Performance and economic optimization of hybrid solar thermal and photovoltaic power plants with dynamic simulation

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Abstract

Energy storage is a critical determinant of grid stability under scenarios with a high percentage of renewables in the generation portfolio. Concentrating solar thermal power traditionally offers high capacity thermal energy storage (TES) on timescales up to 24 hours, while photovoltaics operate with comparatively better economy but are limited to direct injection into the grid during the daytime in the absence of mature, high throughput battery storage technology. Obtaining the advantages of both systems through hybridization has been proposed in the ARPA-E FOCUS program, and this work investigates the performance and cost trade-offs of updating existing CSP infrastructure to include superimposed spectral filtering and concentrating photovoltaics in a linear optical configuration. A numerical energy balance model for a retrofit parabolic trough collector is deployed in an hourly simulation using plant characteristics and typical meteorological year (TMY) data for a location of interest. Design features including PV band pass filtering, operating temperature, and primary optics intercept are varied for an optimization of levelized cost of electricity. A case study for the US southwest illustrates the potential for performance enhancement relative to a CSP baseline via increased photovoltaic output (>30%), and favourable financial returns in comparison to greenfield PV plant development (with installed specific costs <1.5 USD/W), that preserves the advantages for grid operators of maintaining the dispatchability of TES.

Keywords: Solar thermal, concentrating photovoltaics, energy storage, dynamic simulation, hybrid system, CSP, CPV

1. Introduction

The hybridization of CSP and concentrated photovoltaics (CPV) technologies combines the energy storage capabilities of CSP with the economy of PV conversion. Retrofitting an existing parabolic trough collector CSP plant with a spectral splitting filter reflecting optimal wavelengths to a CPV receiver is expected to increase the annual power output of a traditionally configured CSP plant using linear Parabolic Trough Collectors (PTCs). This is due to the relatively higher in-band efficiency of PV cells compared to the output of a steam Rankine cycle after accounting for optical and thermal losses in the CSP array. The concept of interposed secondary optics has been considered previously as means to increase the concentration ratio onto the PV cell, however, in this study we take advantage of an existing as-built CSP array, with its energy storage benefits, and add secondary optics to redirect specific wavelengths of light to a CPV receiver. The key advantage of the hybrid CSP-CPV system is that the filter can be designed to reflect wavelengths optimal for conversion in the PV cell, while passing the poorly utilized wavelengths through to the CSP, thus allowing the PV cell to operate effectively while ensuring that light wavelengths that would otherwise go to waste are exploited (Orosz 2015). The hybrid CPV retrofit of a CSP plant would be an economical option to increase the annual power output, while still utilizing the energy storage capabilities of CSP.

The secondary optic consists of a dichroic filter attached in plane intermediate between the primary mirror and the focal line of the parabolic trough mirror, with the CSP heat collection element (HCE) above it and the CPV receiver below, as shown in Figure 1. The filter splits the spectrum such that ultraviolet and infrared wavelengths pass through the dichroic mirror to the HCE while wavelengths that are efficiently used by the CPV cell are reflected down to the CPV receiver. The diversion of part of the solar spectrum results in reduced CSP power output, however, the CPV power output increases the net output of the plant due to its higher in-band conversion efficiency.

