# Development of a Combined Concentrated Photovoltaic and Fluidic Thermal Extraction for Harnessing the Sun Energy – Undergraduate Research Experience

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## Abstract

Emerging technologies within the renewable energy sector have shown great potential for more efficiently harnessing energy from sun radiation. The concentrated photovoltaic (CPV) receivers allows conversion capabilities exceeding 40% efficiency [1], with one caveat; they must be operated within a temperature range of 100-180$^{o}$ C to maintain maximum efficiency. Currently, temperature is regulated through the use of aluminum heat sinks. While effective at dissipating heat, this dissipation represents a consider source of "wasted" energy. This research paper examined, by testing and analysis, additional gains in solar efficiency available through a combination of solar photovoltaic and solar thermal energy extraction. Our system design included the utilization of a parabolic reflector, CPV receivers, and fluidic thermal extraction mechanisms (along with their associated subsystems). A data acquisition system recorded information to analyze and determine efficiency capabilities based on the combination of current technologies. Currently, thermal extraction solar fields operate at 14-20% peak plant efficiency, and CPV solar fields operate at 30% peak plant efficiency [2]. Our innovative design successfully obtained a theoretical targeted combined efficiency of 45%, which theoretically allows solar energy levelized cost of electricity (LCOE) to be fiscally competitive with coal power plants [3]. Since target efficiencies have been met, this combined method of harnessing solar energy may potentially allow the maintenance of current consumer energy costs while drastically reducing greenhouse gas emissions.

## Introduction

Concentrator photovoltaics (CPV) is a photovoltaic technology that generates electricity from sunlight. CPV uses lenses and curved mirror to focus sunlight onto small, but highly efficient solar cells. CPV systems often use solar trackers and a cooling system to further increase their efficiency [4]. This system is intended for use in areas of high solar irradiation. This sort of solar technology can be thus used in smaller areas.

This investigation was intended to provide analytical data on the feasibility of extracting heat, a byproduct of current CPV systems, in effort to optimize solar efficiency levels, potentially allowing solar energy LCOE to be competitive with coal power plants. Prior to system development, several theoretical Combined Heat and Power Solar (CHAPS) concentrator systems were investigated for their respective energy potentials, ease of conversion and implementation, and overall costs. A parabolic-trough reflector design was ultimately selected given the above criteria. In order to optimize efficiency, appropriate tracking systems were evaluated, resulting in the conclusion that dual axis active tracking would provide the greatest overall efficiency within the scope of this research. Solar power extraction, through the use of CPVs, was selected based upon the availability of salvageable components. Thermal Extraction design was based upon acquired CPV dimensions, allowing for conversion techniques to be readily implemented, given the predefined design of salvage components. Final assembly of componentry also included a Raspberry Pi designed programmable data acquisition microcomputer implemented for accurate measurement recording and analysis. The resulting system efficiency met target estimated LCOE goals and, due to limited time constraints and resources, also reflected potential for further efficiency improvements.

## Experimental Procedures

The outline of this investigation begins with the selection process and descriptions of individual components associated with this study in items (A-E). The resultant data follows item (F), concluding with the examination of efficiency improvement potentials items (G) and figures and tables (H).

### *A. Parabolic Reflector*

Parabolic reflectors with a focal point of 0.5 to 0.6 times the diameter of the reflector provide the greatest efficiency in solar reflectivity [4]. The conceptual assembly was designed utilizing the parametric Computer Aided Design shown in Figure 1. After initial space constraints were determined, the system components could be optimized. The reflector selected for use in this experiment was a satellite-antenna-grade, cold-formed, mild steel elliptical parabolic dish. The minor diameter was 0.70 meters, while major diameter of 0.78 meters, and the focal point was 0.42 meters. Percent reflectivity on the parabolic dish is a critical component in solar concentration. Any loss in reflectivity relates a directly proportional loss in system efficiency due to the nature of the design. Mild steel has a relatively low reflectivity of approximately 60% [6], and therefore would not allow for the reflector to be a suitable candidate without surface improvements. Reflective coatings were evaluated for performance considerations and costs.

