Design, Construction and Operation of CSP Solar Thermal Power Plants in Florida

FINAL REPORT

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Executive Summary
Florida utilities are mandated to achieve 20% renewable energy contribution to their generation mix by 2020. While technologically feasible with solar energy, the capital costs are still high. This project targets the development of solar thermal power technology for bulk power and distributed generation, which will diversify energy resources in Florida and reduce greenhouse emissions by utilizing renewable sources. Also, there will be economic impacts with the establishment of a new power industry in Florida, which will help the electrical utilities of the state to meet the renewable portfolio standards. The project has three main tasks; the first one is to develop design methodologies for the proven solar thermal power technologies based on Florida conditions and resources. Secondly, the project aims to set up demonstration and test facilities for these technologies for optimization for Florida conditions, and the final task is to develop and commercialize innovative technologies of solar thermal power.

The main research objectives are the development of a test facility and a pilot demonstration solar thermal power system based on the parabolic trough technology.

Parabolic Trough Concentrators
The performance of parabolic trough based solar power plants over the last 25 years has proven that this technology is an excellent alternative for the commercial power industry. Compared to conventional power plants, parabolic trough solar power plants produce significantly lower levels of carbon dioxide, although additional research is required to bring the cost of concentrator solar plants to a competitive level. The cost reduction is focused on three areas: thermodynamic efficiency improvements by research and development, scaling up of the unit size, and mass production of the components and equipment. The optimum design, performance simulation and cost analysis of the parabolic trough solar plants are essential for the successful implementation of this technology. A detailed solar power plant simulation and analysis of its components is needed for the design of parabolic trough solar systems which is the subject of this research.

A preliminary analysis was carried out by complex models of the solar field components. These components were then integrated into the system whose performance is simulated to emulate real operating conditions. Sensitivity analysis was conducted to get the optimum conditions and minimum levelized cost of electricity (LCOE). A simplified methodology was then developed based on correlations obtained from the detailed component simulations.

A comprehensive numerical simulation of a parabolic trough solar power plant was developed, focusing primarily on obtaining a preliminary optimum design through the simplified methodology developed in this research. The proposed methodology is used to obtain optimum parameters and conditions such as: solar field size, operating conditions, parasitic losses, initial investment and LCOE. The methodology is also used to evaluate different scenarios and conditions of operation.

The new methodology was implemented for a parabolic trough solar power plant for two cities: Tampa and Daggett. The results obtained for the proposed methodology were compared to another physical model

(System Advisor Model, SAM) and a good agreement was achieved, thus showing that this methodology is suitable for any location.

Power Cycles for Solar Thermal Power

Low-grade heat sources below 300ºC, are abundantly available as industrial waste heat, solar thermal using low cost solar concentrators, and geothermal, to name a few. However, they are under-exploited for conversion to power because of the low efficiency of conversion. The utilization of low-grade heat is advantageous for many reasons. Technologies that allow the efficient conversion of low-grade heat into mechanical or electrical power are very important to develop. Supercritical Rankine cycles were investigated for the conversion of low-grade heat into power. The performance of these cycles was studied using ChemCAD linked with customized excel macros written in Visual Basic and programs written in C++.

The selection of working fluids for a supercritical Rankine cycle is of key importance. A rigorous investigation into the potential working fluids was carried out, and more than 30 substances were screened out from all the available fluid candidates. Zeotropic mixtures were proposed to be used in supercritical Rankine cycles to improve the system efficiency. Supercritical Rankine cycles and organic Rankine cycles with pure working fluids as well as zeotropic mixtures were optimized for efficient conversion of low-grade heat into power. The results show that it is theoretically possible to extract and convert more energy from such heat sources using the cycle developed in this research than the conventional organic Rankine cycles. A theory on the selection of appropriate working fluids for different heat source and heat sink profiles was developed to customize and maximize the thermodynamic cycle performance.

The outcomes of this research will eventually contribute to the utilization of low-grade waste heat more efficiently.

