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# Full Spectrum Solar System: Hybrid Concentrated Photovoltaic/Concentrated Solar Power (CPV-CSP)

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## ABSTRACT

Gas Technology Institute (GTI), together with its partners University of California at Merced (UC Merced) and MicroLink Devices Inc. (MicroLink) are developing a full spectrum solar energy collection system to deliver variable electricity and on-demand heat. The technology uses secondary optics in a solar receiver to achieve high efficiency at high temperature, collects heat in particles for low fire danger, stores heat in particles instead of molten salt for low cost, and uses double junction (2J) photovoltaic (PV) cells with backside infrared (IR) reflectors on the secondary optical element to raise exergy efficiency. The overall goal is to deliver enhancement to established trough technology while exceeding the heliostat power tower molten salt temperature limit. The use of inert particles for heat transfer may make parabolic troughs safer near population centers and may be valuable for industrial facilities.

## INTRODUCTION

High utilization of solar energy is an important component for future energy needs that will ensure U.S. energy independence with a corresponding low environmental impact [1]. Solar energy is available at no cost, but efficient collection, storage, and use of this energy in an economical way remains a challenge. Current examples of energy conversion technologies include photovoltaic (PV), concentrated photovoltaics (CPV), concentrating solar power (CSP), solar thermal, and hybrid photovoltaic/thermal (PV/T).

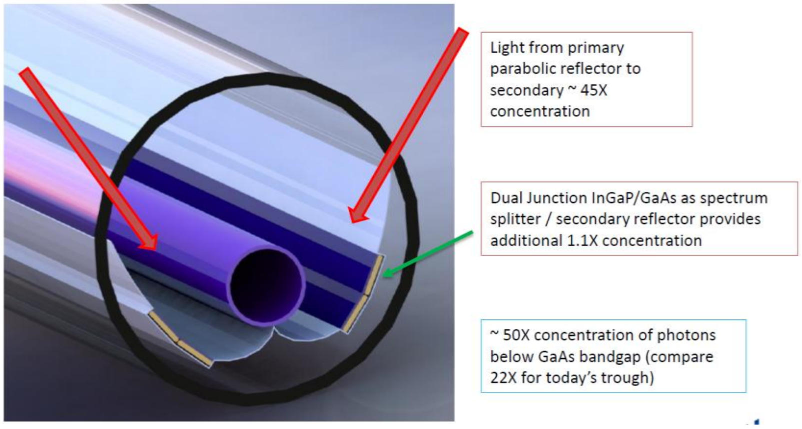
PV and CPV technologies convert solar radiation into electricity with champion efficiency ranging from ~29% (single junction GaAs PV cell) to ~46% (four junction CPV cell) [2]. CPV systems concentrate sunlight onto small and high efficiency PV cells. CSP systems generate electricity by concentrating direct beam sunlight to a point or line receiver to produce heat, at temperatures up to 1000°C, which is carried by a heat transfer fluid (thermal oil, molten salt, water, air, hydrogen, or helium) and used to power an electricity-generating turbine [3].

This paper discusses a hybrid concentrated photovoltaic-concentrated solar power (CPV-CSP) system wherein the incident photon energy is concentrated and converted first to electric energy. The remaining energy is recovered in a heat transfer fluid. The hybrid solar systems differ in heat transfer fluid type, fluid temperature, concentration ratio, PV type, system efficiency, and storage materials [3]-[6] The conventional designs are limited to relatively low fluid output temperatures due to reduced solar cell efficiency at higher temperatures and use a heat transfer mechanism that is directly attached to the monocrystalline Si PV cells. Monocrystalline Si (1.12 eV indirect bandgap) PV cells are typically more adversely affected by an increase in cell operating temperature compared to equivalent quality GaAs (1.42 eV direct bandgap) PV cells [7]-[9].

State-of-the-art high temperature thermal storage is carried out using mixtures of nitrate salts, commonly saltpeter or mixtures of sodium and potassium nitrates. Molten salt is pumped through the solar array, collects heat, and serves as a heat sink to generate steam at a later time. Molten salts have a maximum working temperature in the range of 400-550°C, and must be kept above their melting temperatures to prevent freezing.

## DESIGN

The PV/T technology discussed here integrates innovations in collector design and heat transfer and storage to deliver variable electricity together with on-demand heat. Using non-imaging optics [10], a parabolic trough commonly used in CSP plants is transformed into an integrated spectrum-splitting device (Figure 1) by placing a spectrum-sensitive topping element on a secondary reflector associated with the thermal collection loop. The secondary reflector transmits higher energy photons for PV topping, while diverting the remaining lower energy photons to a high temperature thermal collection system. By using non-imaging optics, a 50x concentration ratio is achieved compared to the conventional parabolic trough concentration ratio of 22x. This helps the secondary thermal receiver to achieve higher temperatures even under partial utilization of the solar spectrum. The entire receiver assembly is encased in an evacuated glass tube to minimize thermal loss.