doi:10.18086/swc.2017.20.07 Available at http://proceedings.ises.org

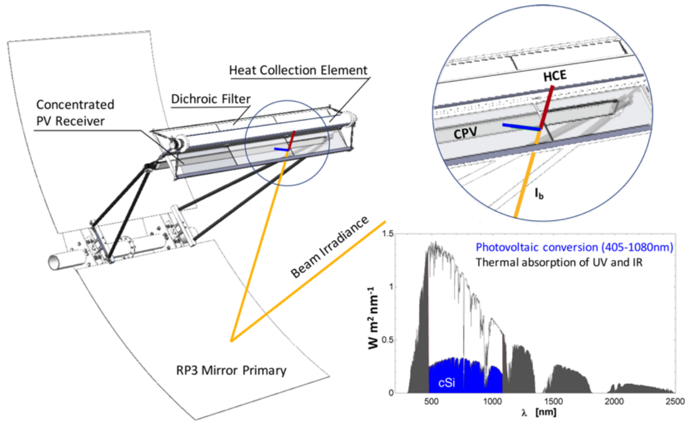

Figure 1: A CPV retrofit attaches to and operates with an existing standard parabolic trough collector (RP3 outer mirrors not shown). Inset shows a detail of the beam splitting secondary optics, the respective CSP and CPV targets, and the AM1.5 band of photovoltaic conversion (lower right) where the right band edge is set to the cSi band gap and the left band edge is tuned to maximize combined CSP and CPV output.

2. Annual Performance Model

Probabilistic yield estimation (monthly and annual energy output) based on design and location is an important input in the development cycle of solar energy projects and critically determines the financial merit of a proposed solar plant. There are many commercial software packages (PVSyst, Helioscope, etc.) in use for determining the annual yield of a solar PV power plant. The System Advisor Model (SAM) is a free software developed by NREL (National Renewable Energy Laboratory 2016) that is utilized for both performance and detailed financial modelling. While SAM and other specialized tools are capable of modelling PV, parabolic trough CSP and CPV plants, there is no commercially available platform that can simulate a hybrid of both CSP and CPV, and in particular with reference to spectral dependencies e.g. the secondary optics used in the retrofit which our team is developing with support from the U.S. Department of Energy (DOE) Advanced Research Projects Agency (ARPA-E) FOCUS program (ARPA-E n.d.). To address this observed gap in performance prediction tools, a dynamic simulation was created in Python which embeds a previously developed detailed steady-state model of the energy balance of a parabolic trough CSP plant with a coupled spectrum-splitting filter and CPV cell retrofit (Orosz et al. 2016).

2.1. Steady-State Energy Balance Model

A steady-state physics based energy balance model was developed in Python, based on the Forristall energy balance model (Forristall 2003). The heat transfer equations of the Forristall model are combined with the necessary equations to determine PV power generation, in order to determine the net generation of a retrofitted plant. Inputs into the model include collector and HCE geometry, heat transfer fluid (HTF) properties, inlet temperature, and flow rate, optical properties, and ambient weather conditions. In addition to CSP generation, with and without the retrofit and CPV generation, the model also determines HTF outlet temperature, necessary pumping power, and thermal and optical losses.

The HCE is comprised of a stainless steel tube with a selective coating inside a glass envelope, with an evacuated annulus. The model assumes all temperatures, heat fluxes, and thermodynamic properties are uniform around the circumference of the HCE, and that the only heat transfer in the axial direction along the length of the trough is via the HTF. The effective incoming energy is the solar beam irradiance reduced by optical losses incurred through the dichroic filter. The incoming irradiance is predominantly transmitted through the glass jacket, absorbed and conducted through stainless steel absorber, and finally transferred to the HTF by convection. Residual energy is lost to the environment via convection and radiation. The beam irradiance that is reflected by the dichroic filter is converted to electricity directly by the CPV reciever. These energy losses and gains are calculated along the length of the trough.

2.2 Model Reduction and Annual Simulation

A meaningful comparison between a CSP plant and hybrid retrofitted plant would need to be done on at least an annual scale to determine how the plants differ throughout a year. The computational effort associated with running the steady-state model at every hourly time step for a year to build up an annual generation profile would be extensive. In order to reduce this computational effort a model reduction strategy was implemented by means of a parametric sweep, varying dry bulb temperature and direct normal irradiance. The resulting dataset was subjected to a symbolic regression algorithm (Schmidt and Lipson 2009) to simultaneously search the parameter and form space for highly fitted equations representing the steady-state model's prediction for CSP and CPV yields of the retrofit.