Combined Power/Cooling Cycle

Binary mixtures exhibit variable boiling temperatures during the boiling process, which leads to a good thermal match between the heating fluid and working fluid for efficient heat source utilization. This study presents a theoretical and an experimental analysis of a combined power/cooling cycle, which combines the Rankine power cycle and the absorption refrigeration cycle to produce power and refrigeration in the same cycle, while power is the primary goal. This cycle, also known as the *Goswami Cycle*, can be used as a bottoming cycle to utilize the waste heat from a conventional power cycle or as an independent cycle using low to mid-temperature sources such as geothermal and solar energy. A thermodynamic analysis of power and cooling cogeneration was conducted. The performance of the cycle for a range of boiler pressures, ammonia concentrations, and isentropic turbine efficiencies were studied to find out the sensitivities of network, amount of cooling and effective efficiencies. The thermodynamic analysis covered a broad range of boiler temperatures, from 85 °C to 350 °C. The first law efficiencies of 25-31% are achievable with the boiler temperatures of 250-350 °C. The cycle can operate at an effective exergy efficiency of 60-68% with the boiler temperature range of 200-350 °C. An experimental study was conducted to verify the predicted trends and to test the performance of a scroll type expander. The experimental results of vapor production were verified by the expected trends to some degree, due to heat transfer losses in the separator vessel. The scroll expander isentropic efficiency was between 30-50%, the expander performed better when the vapor was superheated. The small scale of the experimental cycle affected the testing conditions and cycle outputs. This cycle can be designed and scaled from a kilowatt to megawatt systems. Utilization of low temperature sources and heat recovery is definitely an active step in improving the overall energy conversion efficiency and decreasing the capital cost of energy per unit.

Another combined cycle developed in this project can produce both power and desalinated water in the same thermodynamic cycle. This cycle uses a supercritical Rankine cycle from which heat is rejected into the seawater which in turn gets pre-heated before being desalinated in a Reverse Osmosis (RO) system. The power produced in the cycle is used to run the RO system. Preheating the seawater not only makes use of the heat that would normally be wasted, it also reduces the power requirements of the RO system.

Installation and Operation of 50kWe Solar Power Plant

Sopogy Inc. Honolulu, Hawaii was the main contractor for the installation and operation of a 50 kWe Solar Power Plant at USF. Parabolic collectors (Soponova 4.0) were received from Sopogy and were assembled. A power block for generating electricity from GulfCoast Green Energy was also received and installed. The power block is a Green Machine Elite 4000 manufactured by Electratherm. This machine will produce about 50kWh electricity from the thermal energy produced by the solar field that consists of 199 Soponova 4.0 parabolic concentrators from Sopogy, Inc. The installation and commissioning of the solar field and the Electratherm power generating unit is complete.

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1. Summary

The main research objectives for the project are the development of a test facility and pilot demonstration solar thermal power system based on the parabolic trough technology.

This project consists of 4 different tasks.
Task 1: Development of a simulation and design methodology for parabolic trough technology.
Task 2: Development of a test facility and pilot demonstration.
Task 3. Installation and Operation of 50kWe Solar Power Plant.
Task 4: Thermal Energy Storage.

The design and installation of the solar field and the 50 kW power block have been completed. The Soponova 4.0 (Sopogy Inc.) parabolic trough collectors have been used in the solar field designed to provide 430 W/m^2 of thermal energy after losses. The power block that will convert the thermal energy to electricity is based on the Organic Rankine Cycle (ORC). This power block has a nominal capacity of 50 kW$_e$. The power block uses a dry cooled condenser, which demonstrates the operation of a CSP power plant without the use of water. This is an important development as we try to reduce water consumption in solar thermal power.

A thermal energy storage system has been developed based on encapsulated phase change materials. This system can be used at this solar thermal power plant as well as any other solar thermal power plant. This development has reduced the cost of thermal energy storage from the present estimated \$45/kWh$_{th}$ down to \$15/kWh$_{th}$.

