 10 suns and possibly can be operated at even higher concentration when e.g. the 125mm semi-square cell is sliced into $1/6^{th}$ sections (Nesterenkov et. al., 2016).

The Retrosol prototype under development uses a 50mm width CPV receiver but to facilitate testing in parallel with construction, a version using the form factor of a Cogenra Solar T14 concentrator receiver was manufactured using 64 SunPower $1/6^{th}$ form factor cells in series with customized interconnects made of bus wire and encapsulated using liquid silicones (Figure 5).

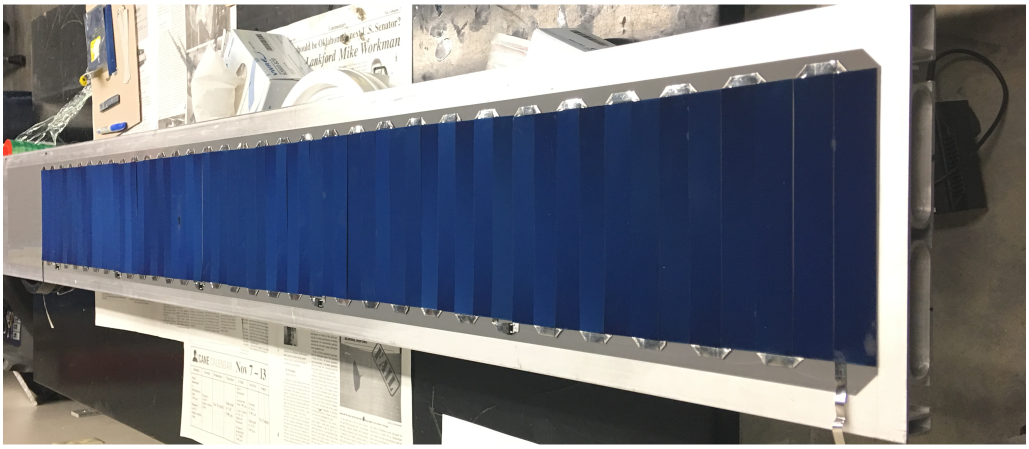

Figure 5. T14-type CPV receiver fabricated at TU using 1/6th SPWR Maxeon cells in series

Vopen (V)	39.59		Area:	0.17	m^2
Ishort (A)	0.985		Irradiance:	1031	W/m^2
Vmaxp (V)	31.41		Efficiency:	15.98%	

Imaxp (A)	0.891
Pmax (W)	28.01

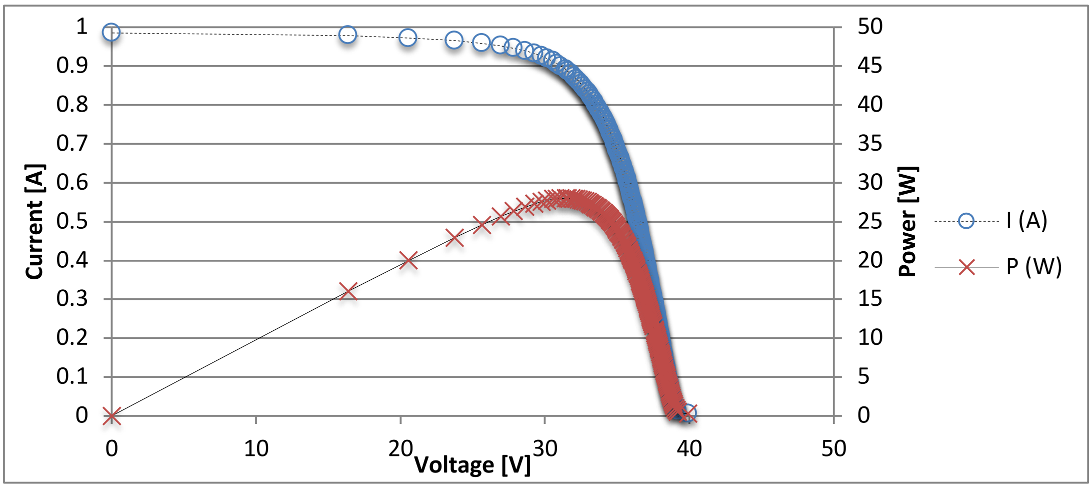

Figure 6. 64 cell SPWR Receiver benchmarked at 1-sun and ambient temperature (electrical data in table above)

