FESC
Florida Energy Systems Consortium

University of South Florida

Power Generation Expansion under a CO_2 Cap-and-Trade Program

PI: Tapas Das, USF; **Co-PI:** Ralph Fehr, USF
Students: Patricio Rocha (Ph. D. Candidate), Ehsan Salimi (Ph. D. Student). Industrial and Management Systems Engineering Department

Description: The objectives of the proposed research are to 1) develop a comprehensive generation technology based portfolio optimization (GTPO) model and its solution algorithm, and 2) develop educational resources to enhance training of scientific workforce for the state of Florida. The research will directly address three major challenges: fulfillment of the growing power demand, meeting the emissions targets, and supply of technology workforce. The potential economic impact of the proposed research on the State of Florida is expected to be very high, since an energy-secure environment is a basic necessity to support the current trend of explosive growth both in industry and human resources.

Budget: $71,906

Universities: USF

External Collaborators: Argonne National Lab

Progress Summary

During the last year the efforts of the research team have been focused on developing a generation capacity expansion model that incorporates the implications of the implementation of a CO2 cap-and-trade program in the U.S. A CO2 cap-and-trade program will change the way generators make capacity expansion decisions, especially if the allowances (or pollution permits) created with the program are distributed via auction (as opposed to be given away for free based on historical emissions). In fact, the profitability of a particular expansion plan is measured by adding the profits obtained by the generator in the allowance and electricity markets. Furthermore, the generators' bids and profits in the electricity market are directly impacted by the additional cost generators incur in purchasing allowances.

To model the interaction between the expansion decisions made by generators and the decisions they make in the allowances and electricity markets we develop a game theoretic model whose objective is to find the equilibrium expansion plan, CO2 allowances bidding strategy, and electricity bidding strategy for each generator in a particular power network.
In general, each generator $\boldsymbol{i}$ maximizes the profitability of a expansion plan $\boldsymbol{x_i}$, which is a function of the decisions made by the generators in the allowances and electricity markets ($\boldsymbol{y_i}$ and $\boldsymbol{z_i}$, respectively), while taking into consideration the actions of the other generators ($\boldsymbol{x_{-i}}, \boldsymbol{y_{-i}}, \boldsymbol{z_{-i}}$).

We have developed a solution algorithm for the game theoretic model that is included in an upcoming paper that we intend to submit to a peer-reviewed journal. In the paper, we also include an application of the game theoretic model to the Illinois electricity market. Our collaboration with Argonne National Laboratory has allowed us to have access to a significant amount of data on the operation of the electricity market in Illinois. Using the market data, we were able to develop a version of the Illinois power network, which we then assumed to be working under a cap-and-trade program similar to the Regional Greenhouse

Gas Initiative. We then applied our methodology considering different choices of expansion plans for the generators in the network. We present the results in the upcoming paper.

Besides the upcoming submission of this paper, the research team has presented the work at the IIE Conference and the INFORMS Annual Meeting.
The team has also made strides on topics that are directly connected with this research, namely, how to redistribute (among market participants) the revenue collected from the auction of allowances.

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Introduction

According to the EIA (2009), electricity demand in the U.S. is expected to increase at an average rate of 1.1 % per year from 3,659 billion KWH in 2006 to 4,705 billion in 2030. Electricity generators throughout the country are faced with the challenge of determining when, where, and what type of capacity to add in order to increase their market share. System operators, on the other hand, face the challenge of ensuring that installed capacity adequately meets this projected demand growth.

In recent years, power markets have been subjected to new environmental regulations. In 1990, the Environmental Protection Agency in the U.S. introduced a federal market-based initiative to reduce the levels of SO2 and NOx emitted by power plants. The current environmental debate is centered around implementing similar market-based programs to reduce the level of CO2 in the atmosphere. Since electricity generators are responsible for about 40% of the CO2 emissions in the U.S. (Stavins, 2007), any program aimed at reducing CO2 emissions will have a significant impact on the power generation sector. In fact, if an emissions control program is to achieve its goals, there will have to be a shift from the current fossil-fuel technologies to nuclear power and renewable sources. Thus, power generators need to assess the potential implications of a CO2 emissions control plan when making generation expansion decisions. The most commonly discussed federal measures to control CO2 emissions are: a carbon tax, and a CO2 cap-and-trade program. Thus far, the only CO2 emissions control program implemented in the U.S. is the Regional Greenhouse Gas Initiative (RGGI), which is a cap-and-trade program. In this research, we develop a game theoretic model to obtain capacity expansion plans for generators in a restructured market under a CO2 cap-and-trade program.

A CO2 cap-and-trade program will establish a cap in the total quantity of CO2 emissions allowed in a geographic region. A certain number of pollution permits or allowances (consistent with the cap) will then be issued. Fossil fuel generators will need to procure a sufficient number of allowances in order to produce electricity and avoid costly penalties. Allowances can be traded among the market participants. This general framework is common to all CO2 cap-and-trade programs that are either already implemented or are being considered. Albeit the common framework, the programs may differ as to how they treat various design attributes including stringency of the cap, upstream or downstream point of regulation, method of allowance distribution (sold via auction, free grandfathering, or a combination of both), and banking of allowances. The choice of these attributes continues to be a source of debate among the policymakers. The capacity expansion model developed in this research provides an effective instrument for policymakers to assess choice alternatives.