2. Goals and Objectives

The main research objectives of the project are:

1. Development of a test facility for various components of a parabolic trough based solar thermal power plant, including thermal energy storage, power block and dry cooling.
2. Design and construction of a pilot demonstration solar thermal power plant based on the parabolic trough technology.

3. Project Activities

Task 1: Development of simulation and design methodology for parabolic trough
The objective of task one is to develop a simulation and design methodology for the parabolic trough and parabolic dish based technologies for Florida conditions.

The daily integration (DI) approach was used to obtain the average direct normal solar radiation for the location of the pilot demonstration solar plant (USF, Tampa, FL.). The direct normal solar radiation obtained for Tampa is shown in Fig. 1. The annual average for this location is 4.6 kWh/m^2-day. These solar radiation values and the solar shading analysis for the solar collector rows were used for the solar field calculation.

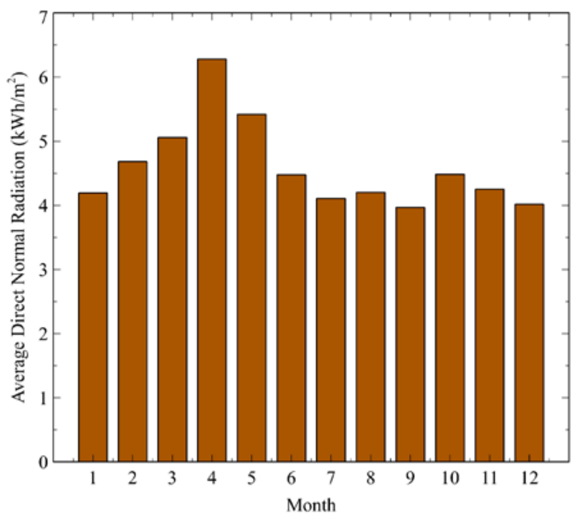

Fig. 1 Direct Normal Radiation for Tampa, FL.

Parabolic trough solar systems are currently one of the most mature and prominent applications of solar energy for the production of electricity. Compared to conventional power plants, parabolic trough solar power plants produce significantly lower levels of emissions and carbon dioxide. Thermal simulations and cost analysis of the system are used to evaluate the economic feasibility. Complex models and components are integrated to emulate real operating conditions, such as: Solar Radiation Model, Solar Thermal Collector, Thermal Energy Storage, Solar Field Piping, Power Block, Cost Analysis, and Integration of all Systems. Fig 2 shows the schematic of a parabolic trough power plant.

An hourly solar radiation model is necessary to calculate the energy input that comes from the sun, since the solar collector performance changes during the whole day. The inputs for the hourly solar radiation model are the long term average values of total horizontal and diffuse radiation, which can be obtained by ground or satellite measurements. Satellite data provide information about solar radiation and meteorological conditions in locations where ground measurement data are not available. Gueymard developed a Daily integration approach model to predict the monthly-average hourly global irradiation by using a large data set of 135 stations with diverse geographic locations (82.58N to 67.68S) and climates. The results showed that the daily integration model is more accurate than other hourly models.