Equation 1:

$$\eta_{CSP} = a_0 + a_1 * T_{amb} + \frac{a_2}{I_b}$$
$$R^2 = 0.99783307$$

Equation 2 (Curzon and Ahlborn 1975):

$$\eta_{carnot} = 1 - \sqrt{\frac{T_{amb} + 273}{663}}$$

Equation 3:

$$CSP\ (MW) = \frac{\eta_{CSP} * \eta_{carnot} * I_b * A}{1000000}$$

Equation 4:

$$CPV\ (MW) = \frac{A * ((b_0 * I_b) - b_1 - (b_2 * T_{amb} * I_b) - (b_3 * I_b{}^2)) / 32}{1000000}$$
$$R^2 = 0.99999724$$

TABLE 1: Values of coefficients for dynamic simulation calculations

Coefficient	Value
a_0	0.81123
a_1	0.000133
a_2	-34.4304
b_0	5.644508
b_1	7.367557
b_2	0.000626
b_3	0.000269
c1	0.000831
c2	3.498752
c3	2.055137
c4	0.001483
c5	4.371873
c6	7.378e-6
c7	2.141e-9

TABLE 2: Parameters used for dynamic simulation calculations

Parameter	Value
A	Aperture Area (190,338 m^2)
T_{amb}	Ambient Dry Bulb Temperature
I_b	Beam Irradiance
$TES_{SOC\ IN}$	Thermal Energy Storage state of charge from previous time step

To initialize the annual simulation model, typical meteorological year (TMY) data (National Renewable Energy Laboratory 2003), consisting of 8760 hourly values for ambient conditions, is read into the model. The correlation equations, from the symbolic regression, that make up the annual simulation model are shown in equations 1-4, with coefficients in Table 1, and parameters in Table 2. The ambient dry bulb temperature and direct normal irradiance is applied to these equations at each hourly time step for a year. The model calculates the CSP yield before the retrofit, as well as the CSP and CPV yields with the retrofit. This simulation can be applied to any plant as long at the aperture area and TMY data is available. After the model calculates the yields of the plant, the CSP yields are compared to the nameplate capacity of the power block to ensure the power block is not being overloaded. If the CSP load is greater than the nameplate capacity, the model assumes that collectors will be defocused to avoid this overload and therefore the CSP yield is set equal to the nameplate capacity of the power block, as shown in Figure 2. The model also assumes that there will be no yield of any kind if the sun is not shining, e.g. direct normal irradiance is less than 200 W/m^2.