Our approach is different from what is presented in the literature in that we consider a discrete set of feasible expansion plans for each generator, for a time horizon and a forecasted growth in demand. The expansion plans take into account the constraints of capital availability, network location, lead time, and

technology. We assess the financial performance of these plans by assuming that all generators implement their plans simultaneously at the beginning of the time horizon (i.e., no leader-follower dynamics is present). This assessment is based on the outcome of the competition between the generators in both the electricity market and the CO2 allowances market. The competition in the electricity market is modeled for smaller segments of the time horizon (e.g., a year), assuming that each generator has a discrete set of supply function bids that is consistent with its mix of available capacity and technology. We consider transmission constraints and resulting congestion to accurately assess the performance of each of the expansion plans.
The CO2 allowances market is also modeled for suitable segments of the time horizon assuming that generators have a discrete set of allowance bids comprising price and quantity. The set of allowance bids is consistent with the mix of available capacity and technology. As in Linares et al. (2008), allowance prices are determined endogenously by our model. Our approach considers discrete sets of expansion plans and supply function bids as in Nanduri et al. (2008). However, we also model the competition among the generators in the allowance market. Additionally, we consider a multi-year time horizon with construction lead times for new plants.

To summarize, in this research we develop a game theoretic model for capacity expansion in restructured electricity markets that incorporates CO2 emissions trading. We consider transmission constraints and the effect of congestion in the electricity market. The model allows for the consideration different design attributes of the CO2 cap-and-trade program. The expansion plans derived from our model provide information regarding capacity, location, technology, and the time of expansion. The model is intended to be used by the generators to obtain expansion plans under different CO2 cap-and-trade programs for a given time horizon and a given forecast in demand growth.

Game Theoretic Model

We consider a network with N nodes, T transmission lines and n suppliers. Each supplier owns an array of plants at different nodes in the network. Suppliers are not restricted to the use of only one technology. We assume that there is a demand forecast for the network, similar to the forecasts issued by the Energy Information Administration (EIA). We denote the length of the forecast horizon as H. The forecasted demand growth is assumed to be linear and is applied homogeneously to all the demand nodes in the network. We assume that the region served by the power network operates under a CO2 cap-and-trade program and the generators are required to obtain allowances in order to produce electricity. These allowances are allocated via auction for which the generators bid with price and quantity. It is assumed that the generators pass the cost of the allowances on to the consumers in the electricity market.

Let $\boldsymbol{x_i} = (\boldsymbol{x_i^1}, \dots, \boldsymbol{x_i^H})$ denote an expansion plan vector for the ith generator, of which each element is also a vector comprising expansion capacity, technology, and node location. Let $\boldsymbol{y_i} = (\boldsymbol{y_i^1}, \dots, \boldsymbol{y_i^H})$ and $\boldsymbol{z_i} = (\boldsymbol{z_i^1}, \dots, \boldsymbol{z_i^H})$ denote the allowance bid and the supply function bid vectors, respectively, where, for any year t, $\boldsymbol{y_i^t}$ is a 2-tuple comprising price and quantity, and $\boldsymbol{z_i^t}$ is also a 2-tuple comprising the intercept and the slope of the supply function. Similarly, let $\boldsymbol{x_{-i}}$, $\boldsymbol{y_{-i}}$, and $\boldsymbol{z_{-i}}$, denote the combinations of expansion plans, allowance bids, and supply function bid vectors, of the rest of the generators. Each generator $\boldsymbol{i} = \boldsymbol{1}, \dots, \boldsymbol{n}$ selects $\boldsymbol{x_i}$, $\boldsymbol{y_i}$, and $\boldsymbol{z_i}$ via the following discrete maximization problem,

$$\max_{x_i} \sum_{t=1}^{H} \frac{f^t[x_i^t, y_i^t, z_i^t, x_{-i}^t, y_{-i}^t, z_{-i}^t]}{r} - C(x_i) \qquad (1)$$

$$\textit{subject to}$$

$$\max_{y_i} g^t[y_i, z_i, y_{-i}, z_{-i}] \quad \textit{for each } t \qquad (2)$$

$$\max_{z_i} h^t[z_i, z_{-i}] \quad \textit{for each } t \qquad (3)$$

$$x_i \in \Phi_i,\ y_i \in \Omega_{x_i},\ z_i \in \Psi_{x_i, y_i}$$

where $f^t[x_i^t, y_i^t, z_i^t, x_{-i}^t, y_{-i}^t, z_{-i}^t]$ is the joint profit from the allowances and electricity markets for generator i for year t if expansion plan x_i, allowance bid y_i, and electricity bid z_i are implemented, $C(x_i)$ is the overnight cost of plan x_i, $\Phi_i = \{x_{i1}, x_{i2}, \ldots, x_{im_i}\}$ is a discrete set of m_i expansion plans for generator i where each element of the set is a feasible expansion plan indicating new capacity, technology, location, and year of the expansion (year when construction of new capacity begins), Ω_{x_i} is a finite discrete set of CO2 allowances bid strategies determined by each expansion plan x_i, Ψ_{x_i, y_i} is a finite discrete set of electricity bid strategies determined by each expansion plan x_i and each CO2 allowances bid strategy y_i, and r is the discount rate.