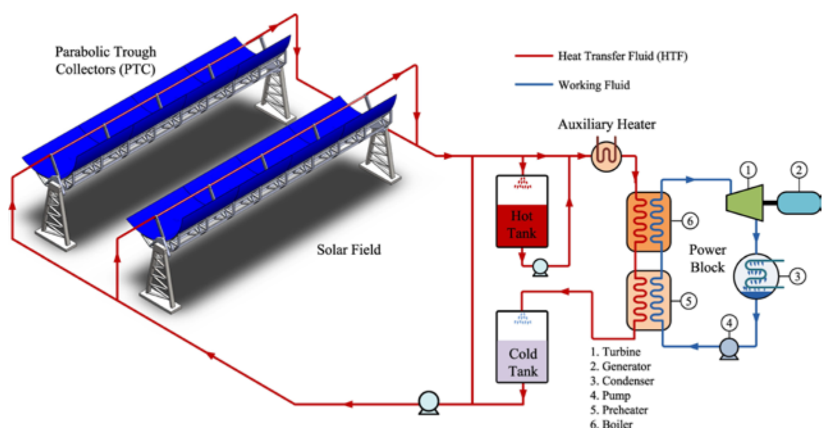

Fig. 2 Parabolic Trough Power Plant

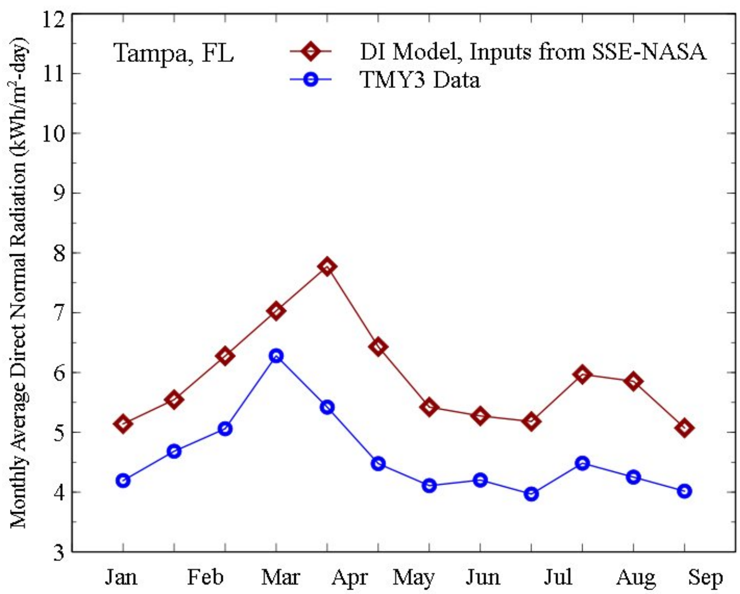

Fig. 3 Comparison of two models

The second part of this task is about the numerical heat transfer model. The receiver consists of an absorber surrounded by a glass envelope. The absorber is typically a stainless steel tube with a selective absorber surface. The glass envelope is an antireflective evacuated glass tube which protects the absorber from degradation and reduces heat losses. The Solar receiver uses conventional glass to metal seals and bellows to achieve the necessary vacuum enclosure and for thermal expansion.

The heat transfer model is based on an energy balance between the heat transfer fluid and the surroundings (atmosphere and sky). A comprehensive radiation exchange model between the absorber and the envelope is included in this study. The results showed that the new model has lower RMSE than the NREL Model (0.985% and 1.382%, respectively). The numerical heat transfer model integrated with the solar radiation model can be used for evaluating the performance of solar collectors for any location.

Task 2: Development of a test facility and pilot demonstration

The second task targets the development of a test facility and pilot demonstration systems based on parabolic trough technologies. The experimental combined power and cooling setup will be used as a preliminary study of the demonstration system that will be developed.

2.1 Performance analysis of a Rankine-Goswami Combined Cycle

Improving the efficiency of thermodynamic cycles plays a fundamental role for the development of solar power plants. These plants work normally with Rankine cycles which present some disadvantages due to the thermodynamic behavior of steam at low pressures. These disadvantages can be reduced by introducing alternatives such as combined cycles which combine the best features of each cycle. In the present study a combined Rankine-Goswami cycle is proposed and a thermodynamic analysis is conducted. The Goswami cycle, used as a bottoming cycle, uses ammonia-water mixture as the working fluid and produces power and refrigeration while power is the primary goal. The experimental Goswami cycle setup is shown in Fig. 4. Figure 5 shows a schematic of the Rankine-Goswami cycle.

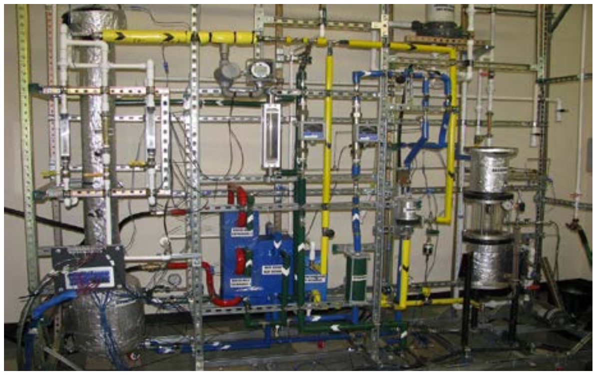

Fig. 4 Experimental Setup of the Goswami Cycle

Parametric studies were conducted for the following cases.