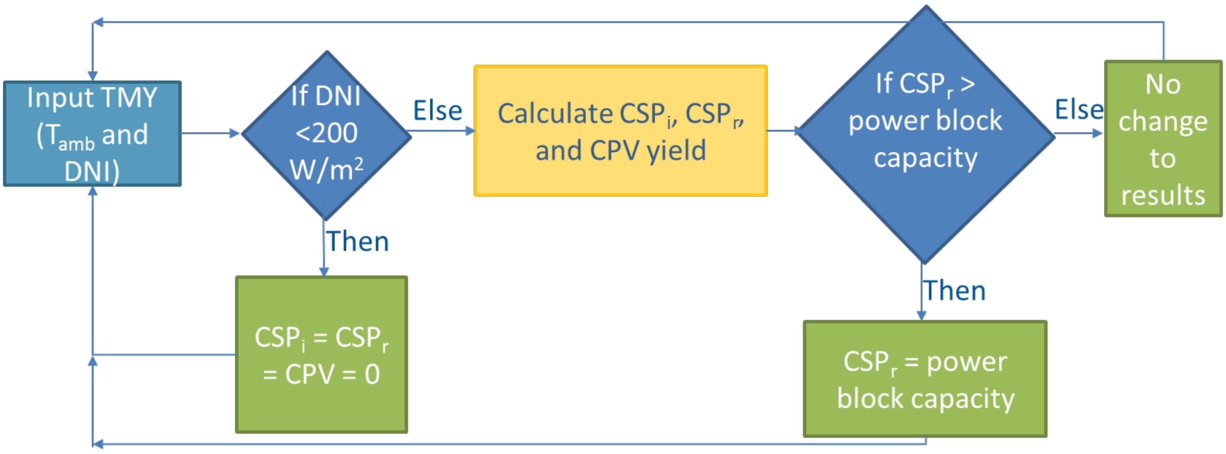

Figure 2: Annual performance model block diagram

3. Case Study

For this study the CPV retrofit of the Genesis solar trough plant in the Mojave Desert near Blythe, California (33.6650°N, 114.9948°W) is investigated. The Genesis CSP plant features linear parabolic trough collectors in a solar field with an aperture area of 1,928,320 m^2 and average annual power block output of 580,000 MWh (National Renewable Energy Laboratory 2014). This facility has a steam Rankine power block of 250 MW net capacity and no Thermal Energy Storage (TES)(U.S. Department of the Interior Bureau of Land Management 2016), consequently the CSP electricity power output in the model was capped at 250 MW. The model assumes that the entire solar field aperture area is retrofitted with the hybrid CPV system.

The Genesis plant's first full year of operation was 2014 and monthly data for the energy output in MWh is published online (National Renewable Energy Laboratory 2014). Actual meteorological data for Blythe, CA for 2014, 2015, and 2016 was obtained to initialize the dynamic simulation; the dry bulb temperatures and irradiances for every hour of those years are shown in Figure 3. The measured data provides direct normal irradiance, which does not account for the cosine losses of a single axis tracking plane. To increase the accuracy of the dynamic simulation, the direct normal irradiance is multiplied by the plane of array cosine loss factor for each hour, using a method adapted from (Duffie, Beckman, and Worek 1994).

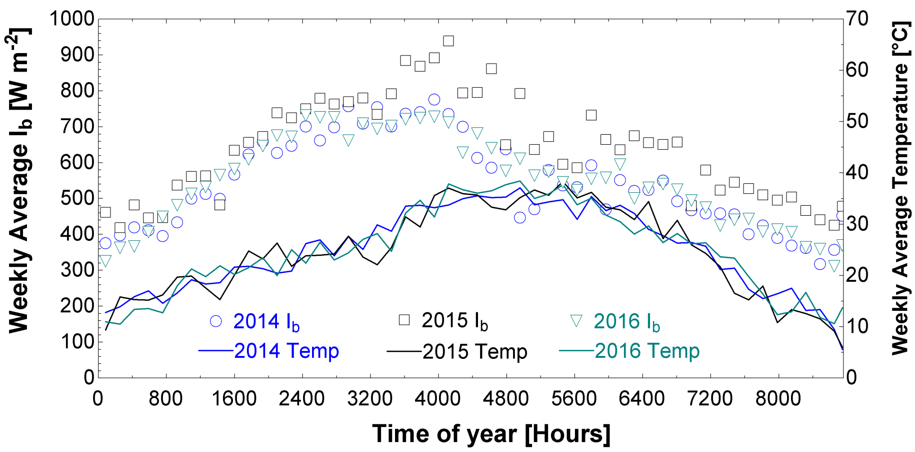

Figure 3: Beam Irradiance and Dry Bulb Temperature for 2014, 2015, and 2016 in Blythe, CA. The beam irradiance is a modification of the direct normal irradiance considering cosine losses of a single axis tracking plane.

4. Results

4.1. Model Validation

The optical and thermal validation and parametric tuning of the dynamic simulation is achieved through comparison of the predicted output of the CSP component (without the retrofit) to the published output data for the Genesis plant. The model calculates the output for every hour. These were summed into each month for comparison to the measured

data. Each of the modelled months was then compared to the measured data. A relationship is found to improve the closeness of fit between the results of physical modeling and the published output of the genesis plant:
Equation 5:

$$Model_2 = c_1 * I_b + c_2 * CSP * T_{amb} + \frac{c_3 * \tan\left({}^{c_4}/_{I_b}\right)}{{T_{amb}}^2} + \tan(c_5 * I_b + c_6 * CSP * T_{amb}) - c_7 * CSP - c_8 * T_{amb} * I_b - c_9 * \sin(c_{10} * I_b)$$