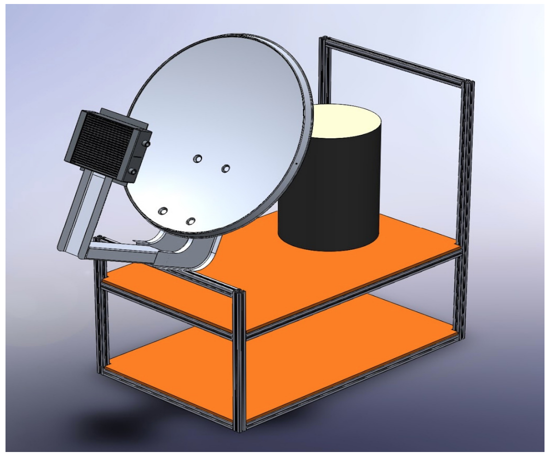
Figure 1: Initial Design

Since a considerable portion of LCOE in solar energy is contributed to manufacturing and maintenance costs, ultra-high reflectivity coatings such as silver or rhodium were relegated, opting instead for a metalized adhesive coating of approximately 90% reflectivity for experimentation purposes. The strips were applied horizontally, alternating initial layout from right -> left then left -> right in order to compensate for strip divergence due to the parabolic curvature of the dish. Starting from the center, outward, allowed for best judgment in aligning the strips with minimal overlap (thus, less waste.) Silver/aluminum surface finishing has been calculated as a more suitable process in large-scale and mass production manufacturing environments due to automated application possibilities and superior longevity [7] as compared with typical adhesive films, but was found to be fiscally prohibitive within the confounds of this research.

*B. Concentrated Photovoltaics*

While technological breakthroughs have advanced CPV technology over the past thirty years [8], the newest technology was not available able to be sourced from local manufactures "off-the-shelf." Fortunately we were able to locate cells of similar technology through a solar salvage company out of California, USA. The CPV we acquired was extracted from a Fresnel lens type solar panel, rated at approximately 2.5 watts under the 60 suns. By decreasing the distance between the CPV and the parabolic reflector, we were able to reduce the focusing power from approximately 900 suns to 100 suns, with a focal surface area large enough to accommodate 9 CPVs in a three-cell by three-cell square orientation. Initial testing of our cell reflected an increase in output from 2.5watts (rated) to 3.9 Watts, at approximately 100 suns.

Rated output: $2.5W = 57.6\Omega * 0.2083A\verb|^|2$

Performance (at 100 suns): $3.9W = 74.1\Omega * 0.2294A\verb|^|2$


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Power output was measured utilizing a variable power resistor rated for 50 watts (also known as a rheostat or potentiometer) along with a digital volt - ohmmeter (DVOM), and a clamp-style ammeter. Testing for a CPV's (And most solar panels in general) maximum power output requires finding the optimal load to current output. While under direct sunlight, resistance and current values were recorded while sliding the power resistor contacts back and forth, therefore varying the load. This method was repeated 5 times, averaging the highest values between each data set. Analysis of efficiency has been calculated at the recorded 3.9 Watts per CPV. Due to thermal constraints on the CPV's secondary culminating lens used in this experiment, we were unable to document long-term efficiency data at 100 suns. The culminating lens is constructed of a thermoplastic material, and quickly began reaching its glass transition temperature during testing, ultimately causing surface irregularities. Further investigation is needed to implement a more suitable optics set, or for additional cooling requirements for CPV optics when used under such environments.

### *C. Solar Energy Collector Design*

In order to mitigate risks of damaging the CPV cell which included an integrated aluminum fin-type heat sink, the solar energy collector design was based around the existing structure. Several design iterations were tested via computational fluid dynamics software prior to executing prototyping design. Considerations in the design included: relatively even distribution of flow over existing heat sink fins, low pressure loss, inlet and outlet orientation optimization, ease of manufacturing using common tooling, and cost of manufacturing.