Case	Rectifier	Superheater	Controlled Parameter
R	Yes	No	$x_{rectifier} = 0.995$ $T_{superheater} = T_{rectifier}$
R+S	Yes	Yes	$x_{rectifier} = 0.98$ $T_{superheater} = T_{boiler}$
B (Base)	No	No	Saturated vapor condition at the boiler exit

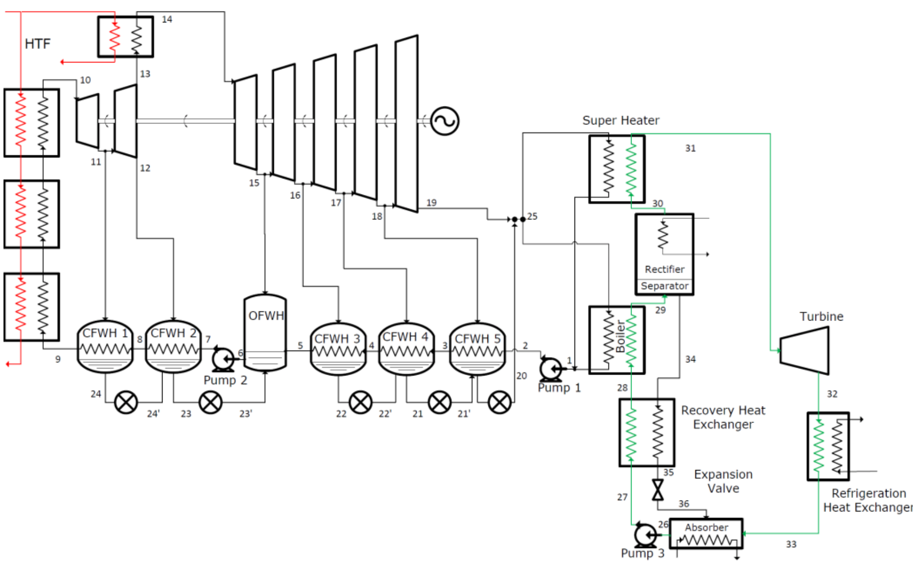

Fig.5 A schematic of a combined Rankine-Goswami thermodynamic cycle

The thermodynamic properties of water and steam were implemented in Python 2.6 by using the international-standard IAPWS-IF97 steam tables. For the Goswami cycle, the properties of ammonia water were obtained from a Gibbs free energy formulation given by Xu and Goswami. In this study the amount of the electric work obtained from the topping cycle was held constant at 50 MWe while for the bottoming cycle the turbine work was considered as an output parameter. Only selected results of the energy efficiency, cooling capacity and the exergy efficiency are given here.

Figure 6 shows the effective First Law efficiency while the cooling capacity of the Goswami bottoming cycle is presented in Figure 7. The effective exergy efficiency in the cycle as a function of the condenser pressure and ammonia mass fraction is also presented in Figure8.