The above mathematical formulation is pictorially represented in the following figure,

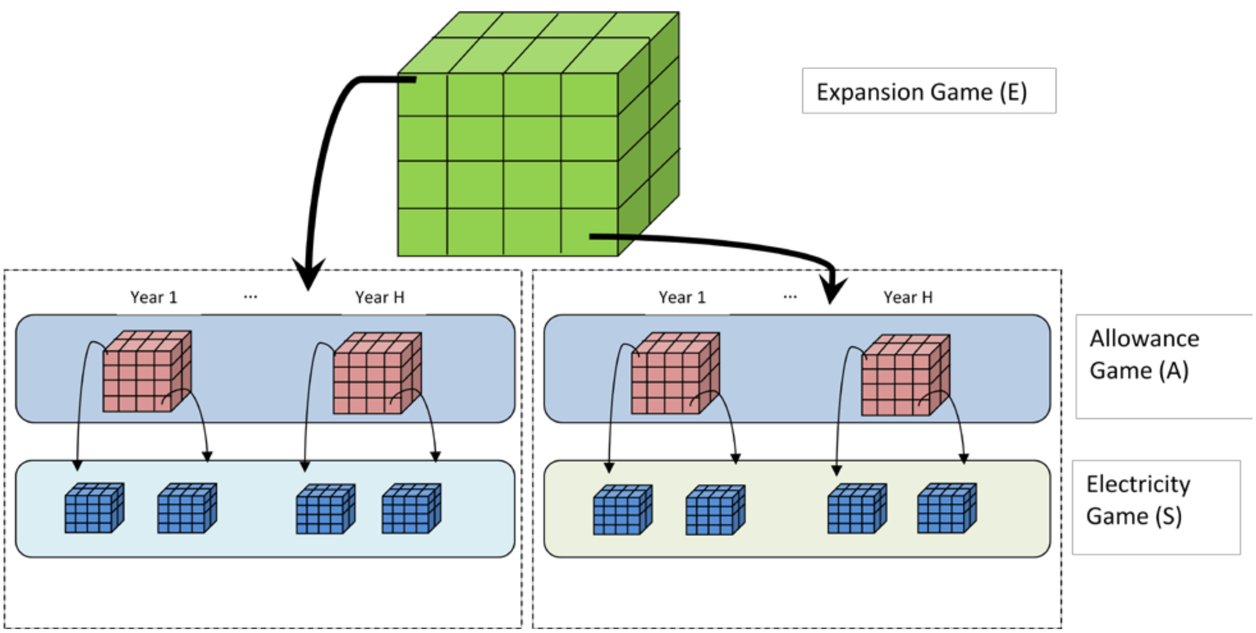

Figure 10: Game Theoretic Model

For simplicity of exposition, in the figure we assume that there are 3 generators competing in the network. The upper cube represents the expansion game and each of the inner sub-cubes represents a combination of expansion plans of the generators. Each one of the expansion plan combinations determine the technology, location, and capacity of the generation plants in the network for a time horizon $t = 1, \ldots, H$, inputs that the generators use to develop allowance bid strategies for each period of the time horizon. The competition of the generators in the allowance market is represented by the pink cubes. The inner sub-cubes in pink represent combinations of allowance bid strategies that generators submit to the allowance auction. Once the auction is cleared, the allowances are allocated and generators learn their allowance cost, which will then pass on to the consumers in the electricity market. Different combinations of allowance bid strategies result in different allocations and different costs. This is the rationale behind the assumption that each combination of allowance bid strategies determines a different electricity game (blue cubes).

Solution Methodology

We consider a bottom-up approach to solve the model, starting with the solution of the lower level games (electricity games) then continuing with the allowance games, and ending with the solution of the expansion game. By adopting this approach we ensure that for the selected expansion plan of a generator, the corresponding allowance bid strategies and supply function bid strategies for each period of the time horizon are also equilibrium solutions in the respective games.