Table 3: Values of coefficients for tuned model simulation

Coefficient	Value
c_1	329.1380845
c_2	0.168203567
c_3	332684.8232
c_4	367.1260423
c_5	329.1380845
c_6	0.168203567
c_7	3.462152074
c_8	12.08652194
c_9	5303.369644
c_{10}	13796.71749

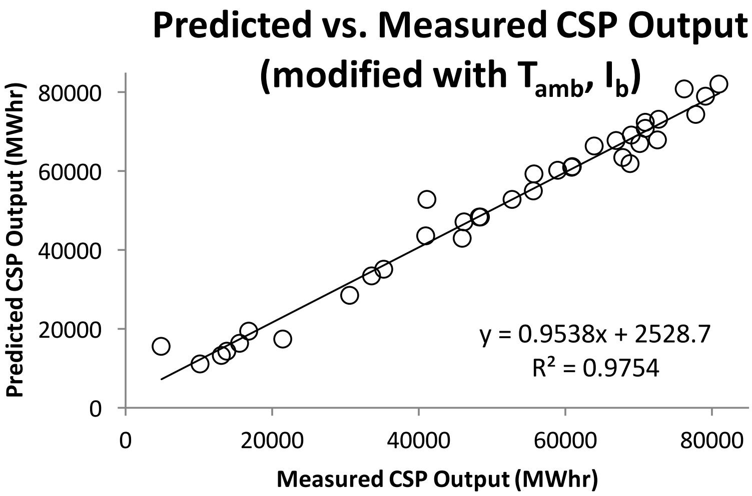

Figure 4: Predicted vs. measured CSP output modified by equation 5 with temperature and irradiance dependencies

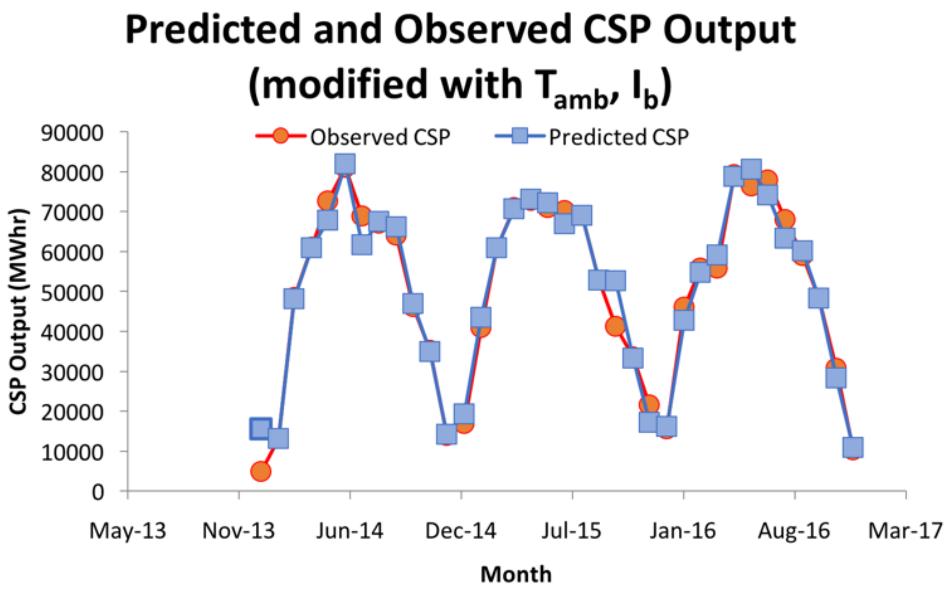

Figure 5: Modelled and Actual CSP Output (MWhr) for each month of the years of operation, modified equation 5.

As shown in **Figure 4**, using average temperature and daytime irradiance the predicted data matches closely with the measured data, with an R^2 value of 0.9754. Accuracy can be improved in sub-annual time periods by using the average data. The predicted CSP output matches the observed data well for each month, as shown in Figure 5.