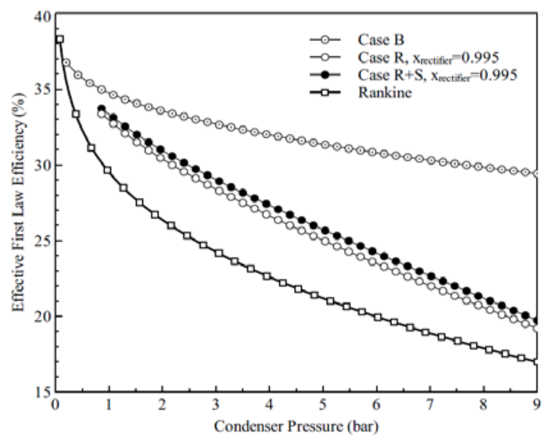

Figure 6 Energy efficiency of the combined cycle

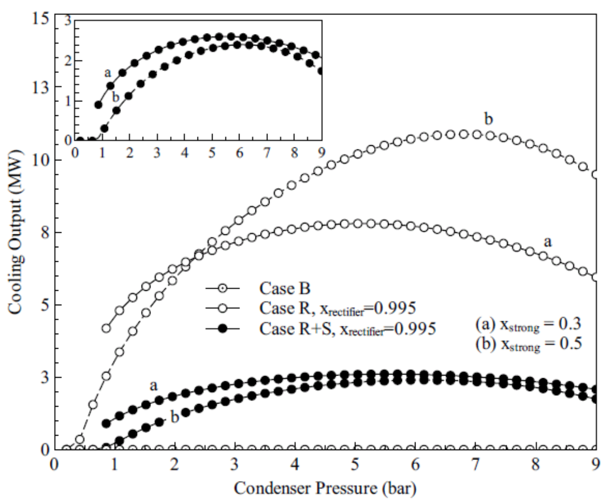

Figure 7 Cooling capacity of the bottoming Goswami cycle

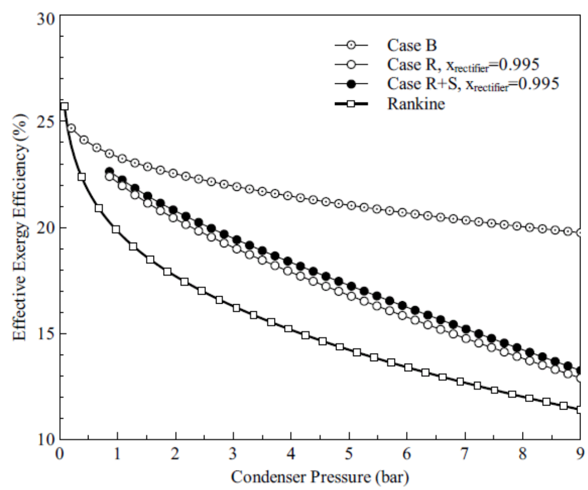

Figure 8 Exergy efficiency of the combined cycle

Task 3. Installation and Operation of 50kWe Solar Power Plant

Sopogy Inc. Honolulu, Hawaii was the main contractor for the installation and operation of the 50kWe Solar Power Plant at USF (Figure 9). Parabolic collectors (Soponova 4.0) were received from Sopogy and were assembled. The power block for generating electricity was receive from and installed by GulfCoast Green Energy. The power block is a Green Machine Elite 4000 manufactured by Electratherm. This machine will produce about 50kWh electricity from the thermal energy produced by the solar field that has 199 Soponova 4.0 parabolic concentrators from Sopogy, Inc. Figures 10 to 14 show various parts of the CSP solar power plant. Figure 10 shows the photo of the Electratherm power generator with the air-cooled condenser. Installation and commissioning of the solar field is complete. Installation and commissioning of the Electratherm power generating unit is also complete.

Figure 9. A view of the parabolic trough solar thermal power plant.

Figure 10 The Power block with the air-cooled condenser.

Figure 11 Solar collectors showing the header connections.

Figure 12 A row of parabolic trough solar collectors.