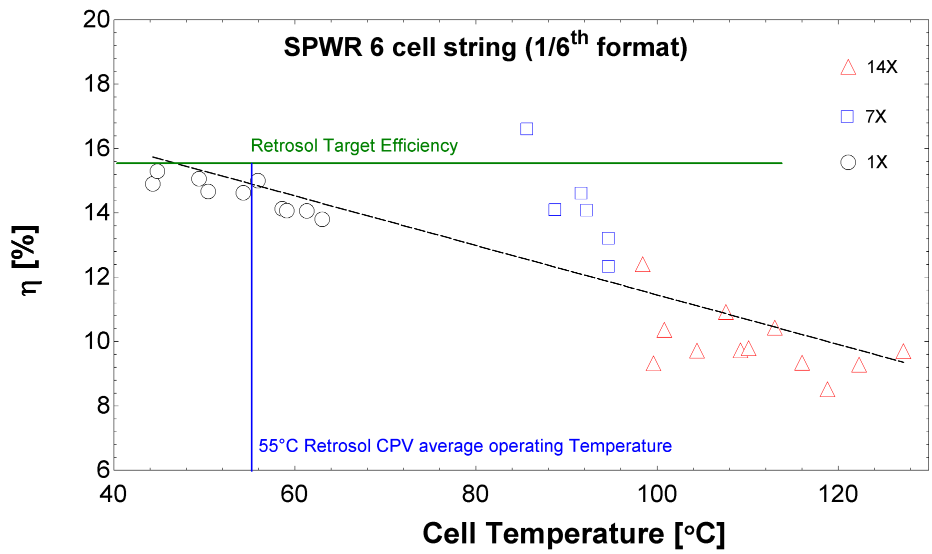

Figure 7. Test data for a 6-cell SPWR CPV Reciever at 1, 7 and 14X and a range of temperatures

Test sections of the SunPower T14 type CPV receiver were tested at 1, 7 and 14X (Figure 7) in a T14 concentrator (Morad, 2014), and the data indicates that concentration (at least up to 14X) is not significantly impairing receiver performance whereas temperature plays a driving role in CPV receiver efficiency. Further testing is underway but extrapolation of this dataset indicates that operational efficiencies at an average receiver temperature of 55°C will be approximately 95% of the targeted 15.8% efficiency.

3.4 Retrofit mounting considerations

The prototype provides an example of a design that uses a torque tube as the foundation for the attachment of mounting struts for the HCE. Torque tubes are a common design feature in parabolic trough collectors, beginning with the LS-2 design used at SEGS I-VII in California as well as troughs designed by Sener (Extrasol and Valle plants in Spain, Genesis in the US) and ENEA. Similar to these collectors, the prototype mounts the primary mirror on cantilevered arms. The prototype is compatible with torque tube designs with the only modification being the U-bolt clamp to accommodate variation in torque tube diameters, which are generally standard pipe cross sections so only a few variants would be needed. Alternative designs in the market would require more modification to the attachment format. These include Flabeg's torque box design (Andasol plants in Spain and Kuraymat in Egypt) and Acciona (Nevada Solar One) and Abengoa (Solana, Mojave in the US) space frame mirror support structures. For these formats the prototype mounting structure would require additional modification to adjust the mode and orientation of the fixture to the frame elements, as well as variation in the length of the support. These aspects are considered to be relatively straightforward mechanical engineering challenges that could be addressed quickly with access (via partnership) to the relevant structural design drawings and documentation.

4. Prototype Evaluation

Figure 8 Prototype hybrid CSP-CPV system in on sun operation

Initial on-sun testing of the Retrosol prototype (Figure 8) has been dedicated to experiments that have benchmarked the durability of the ~65W 0.5m length CPV receiver section installed (no degradation of maximum power point output after daily use at operating temperatures) under conditions of 45x concentrated sunlight (reflected in the 500-1000nm band) and evaluating various power evacuation techniques. The remaining (~23%) of concentrated sunlight not utilized by the CPV receiver passes through the dichroic filter and is absorbed by the HCE. Because radiative and convective heat losses to the ambient are a function of operating temperature (averaging around 300°C in the collector field) , the diversion of a significant portion of the solar spectrum to the CPV receiver results in a corresponding reduction in the efficiency of the HCE due to constant losses and less heat gain per unit length under lower incident irradiance (Figure 9). The dichroic filter effectively increases thermal losses by up to 30% at operating temperatures, however, this thermal efficiency penalty is compensated by the increased in-band quantum efficiency of the CPV receiver.

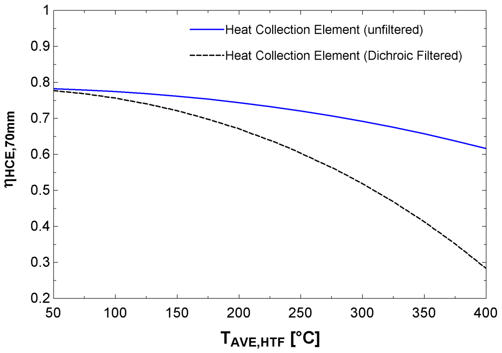

Figure 9 HCE performance pre (solid blue line) and post (dashed black line) retrofit

5. Summary and future work

This work describes technical aspects of an approach for modifying CSP power plants using linear PTC solar fields with the addition of hybrid CPV receivers for increased power output using spectrum-splitting secondary optics. A practical motivation for this exists as evidenced by the example of a CSP plant (SEGS II) which was decommissioned and redeveloped with PV. Retrofitting the existing solar field with a CPV receiver represents an alternative means to achieve PV conversion and increased capacity. The output improvement compared to investment requirement possible with this retrofit is comparatively advantageous as described in (O'Hern et al., 2017) and the validation of the performance simulation is carried out by component and system level validations, including those described in this work: spectral selectivity of the dichroic filter secondary optic and the CPV receiver efficiency at various concentrations and temperatures. The remaining components (standard HCE and CSP primary optics) are modelled using validated and well understood energy balance models based on (Forristall, 2003).

Future work includes translating the learnings from the proof of concept prototype to a full scale pilot on a collector assembly at an operating parabolic trough plant in partnership with a CSP operator to demonstrate the feasibility and benefits of retrofitting PTC plants with CPV receivers.

6. Acknowledgments

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