The material utilized for construction was 3 mm Aluminum flat stock. The flat panel was initially cut to assume a proper forming shape with a vertical band saw, followed by appropriate bending via a metal brake. All external seems were TIG welded, an aluminum mounting tab fabricated, and all passageways were threaded prior to final assembly. Final assembly included mounting of the CPV cell with a waterproof epoxy, insertion of the inlet and outlet fittings, Cure time, and pressure testing to 620 kPa (90 PSI), before coating the assembly with a thermally absorbent paint [Figure 2]. Reference [8] indicated that Black Chrome plating may provide cost effective efficiency gains in large-scale production, but was found to be cost prohibitive in the current prototype.

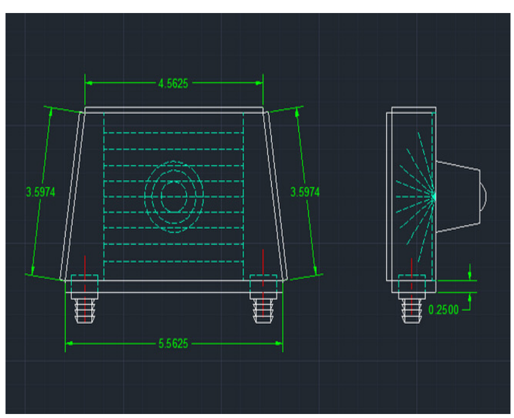


Figure 2: Heat Collector & CPV Assembly

*D. Dual Axis Active Tracking Design*

Inherent within the nature of a parabolic reflector design is the requirement to be precisely directed towards the point target source. The slightest deviation may have a profoundly adverse effect on efficiency [10], and may also be unsafe to the reflector system and personnel. In a solar parabolic reflector, as the culminated light shifts off axis from the collector apparatus, the focused beam, capable of exceeding 2000 $^{o}$C [11], may cause unsafe operating conditions. A dual axis Active Tracking system was designed in order to address efficiency and safety concerns. The mounting station, incorporating a north to south fulcrum and an axial pivot in east to west orientation, was designed using SolidWorks, in order to test the required characteristics through the software's modeling assembly feature. The tracking apparatus was constructed of gas tungsten ark welded (GTAW) steel, allowing approximately one-hundred-seventy degrees rotation from East to West, and ninety degrees of freedom from North to South. Two twelve inch linear actuators rated for two hundred pounds of force were installed, providing movement, one in each axis of rotation, to allow for precise orientation [Figure 3].

An Arduino Mega microcontroller was used for control, by mathematically implementing comparative analysis of voltage data from four Light Dependent Resistors (LDRs) that were oriented in each direction of freedom, located in front of the CPV heat-collector assembly. A six inch piece of extruded aluminum was modified using an end mill, allowing the directional light source from the sun to be isolated from one-another, allowing for comparative analysis accuracy to less than one degrees off axis during tracking.

Several fail-safes were integrated into the programming language, allowing for the system to "break contact" from the solar path in the event of a mechanical failure, including: Pump failure/ flow blockage, fluidic Over-temperature diversions, tracking system low voltage, Tracking system over-amperage, and tracking system linear actuator open circuit. In each of the preceding events, commands are sent to the motor control board initiating movement to the system's mechanical zero, beyond the eastern-most receptive area of the solar path.


Figure 3: Implemented Design

*E. Data Acquisition System*

Accurate data acquisition was paramount in the analyses of this CHAPS prototype system. A secondary objective of this investigation was to correlate comparative data with similarly sized solar cells and solar thermal trough collectors that were available to students at Tennessee Technological University for concurrent testing. Our Data Acquisition system was based off of a design by a previous senior design team who developed the solar thermal trough collector. A Raspberry Pi Model B+ Microcomputer, along with flow meters and temperature sensors, was programmed to record the necessary data to calculate system efficiency. In addition to data acquisition, a feedback loop was programmed to communicate additional information between the micro-controller and microcomputer. This analog correspondence allowed for the implementation of additional fail-safes, recording of only relevant event data, and greater system flexibility for future research.