Light from primary parabolic reflector to secondary ~ 45X concentration

Dual Junction InGaP/GaAs as spectrum splitter / secondary reflector provides additional 1.1X concentration

~ 50X concentration of photons below GaAs bandgap (compare 22X for today's trough)

***Figure 1.*** *PV/T receiver.*

The receiver will use backside IR-reflective double junction (2J) InGaP/GaAs epitaxial lift-off (ELO) PV cells from MicroLink [11].

The PV cells will be bonded with thermally conductive silicone to water-cooled Cu channels thus allowing the cells to operate at ~40°C. The backside of the cells will be designed for maximum reflectance of incident IR solar photons with energy <1.4 eV (i.e. the bandgap energy of the bottom GaAs subcell) by using Ag-based reflectors. Considering manufacturing limitations for large area ELO cells, an IR reflectance of ~85-90% is expected. Mass production PV cell power conversion efficiency is expected to reach ~28-30% at 20x sunlight concentration and 40°C cell temperature.

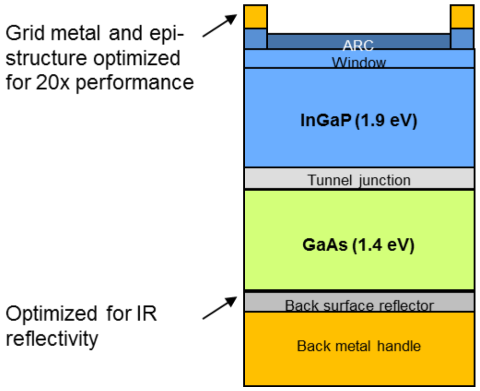


***Figure 2.*** *InGaP/GaAs 2J ELO PV cell with backside IR reflector.*

The thermal media is comprised of fine particles in air that allow operation up to the working temperature of the solid particles. The specific material and size of the particles (proprietary) have been selected based on their thermal (high softening/melting point, specific heat capacity and thermal conductivity), mechanical (low abrasion and attrition), low hazard ratings, and good fluidization and flow characteristics. Some of the particles considered were corundum, silica sand, silicon carbide, glass and metal. As illustrated in Figure 3, during the day, hot media from the collectors transfers heat to the work load for process heating or power generation, before returning to the collectors for reheating. Any excess media (heat) flows to an insulated hopper for separation and storage of the hot particles. The mostly particle-free hot air is either vented or picks up cooler particles from a second hopper before returning to the collector. When the solar intensity drops below a set threshold, the stored hot particles are picked up by air and heat is transferred to the work load and the resulting cooler particles are separated and stored.

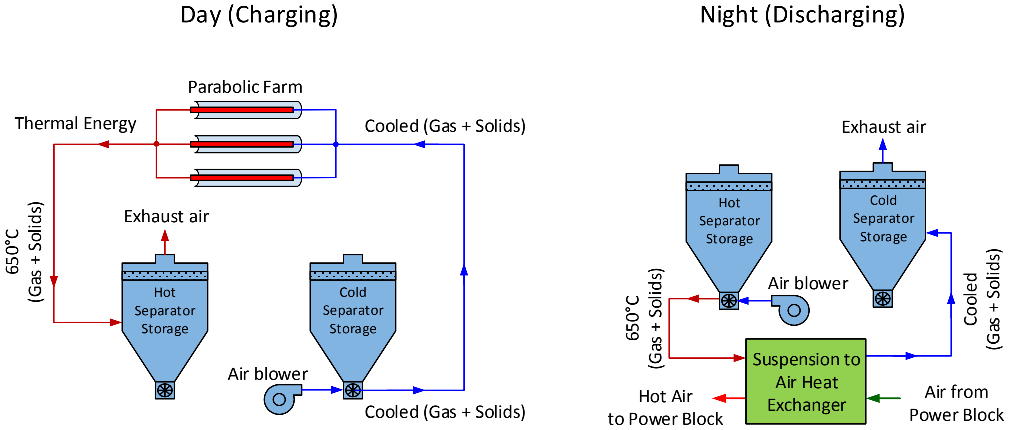


***Figure 3****. Particle media loop.*

## EXPERIMENTS AND RESULTS

A test platform was constructed at UC Merced to allow measurements of instantaneous incident solar irradiation, environmental temperature, solar-to-thermal efficiency with Therminol VP-1 fluid, and solar-to-electric efficiency of a 5 $m^2$ aperture area prototype. Figure 4 shows experimental thermal efficiency of the collector measured at a peak Direct Normal Irradiance of 700 $W/m^2$ for different Therminol temperatures at the receiver outlet. Thermal efficiencies of 35-38% approach the modeled results of 47%. Based on these results, the collector design is currently being modified to further improve its performance.