The solution algorithm is as follows,

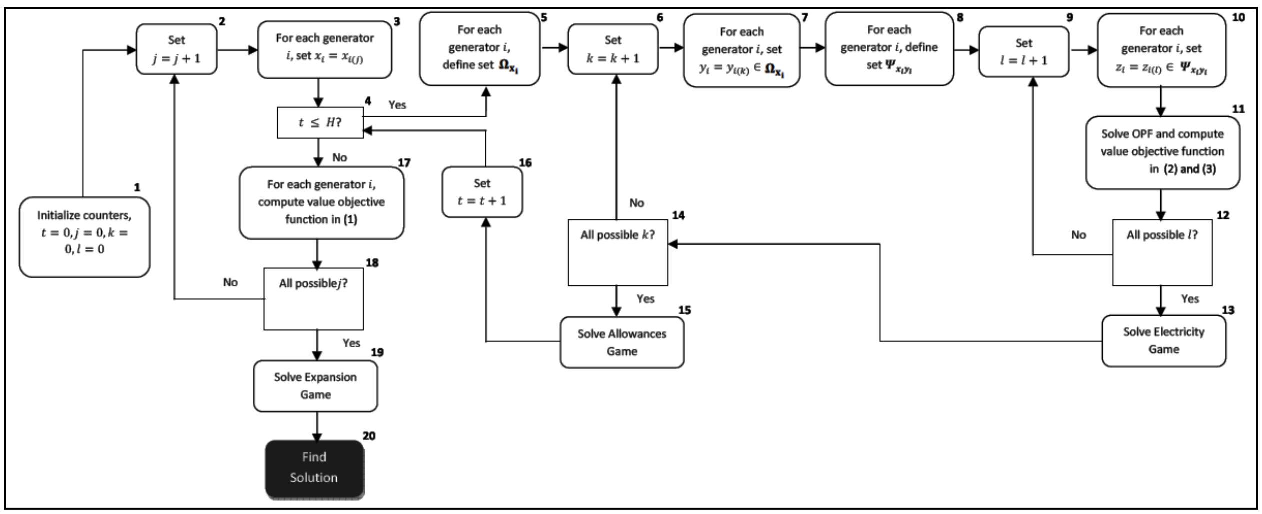

FIGURE 11: SOLUTION ALGORITHM

Application To Illinois Electricity Market

We used the above model to obtain equilibrium expansion plans for the main four generators in the Illinois electricity market. The market data were provided to us by Argonne National Laboratory (ANL), which originally simulated them for a report submitted to the Illinois Commerce Commission, Cirillo et al. (2006). According to the report, in 2007, the Illinois electricity market had 4 main producers of electricity, whose combined market share was around 90%. We build a reduced-size version of the Illinois power network and we replicated the electricity market conditions found in Cirillo et al. (2006). These conditions are used to describe the market on year 0 of the time horizon in our expansion model.
We develop 4 expansion plans for each of the 4 generators.

	Plan	Technology	Cap. (MW)	Node	Construction Begins
Gen 1	Plan 1	Nuclear	1,221	NI-A	2007
		Nuclear	867	NI-A	2013
	Plan 2	Nuclear	1,221	NI-A	2018
		Nuclear	867	NI-A	2024
	Plan 3	Nuclear	1,221	NI-A	2007
		Coal	320	IN	2013
	Plan 4	Nuclear	1,221	NI-A	2024
		Coal	320	IN	2021
Gen 2	Plan 1	Nuclear	1,221	NI-A	2007
		Nuclear	1,221	NI-A	2013
		Gas	554	NI-D	2019
	Plan 2	Nuclear	1,221	NI-A	2018
		Nuclear	1,221	NI-A	2024
		Gas	554	NI-D	2015
	Plan 3	Nuclear	1,221	NI-A	2007
		Nuclear	867	NI-A	2013
		Nuclear	867	NI-A	2019
	Plan 4	Nuclear	1,221	NI-A	2024
		Nuclear	867	NI-A	2012
		Nuclear	867	NI-A	2018
Gen 3	Plan 1	Nuclear	1,221	NI-A	2007
	Plan 2	Nuclear	1,221	NI-A	2024
	Plan 3	Gas	67	NI-B	2007
		Gas	67	NI-B	2009
		Gas	67	NI-B	2011
		Coal	320	IN	2013
	Plan 4	Gas	67	NI-B	2024
		Gas	67	NI-B	2026
		Gas	67	NI-B	2028
		Coal	320	IN	2021
Gen 4	Plan 1	Nuclear	1,221	NI-A	2007
		Nuclear	867	NI-A	2013
	Plan 2	Nuclear	1,221	NI-A	2018
		Nuclear	867	NI-A	2024
	Plan 3	Coal	769	NI-B	2007
		Coal	769	NI-B	2011
		Coal	320	NI-B	2015
	Plan 4	Coal	769	NI-B	2022
		Coal	769	NI-B	2026
		Coal	320	NI-B	2019

TABLE 1: ALTERNATIVE EXPANSION PLANS FOR

We assumed that the Illinois market was subjected to a CO2 cap-and-trade program similar to the Regional Greenhouse Gas Initiative (RGGI) and that there is a forecast of increase of demand for the network of 30% for year 2030 (EIA, 2009).

The results obtained with model are shown in Table 2,

	Plan	Technology	Capacity	Node	Construction Begins
Gen 1	Plan 1	Nuclear	1221 MW	NI-A	2007
		Nuclear	867 MW	NI-A	2013
Gen 2	Plan 1	Nuclear	1221 MW	NI-A	2007
		Nuclear	1221 MW	NI-A	2013
		Gas	554 MW	NI-D	2019
Gen 3	Plan 1	Nuclear	1221 MW	NI-A	2007
Gen 4	Plan 4	Coal	769 MW	NI-B	2022
		Coal	769 MW	NI-B	2026
		Coal	320 MW	NI-B	2019