## Project's Parts List and Cost Estimating

| System: | Item: | Item Description: | Cost per Unit: | Units required: | Total Cost: |
|---|---|---|---|---|---|
| Reflector Dish | | | $0 | 1 | $0 |
| | 1" Mylar Tape | Metalized Polymer reflective tape | $16 | 1 | $16 |
| | Aircraft Stripper | Aerosol Paint stripper | $8 | 1 | $24 |
| | | | | | $24 |
| Tracking - Mechanical | | | | | $24 |
| | 12" Linear Act. | 150lb Thrust, 12v, 12mm/sec. Set of 2 | $120 | 1 | $144 |
| | Swivel | Attwood Boat Seat Swivel, 0*, 6.25"x6.25" square | $8 | 1 | $152 |
| | 12V 6A PS | 12 volt 6 Amp Power Supply | $20 | 1 | $172 |
| | | | | | $172 |
| Tracking- Control | | | | | $172 |
| | Arduino | Mega R3 | $50 | 1 | $222 |
| | Photocells | Pack of 5 | $10 | 1 | $232 |
| | Monster Moto | High Amp DC Motor Controller | $70 | 1 | $302 |
| | 12V 1A PS | 12 volt, 1 Amp regulated power supply | $10 | 1 | $312 |
| | Arduino Header | Header Pins | $10 | 1 | $322 |
| | AMega Shield | Arduino Mega Shield Kit | $20 | 1 | $342 |
| | | | | | $342 |
| Solarthermal Collector | | | | | $322 |
| | CPV cell | 5.5MM concentrated CPV cell | $25 | 1 | $347 |
| | Water Fittings | 3/8" x 3/8" Barb fitting | $3.79 | 2 | $355 |
| | JB weld | Adhesive for Concentrated photovoteic cell | $5.28 | 1 | $360 |
| | 11ga. Aluminum | material for collector body | $15.00 | 1 | $375 |
| | Solar Panel | 15w solar panel | $0.00 | 1 | $375 |
| Thermal Storage | | | | | $375 |
| | Cooler | 5 gallon insulated Igloo Cooler | $25 | 1 | $400 |
| | Pump | 100GPH A/C Pump | $40 | 1 | $440 |
| | water lines | 1/2" PVC clear vinyl tubing | $7.49 | 1 | $447 |
| | pipe insulation | 1/2" Frost King Pipe Insulation 6' length | $0.97 | 2 | $449 |
| | clamps | 7/16"-29/32" OD adjustable stainless clamps | $1.68 | 2 | $453 |
| | high temp pump | 15w solar powered high temp pump | $75.00 | 1 | $527.63 |
| | | | | | |
| Estimated Labor Cost for Production | | Expected time for experienced employee | $20.00 | 20 | $927.63 |

## Results and Discussions

The preliminary data was collected over two consecutive days. Atmospheric conditions included an average ambient temperature of 16°C (62°F). Solar irradiance was approximated at an average of 1000 watts per square meter as indicated by exposure value conversions taken off of exposures from a calibrated 18% Gray Card.

Day 1 included complete prototype testing, tracking system debugging, system control measurements, and preliminary thermal extraction testing [Figure 4]. Day 2 involved raw sample collection of thermal extraction. Data was collected for a period of approximately 2.5 hours before the temperature exceeded the thermal operational limits of our water pump during testing on day 2 [Figure 5].