4.2. Retrofit Yield Estimate

The overall yield of the plant with the retrofit, as well as the baseline measured CSP yield for the three years of operation is shown in Figure 6. The total yield of the plant is increased by 25%.

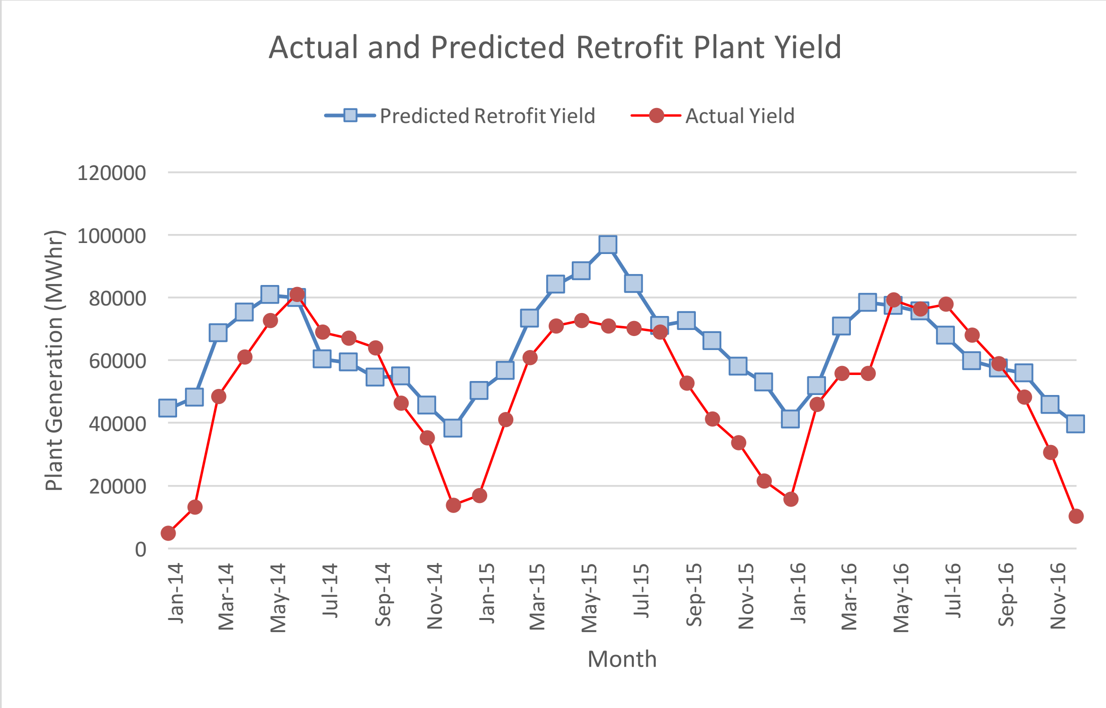

Figure 6: Actual and predicted retrofit(modelled) annual yield of Genesis plant.

5. Conclusions

The addition of a dichroic filter as a secondary optic in a Parabolic Trough Collector allows for the concentration of selected bands of the solar spectrum onto two physically and thermally decoupled receiver targets. This approach is proposed as a retrofit to existing CSP plants using the PTC format, whereby the second receiver is a solar panel. To characterize the performance of this hybrid retrofit, a dynamic simulation model is developed using correlation equations derived from a detailed steady state energy balance model, as a tool to facilitate the calculation of the change in yield of an existing CSP plant with the addition of a CPV retrofit. The overall yield of the plant with the retrofit, as well as the baseline measured CSP yield for the three years of operation is evaluated for a case study CSP plant (Genesis) located in California in the USA, and the results of this analysis indicate that the total yield of the plant is increased by 25%. The magnitude of the performance increase and the comparatively minor equipment investment supports further investigation of this technology as a retrofit to the currently operating fleet of PTC plants, and future work includes experimental validation of a prototype retrofit in a controlled environment in operating solar fields.

6. Acknowledgements

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000729

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