TABLE 2: SELECTED EXPANSION PLANS

Other results obtained with the model a

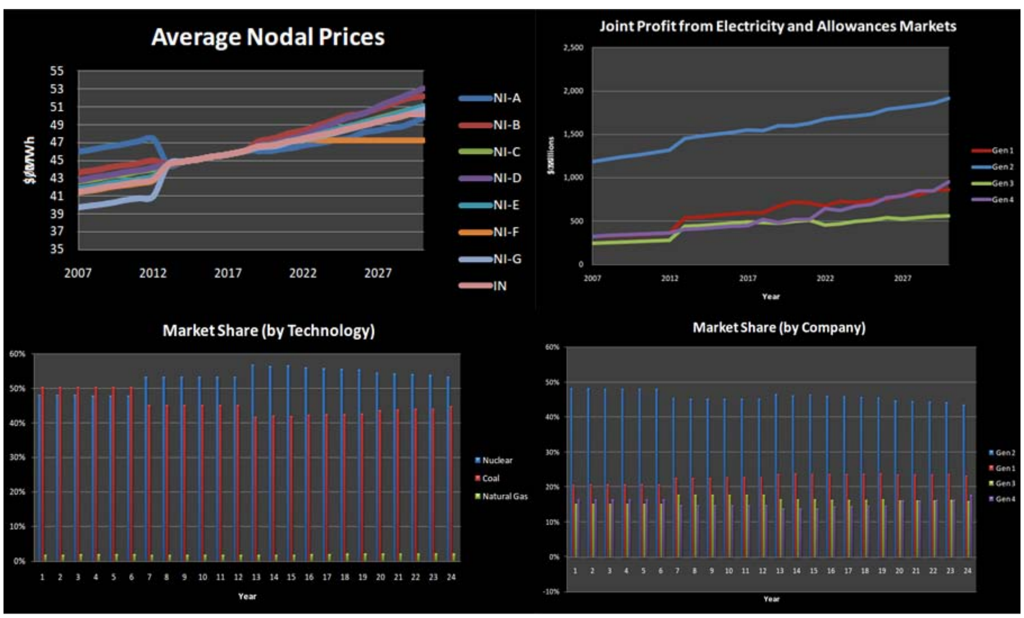

FIGURE 12: OTHER RESULTS

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Production of Liquid Fuels Biomass via Thermo-Chemical Conversion Processes

PI: B. Joseph, USF; **Co-PI's:** Y. Goswami, V. Bhethanabotla, J. Wolan, V. Gupta, USF
Students: Ali Gardezi, Nianthrini Balakrishnan, Bijith Mankidy

Description: The objective of this project is to develop technology for the economical thermo-chemical conversion of lingocellulosic biomass (non-food grade biomass such as agricultural waste, bagasse from sugar mills, citrus peels, switch grass, municipal green waste, etc.) to clean burning liquid fuels. Five of the major advantages of this process over a biochemical route to production of ethanol are: (i) it does not utilize food-grade feed stocks and therefore complements and does not compete with the agricultural food production in the state, (ii) the fuel produced is similar to those derived from petroleum unlike ethanol derived fuels which have at least a 25% lower energy content, (iii) the conversion is accomplished in using fast chemical reactions unlike the slow biological reactions for fermenting alcohol, (iv) the process does not require large amounts of water and associated energy costs of separating the water from the fuel as in bioethanol processes, (v) it can utilize a wide variety of biomass sources unlike the biochemical route which cannot work with high lignin containing biomass.

Budget: $554,447

Universities: USF

External Collaborators: Prado & Associates

Progress Summary

During the past year, we made progress on four fronts: Biomass conversion process design, Reactor testing for synthesis of liquid fuels from bio syngas, catalyst synthesis and catalyst testing.

In the area of process design, we have been evaluating alternative strategies to combine the energy intensive biomass gasification step with the energy producing Fisher-Tropsch synthesis of clean liquid fuels from syngas produced in the gasification step. We are exploring ways of recycling energy by using the methane off gas produced in the FTS to fuel the steam pyrolysis of biomass. Another avenue we are exploring is a novel strategy to combine solar thermal powered steam pyrolysis with the syngas production step.

We successfully tested egg-shell catalysts in our fixed bed reactor setup using both mixtures of CO and H2 as well as Biosyngas produced from poplar wood. The product liquid produced have been analyzed and report good yield in the diesel and jet fuel range.

We also continue with our catalyst characterization process. We are continuing to study the mechanisms of CO dissociation on the catalyst surface using density functional theory calculations. Current focus of this effort is on the effect of catalyst nanoparticle size on the adsorption and dissociation energies.

Catalyst synthesis efforts continue. We have successfully synthesized cobalt nanoparticles and placed them on silica Microparticles. These are currently being characterized and tested for activity.

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In this effort, a novel egg-shell SiO_2 supported cobalt catalyst system has been designed and fabricated (fig. 1) to optimize activity and selectivity toward C_{5+} paraffins, lower attrition and metal support interactions (MSI) over Fe-based systems.

We established the role and cause of MSIs which results in cobalt silicate formation greatly reducing catalytic activity [1]. Once formed, the silicates cannot be reduced back to recover the active metal catalyst phase. Previous work from other groups suggests that cobalt silicates are formed by reaction between aqueous cobalt complexes and surface silanol groups. Ernst et al., attributed cobalt silicate formation to the reaction between CoO and SiO_2 whereas Puskas et al. suspected a two-step process in which CoO first reacts with water to form cobalt hydroxide which in turn reacts with $SiO(OH)_2$ forming cobalt silicate. We have utilized this knowledge into a novel preparation method for a new tailored class of catalysts.