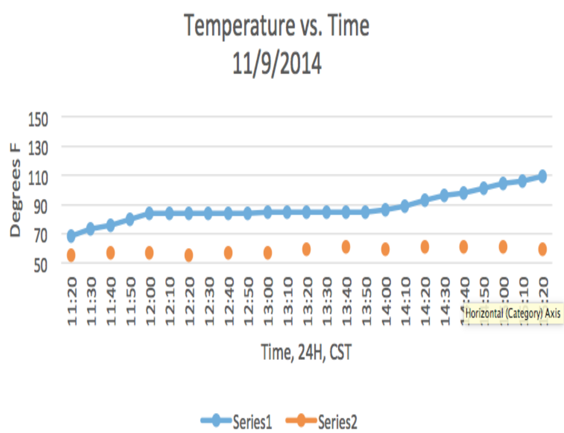


Figure 4: Day 1 Data Collection

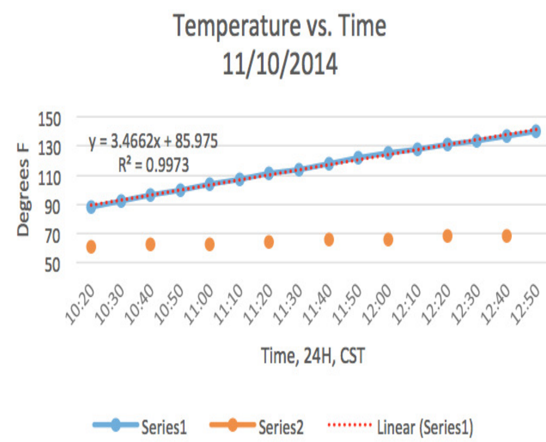


Figure 5: Day 2 Data Collection

The resulting data indicated a calculated thermal extraction of 246 Watts. The calculated CHAPS energy resulted in a combined output of 281.1 watts. System operational requirements, including dual axis tracking system and data acquisition system were approximately 30 Watts (Maximum recorded draw at 12 volts, regulated), resulting in a net combined extraction of 250 Watts over a surface area of approximately 0.5 square meters. This equated to a resultant 45.5 percent system efficiency, meeting target goals for LCOE in solar field applications.

## Conclusions

As a conclusion, this design did work very well under direct sun but not in cloudy days. The resulting system efficiency met target estimated LCOE goals and, due to limited time constraints and resources, also reflected potential for further efficiency improvements. This system will function very well in rural areas in the western states of the United States and other parts of the worlds with high sun radiations.  It can be used in applications such as solar water heaters, power generations, etc.

## Suggestions for Future Work

Greater extraction potentials may be realized with cost effective solutions provided the scale of manufacturing is increased. These potentials include silver plating of the parabolic trough reflector surface, black chrome plating of the heat collector, use of modern CPV cells, and higher rated insulation systems for thermal storage. Additional advancements may further enhance extraction potentials by redesigning the parabolic-trough reflector. A concurrent investigation into such potentials, utilizing Advanced Manufacturing techniques, was underway at time of this investigation [Figure 6]

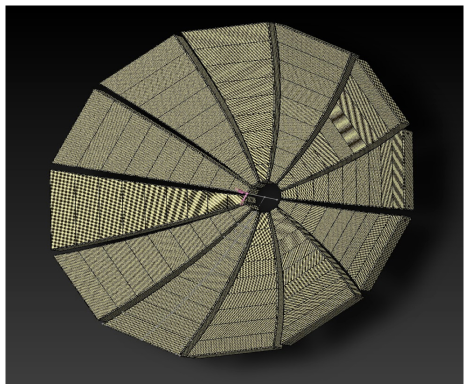

Figure 6: Advanced Manufacturing Parabolic Reflect

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## References

[1] S. Kurtz. (November 2012). Opportunities and Challenges for Development of Mature Concentrating Photovoltaic Power Industry. National Renewable Energy Laboratory. Golden, Colorado. [Online] Available: http://www.nrel.gov/docs/fy13osti/43208.pdf

[2] IRENA. (2012). Cost Analysis of Concentrating Solar Power -Renewable Energy Technologies: Cost Analysis Series. (pp. 10). [Online] Available: http://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-CSP.pdf

[3] USEIA. (April 2014). Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2014. [Online] Available: http://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf

[4] https://en.wikipedia.org/wiki/Concentrator_photovoltaics

[5] R. Dobson and G. Prinsloo. (2014) Solar Tracking. (pp. 235). [Online] Available: https://researchgate.net/publication/263128579_Solar_Tracking

[6] M. Ashby and K. Johnson. (2010). Materials and Design - The Art and Science of Material Selection in Product Design (2nd ed.) - Carbon Steels. (pp. 230).