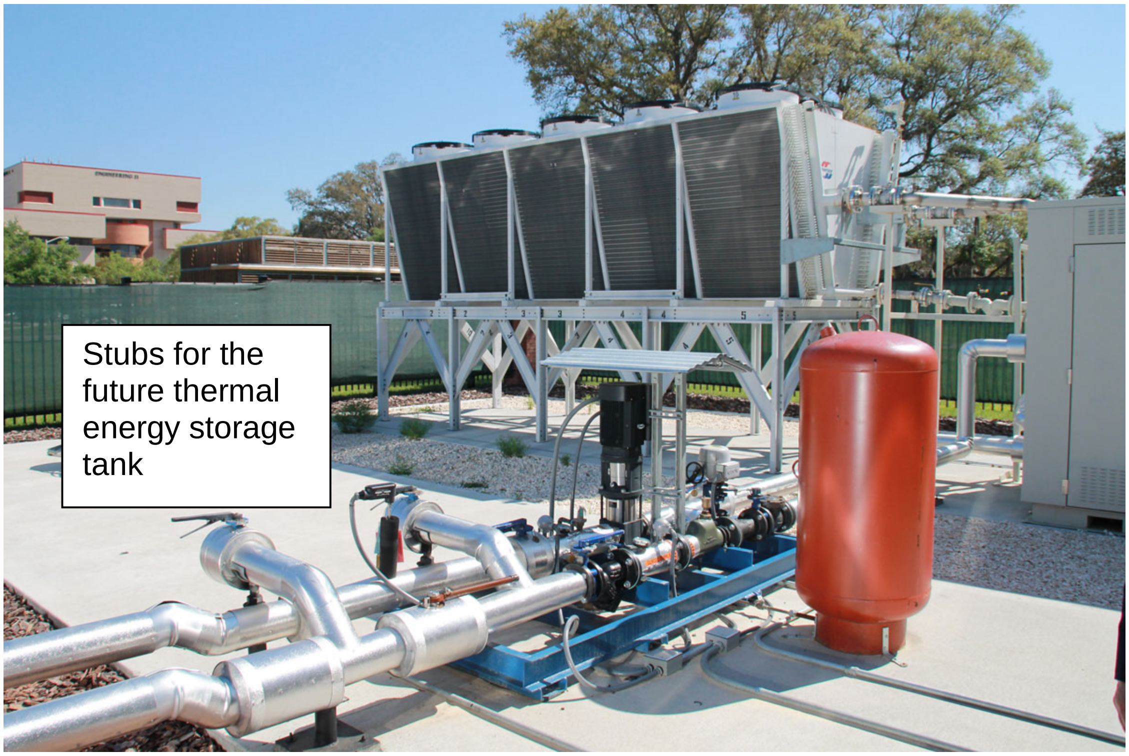

Figure 13 Expansion tank and pump for the heat transfer fluid.

Figure 14 Pump, piping and expansion tank for the heat transfer fluid flow to and from the collector field.

Task 4: Thermal Energy Storage

We have developed a low cost thermal energy storage (TES) system for Concentrating Solar Power (CSP) based on encapsulated phase change materials (PCMs). The system will be able to meet the utility-scale base-load concentrated solar power plant requirements at much lower system costs compared to the existing TES concepts. This project is developing a TES system concept that will allow for an increase of the capacity factor of the present CSP technologies to as much as 75% and reduce the cost to less than \$15/kWh$_{th}$ as compared to the present cost of about \$45/kWh$_{th}$.

We have successfully prepared porous pellets of phase change materials that will allow for the volumetric expansion during PCM melting and hence impose less stress on the encapsulating material. We have also developed the encapsulation techniques and selected the low cost encapsulating materials that will be used to encapsulate the PCM. The following pictures show some of the developed capsules.