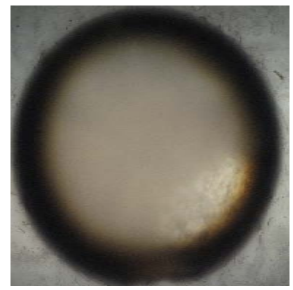
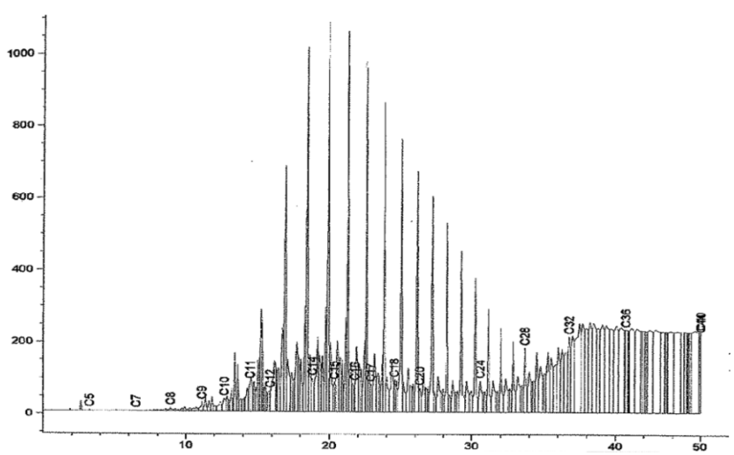


Fig 1.Cross-section SEM of a 2mm diameter Co/SiO2 egg-shell pellet.

The engineered egg-shell Co/SiO_2 Fischer-Tropsch catalysts were synthesized using various preparation precursors and impregnation techniques (patent pending).

The supported catalysts were analyzed by XRD, BET, SEM, adsorption and XPS methods at intermediate stages of preparation. Catalyst performance was studied using a fixed bed reactor and reaction products were analyzed by gas chromatography and FTIR. The effects of deposition techniques, precursors, drying method, calcinations, dispersion and support structure on the performance of the catalyst have been studied. The GC analysis presented below represents our product stream make-up via biomass generated syngas from pine chip.

Diesel and Aviation Fuel Range

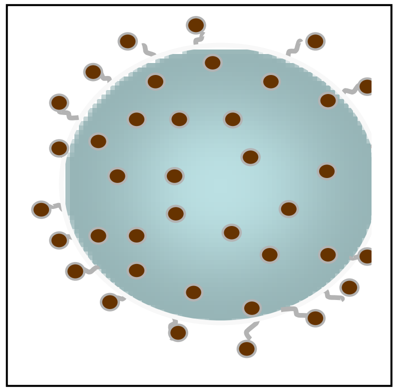


<u>Product distribution</u>

A.H. Kababji, B. Joseph, J.T. Wolan; *"Silica-Supported Cobalt Catalysts for Fischer–Tropsch Synthesis: Effects of Calcination Temperature and Support Surface Area on Cobalt Silicate Formation;"* Catal. Lett (2009) 130: 72-78

Catalyst Synthesis: The objective of this part of the project was to synthesize a model catalyst of nanoparticles of cobalt on silica support to study the particle size effect on Fischer-Tropsch Synthesis of Synthetic Hydrocarbon Fuels.

The influence of the size of catalysts such as cobalt (Co) metal nanoparticles has been the subject of significant debate in scientific literature on Fischer-Tropsch Synthesis (FTS). A key requirement for resolving the debate via experimental and theoretical studies is control over the Co nanoparticles and their immobilization on a support material without changes in size due to sintering, annealing, and aggregation.



In this part of the research project, we have synthesized novel composite colloids of silica microparticles that are surface decorated with nanoparticles of cobalt catalyst. These cobalt nanoparticles can be immobilized onto the surfaces of sub-micrometer silica particles that are surface modified with both small ligands and polymer chains. The interaction of cobalt nanoparticles with the modified silica depends upon parameters such as the functional groups of the small molecule ligands and polymer chains as well as the cobalt precursor and solvent medium that are used.

During this phase of the project, the model catalyst was prepared and characterized to gain insight on the structural and chemical properties such as particle size, shape, crystal structure, reducibility and active surface area before evaluating the catalyst using *in situ* FTIR under FTS conditions. The goal is to provide a fundamental understanding of the reactions on the surface of these nanocatalysts and to provide a well designed experimental system for facilitating theoretical investigations that focus on size effects in the catalytic FTS reaction.