[7] R. Smilgys and C. Kennedy. (2003) SVC - 46th Annual Technical Conference Proceedings - 102. Solar Reflective Material Produced Using a Laboratory-Scale Roll Coater. Society of Vacuum Coaters.

[8] S. Blazev. (2012). Photovoltaics for Commercial and Utilities Power Generation - 4.4 Concentrating PV (CPV) Technology. (pp. 118). Fairmont Press, Inc.

[9] M. Doryabegy, A.R. Mahmoodpoor. (2006) ISESCO Science and Technology Vision. (pp. 35).

[10] M. Geyer, and W. B. Stine. (2001). Power *from the Sun.* (1st ed.) (ch. 8) [Online]. Available: http://powerfromthesun.net/book.html

[11] M. F. Modest. (2013). Radiative Heat Transfer (3rd Edition) - 22.10 Radiation in Concentrating Solar Energy Systems. (pp. 760). Elsevier.

## Biographies

**Michael J. Kronland** graduated from Purdue University Calumet with an Associate's Degree in Industrial Engineering Technology and a BS in Engineering Technology from Tennessee Technological University on May 2014. His employment experience included positions at Marco Pipe & Supply Co., Industrial Valco, Swift Saw & Tool Supply Co., and Fastenal. His special field of interest included Inventory Management. He can be reached at Michaelj.kronland@gmail.com.

**Nicholas B. Leak** is a Manufacturing Engineer at Aphena Pharma Solutions, Inc. since December 2015. Nick was born in Port Charlotte, Florida, USA, on November 11, 1986. He served six years in the United States Army, and afterwards began pursuing a Bachelor's Degree in Engineering Technology at Tennessee Technological University. His employment experience included positions at Component Roadsters Development LLC, Southeastern Auto Sales LLC, and Oak Ridge National Laboratory, USA. His special fields of interest include additive manufacturing and parametric modeling. Leak received an Iraq Campaign Medal with 2 Campaign Stars, An Army Commendation Medal, and several Army Achievement medals while in service to the United States Army. He graduated with BS in

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**Joseph E. Randall** graduated from Northeast State Community College with Associate's Degrees in Machine Tooling and Metal Fabrication. After graduating from an apprenticeship at Eastman Chemical Company he attended Tennessee Technological University and received a BS degree in Engineering Technology on May 2014. He works for Eastman Chemical Company and can be reached at jerandall42@students.tntech.edu

**Cory D. Womack** after graduating from high school in 2009, he attended Tennessee Technological University to pursue a Bachelor's Degree in Manufacturing Engineering. Womack achieved the rank of Eagle Scout in 2008, and collaborated on various projects during his time at Tennessee Technological University. He graduated from Tennessee Tech University with a Bachelor Degree in Engineering Technology on May 2014.

**Dr. Ahmed ElSawy** joined Tennessee Technological University (TTU) as a Professor and Chairperson, Department of Manufacturing and Industrial Technology in July 1999. Prior joining TTU, he was a professor and graduate program coordinator in the Department of Industrial Technology at the University of Northern Iowa. Before that, Dr. Elsawy founded a Manufacturing Engineering Program at St. Cloud State University in Minnesota. He served as a full professor at the Department of Mechanical Design and Production in Cairo University till 2006. Dr. ElSawy teaching and research interests are in the areas of material processing, metallurgy, manufacturing systems, recycling and reuse of solid waste materials and renewable energy. Dr. ElSawy received ~ $2M of state, federal, and industrial grants in support of his laboratory development and research activities. He advised several masters and doctoral students who are holding academic and industrial positions in the USA, Germany and Taiwan. Dr. ElSawy has numerous publications in national and international conferences and refereed journals.