Figure 15 Ceramic encapsulated PCM for high temperature thermal energy storage

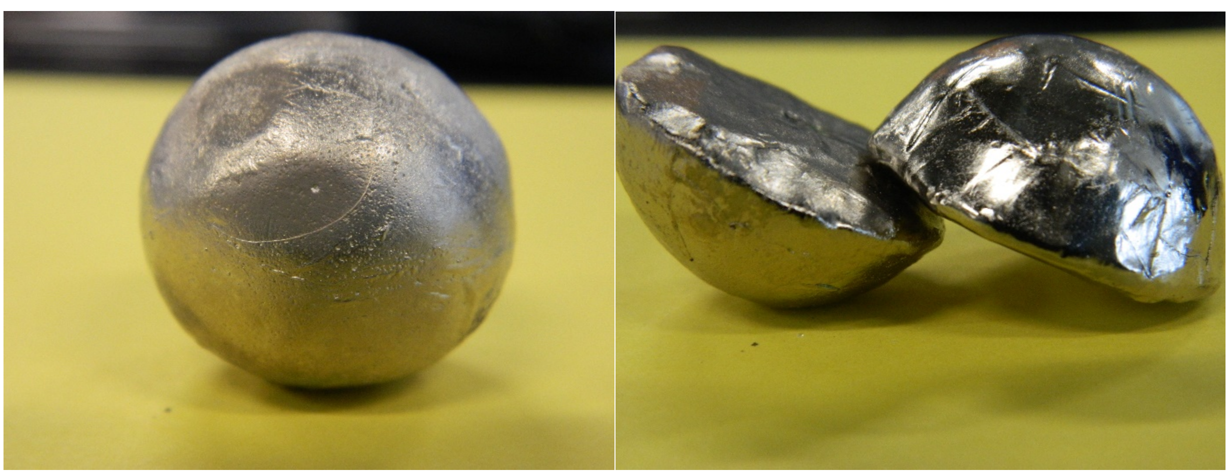

Figure 16 Metal encapsulated PCM for medium temperature thermal energy storage

4. Results and Accomplishments

This FESC funded research has resulted in the development of a test facility and pilot scale demonstration solar thermal power plant based on parabolic trough technology. The nominal capacity of this facility is $50kW_e$. The electric power from this facility will be supplied to the IDR building or to the TECO grid. This test facility will be used to demonstrate the innovative technologies based on new thermodynamic cycles, thermal energy storage and dry cooling. This project will provide a unique opportunity to students for a hands on experience in the real world application of operating a power generating system with solar heat source. Students will be involved in the daily operation of the system and analysis of the data obtained from the system.

5. Concluding Remarks- This project will have a significant impact on the current research areas of thermal energy storage, thermodynamic cycles and dry cooling. This is a unique facility to provide hands on experience to students interested in real world solar applications.

6. Patents

Title	Application Number	Application Date	Patent Number	Grant Date
Dual-Polarized Feed Antenna Apparatus and Method of Use	11/534,781	9/25/2006	7,362,273	4/22/2008
Dual-Polarized Feed Antenna Apparatus and Method of Use	12/107,122	4/22/2008	7,619,570	11/17/2009
Practical Method of CO2 Sequestration	12/335,049	12/15/2008	7,896,953	3/1/2011
Hydrogen-Storing Hydride Complexes	12/407,116	3/19/2009	8,153,020	4/10/2012
Method of Generating Hydrogen-Storing Hydride Complexes	13/422,600	3/16/2012	8,440,100	5/14/2013
Rectenna Solar Energy Harvester	12/436,601	5/6/2009	8,115,683	2/14/2012
Method and System For Generating Power From Low- and Mid-Temperature Heat Sources	13/591,792	8/22/2012		
Systems and Methods for Thermal Energy Storage	13/665,389	10/31/2012		
Integrated Cascading Cycle Solar Thermal Plants	13/665,270	10/31/2012		
Systems and Methods for Desalinization and Power Generation	PCT/US13/55325	8/16/2013		
Thermal Energy Storage Systems and Methods	13/756,098	1/31/2013		

Method of Encapsulating a Phase Change Material with a Metal Oxide	14/159,874	1/21/2014
Low-Cost Chromatic Devices	PCT/US13/68998	11/7/2013
Encapsulation of Thermal Energy Storage Media	PCT/US13/75971	12/18/2013
Enhancement of Photocatalytic Effect with Surface Roughness in Photocatalytic Reactors	14/511,970	10/10/2014
Encapsulation of Thermal Energy Storage Media	62/012,633	6/16/2014

7. Publications

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3. Besarati, S.M., and Goswami, D.Y. (2014) "Analysis of advanced supercritical carbon dioxide power cycles with a bottoming cycle for concentrating solar power applications," *Journal of Solar energy Engineering*, February, Vol. 136, pp 010904-1-7.

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