Experimental Work and Results

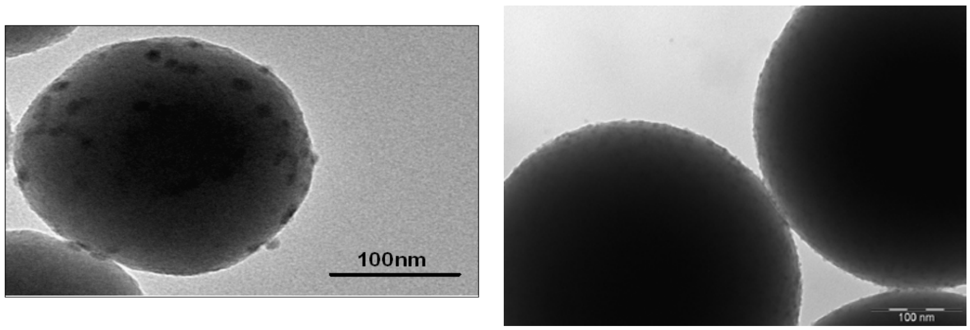
Silica support preparation: Monodisperse silica colloids were prepares using a sol-gel technique known as Stober synthesis wherein tetra-ethyl orthosilicate is hydrolysed. Two distinct particles with (a) diameter ~ 200 nm and (b) diameter ~500nm, were prepared.

Surface functionalization of silica support: The surfaces of the silica particles were modified with short polymer chains and other organic ligands. Specifically, we used poly(acrylic acid) PAA, poly(N-isopropylacrylamide) poly(NIPAM), 3-Methacryloxypropyltrimethoxysilane (MPTMS), or 2-acetoacetoxyethyl methacrylate (AEM).

Characterization of silica particles: Shape and size of the silica particles was characterized using electron microscopy and light scattering techniques. The presence of functional groups on the surface modified silica particles was verified using FTIR spectroscopy.

Cobalt nanoparticles synthesis and characterization: Nanoparticles of cobalt were prepared by (a) thermal decomposition of a organo-metallic cobalt precursor, and (b) reduction of cobalt salt, in the present of stabilizing surfactants. By changing the reaction conditions such as surfactant concentration and/or reaction temperature, the particles diameter was controlled for different sizes ranging from 2 nm and 20 nm. Size and poly-dispersity of cobalt nanoparticles was analyzed using DLS and TEM. The crystallinity of metallic nanoparticles was studied using XRD.

Self-Assembly of Co/SiO$_2$ FT catalyst: Surface decorated cobalt nanoparticles on silica supported catalyst was prepared by mixing cobalt nanoparticle solutions with the surface functionalized silica colloids. The self assembly of cobalt nanoparticles depends on the functional group present on the surface of the silica particles.



Electron microscopy was used to confirm the self assembly of cobalt nanoparticles on silica support. Temperature programmed reduction (TPR) technique revealed that the temperature at which nanoparticles reduce to metallic cobalt from their oxide states depends on the size of these nanoparticles. The active surface area of the catalyst were studied using the hydrogen chemisorption technique.

Ongoing and Future Work

The goal of the ongoing work is to scale up the preparation condition to obtain larger quantities of the novel composite catalyst prepared using self-assembly. This will enable use of the catalyst in in-situ reaction studies with FTIR spectroscopy to to analyze the adsorption of CO or and H$_2$ gases at high temperature. The goal will be to identify the reaction intermediates as function of the cobalt nanoparticle size, understand the impact of using self-assembled cobalt catalyst on formation of undesirable cobalt-silicates, and to provide experimental data to guide theoretical studies that focus on modeling adsorption-reaction phenomena on a cobalt nanoparticle of fixed size using density functional theory (DFT).

Publications resulting from the work so far:

A.H. Kababji, B. Joseph, J.T. Wolan; *"Silica-Supported Cobalt Catalysts for Fischer–Tropsch Synthesis: Effects of Calcination Temperature and Support Surface Area on Cobalt Silicate Formation;"* Catal. Lett (2009) 130: 72-78
S. A.Z. Gardezi, J. T. Wolan, B. Joseph, *An Integrated Approach to the preparation of effective catalyst for Biomass-to-liquid (BTL) process,* 33rd Annual AIChE Clearwater conference, June-2009
S.A. Z. Gardezi, B. Joseph, J. T. Wolan, *Metal support interaction effects in Fischer Tropsch synthesis: significance of catalyst preparation*, AIChE annual meeting Nov-2009.
B. D. Mankidy, C. A. Coutinho, and V. K. Gupta*, "Probing the Interplay of Size, Shape, and Solution Environment on Macromolecular Diffusion using a Simple Refraction Experiment", ***Journal od Chemical Education*** (Accepted).
C. A. Coutinho, B. D. Mankidy, and V. K. Gupta*, "A Simple Refraction Experiment for Probing Diffusion in Ternary Mixtures", ***Chemical Engineering Education*** (Accepted).
C. A. Coutinho and V. K. Gupta*, "Photocatalytic Degradation of Methyl Orange Using Polymer-Titania Microcomposites", ***J Colloid and Interface Science*** **333(2)**, 457-464 (2009).

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Balakrishnan, N.; Bhethanabotla, V. R.; Joseph, B. In *Effect of Cluster Size on CO Adsorption and Dissociation on Cobalt Catalysts: DFT Studies Using Cluster Models*, Accepted for presentation in AIChE Annual Meeting, Conference Proceedings, Nashville, TN, United States, 2009.

Balakrishnan, N.; Bhethanabotla, V. R.; Joseph, B. In *Effect of Cluster Size on CO Adsorption and Dissociation on Cobalt Catalysts: DFT Studies Using Cluster Models*, presented in FESC summit, USF, Tampa, United States, 2009.