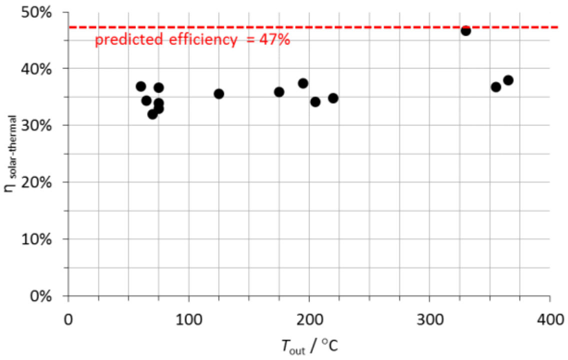


***Figure 4**. PV/T collector efficiency.*

In a parallel effort, air-alumina particle suspension was heated up to 650°C using electric heaters and then cooled to <30°C in a water-cooled heat exchanger for over 4000 cycles with no adverse pressure drop, flow rate, heat transfer or particle degradation impacts. These tests were carried out in a closed heating-cooling loop (¾-inch diameter stainless steel pipe) by loading it with known amounts of particles and using a positive displacement pump to circulate the suspension through the loop. As shown in Figure 5, the heat transfer coefficient for suspension at a particle to air weight ratio of 30 reached 15 times the value compared with air alone, irrespective of temperature from 400°C to 650°C.

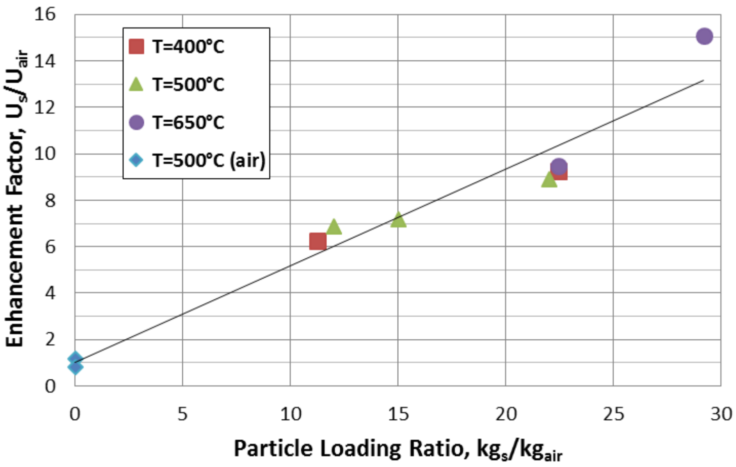


***Figure 5.** Particle media heat transfer enhancement.*

Currently the team is designing the collector to use MicroLink's InGaP/GaAs 2J ELO PV cells. Figure 6 shows preliminary characteristics of a prototype 2J ELO testbed cell (1 cm$^2$ area); data labeled "initial" and "final" represent light *I-V* behavior before and after exposure to 20x irradiance and 140°C heating in the dark for two hours. Although the PV cells will be operated on Sun at ~40°C, the cell here was heated to 140°C for two hours to simulate a bakeout condition to assure degassing as ultimately the PV cells will be operated under vacuum. Light *I-V* of the prototype PV cell was measured at room temperature under a simulated AM1.5G one Sun solar spectrum using a Newport solar simulator. The fill factor (*FF*) of the PV cell improved after heating at 140°C for two hours. This improvement may have been due to contact annealing as the metal contacts had not already been annealed prior to the 140°C heat test. For this preliminary heat test, the testbed cell discussed here was not optimized for efficiency (e.g. large bond pads and grid lines that obscured 21% of the cell area together with a suboptimal antireflection coating resulted in low current).

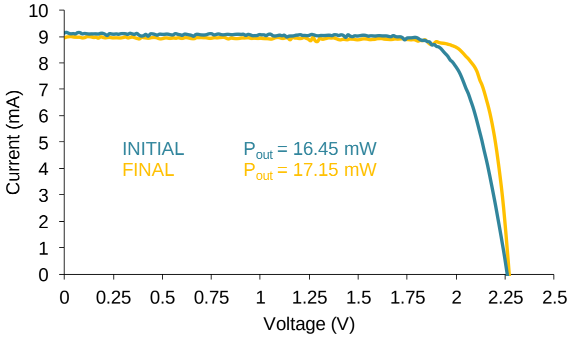


***Figure 6.****Light I-V data for an InGaP/GaAs 2J ELO PV cell before and after exposure to 20x irradiance and 140°C heating.*

## CONCLUSIONS

The full spectrum solar collector technology uses secondary optics in a solar receiver to achieve high efficiency at high temperature, collects heat in particles for high temperature and low fire danger, stores heat in particles instead of molten salt for low cost, and uses actively cooled InGaP/GaAs 2J ELO PV cells with backside IR reflectors on the secondary optical element to raise exergy efficiency. Current results show potential to achieve ≥600°C temperature and ≥40% exergy efficiency.

## ACKNOWLEDGEMENT

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