Choudhury, P.; Balakrishnan, N.; Bhethanabotla, V. R.; Stefanakos, E. In *Complex Borohydride for Reversible Hydrogen Storage* Accepted for presentation in AIChE Annual Meeting, Conference Proceedings, Nashville, TN, United States, 2009.

Balakrishnan, N.; Choudhury, P.; Bhethanabotla, V. R.; Joseph, B. In *Density Functional Theory Studies on a Reversible Hydrogen Storage "Li-Mg-B-N-H" System*, Annual Meeting, Conference Proceedings, Philadelphia, PA, United States, 2008.

Bijith D. Mankidy and Vinay K. Gupta, "Novel Composite Particles for Catalysis: Cobalt Nanoparticles on Silica Colloids", The Southeastern Regional Meeting of American Chemical Society, Nashville (TN), November, 2008.

Bijith Mankidy and Vinay K. Gupta, "Cobalt Nanoparticles on Surface Modified SiO_2 Colloids for Fischer Tropsch Synthesis", Florida Energy Systyems Consortium Summit, University of South Florida, Tampa (FL), September 29-30, 2009.

Babu Joseph, Y. Goswami, V. Bhethanabotla, J. Wolan and V. Gupta, Production of Biomass via Thermochemical Process, FESC Summit, Tampa, Florida,Sept 2009.

Babu Joseph, SURA Workshop on Energy: A brief update and summary, FESC Summit, Tampa, FL, Sept 2009.

UNIVERSITY OF SOUTH FLORIDA

Solar Photovoltaic Manufacturing Facility to Enable a Significant Manufacturing Enterprise within the State and Provide Clean Renewable Energy

PI: Don Morel, USF; **Co-PI's:** Chris Ferekides, USF, Lee Stefanakos, USF, Tim Anderson, UF, Neelkanth Dhere, FSEC
Students: Currently one Ph.D. and two MS Electrical Engineering students are being supported by the project

Description: The primary goal of this project is to enable the establishment and success of local solar photovoltaic manufacturing companies to produce clean energy products for use within the state and beyond and to generate jobs and the skilled workforce needed for them. Thin film technologies have shown record efficiencies of 15.8%, and present tremendous opportunities for new Florida start-up companies. USF, UCF, and UF are collaborating to develop a pilot line facility for thin film solar technologies, which will serve as a test bed for making ongoing improvements in productivity and performance of solar modules, develop advanced manufacturing protocols, and help train a skilled workforce to ensure the success of new companies.

Budget: $1.6M

Universities: USF

External Collaborators: NovaRay Solar, Bedford, MA; Brightwats, Inc., Ft. Lauderdale, FL; US Department of Energy, National Renewable Energy Lab

Progress Summary

Photovoltaic Solar Thin Film Module Pilot Line

The primary objective of this project is to attract photovoltaic solar module manufacturing to the state. The expected outcome will be the creation of significant numbers of high-tech jobs and the means of transitioning the state and nation to a clean renewable source of energy. Faculty at USF, UCF and UF have been key and ongoing contributors to the development of thin film solar technologies that are being commercialized throughout the world. Their expertise is being joined and organized under this project to focus on its primary objective. A new thin film module processing and characterization laboratory is being developed on the USF campus. This module piloting line will be able to accommodate all thin film technologies on 1 ft^2 glass substrates. It will be fully integrated and capable of processing glass into a completed module comparable to commercial products. The initial thin film technology that will be developed in the facility is thin film copper indium gallium diselenide(CIGS). This material has the highest efficiency(20%) of the leading thin film materials, and it is also the material in which the faculty have the greatest expertise. The laboratory has been designed and is in final plan check. Facilities for the laboratory infrastructure have been designed and ordered.

The key piece of equipment for the entire operation is the unit in which the absorber material(CIGS) for the solar cell is deposited. CIGS is a complex material that has been difficult to deposit in the large areas needed for commercialization. Consequently significant time and effort has gone into designing the deposition tool. The design that has been developed will allow evaluation of a variety of potential process recipes. It also accomplishes dual use of the sputtering chamber to also serve as the load lock for the absorber deposition chamber. The combined chambers will allow for significant variations in the utilization of several sputtering and evaporation sources. The initial configuration will be geared toward process recipes that are based upon USF patents. The system has been designed to demonstrate process yield and throughput which are essential for commercial validation. The design has been completed, and we have received initial quotes from several vendors. One of the vendors has expressed interest in partnering with us on the project, and we are currently evaluating that opportunity.

It is necessary to support the module processing lab with experiments on small area devices. USF has had ongoing federal funding to support this laboratory scale research for the past twenty years. The facilities that have been developed and supported are being upgrade to directly address the objectives for this project. One of the lab scale deposition systems is being dedicated to proof-of-concept experiments before transitioning process recipes into the module piloting system. The other is being used to develop new process pathways that address sustainability issues when production of these technologies reaches the gigawatts/year level.

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Photovoltaic Solar Thin Film Module Pilot Line

Background

Photovoltaic solar energy is in a period of rapid growth and that growth is escalating worldwide. Established companies are daily announcing investment in new manufacturing plants with output capacities in the gigawatts/year range. An equal level of activity is occurring with ongoing announcements of new start-up companies. Many of these new operations are based on thin film technologies which are believed to offer the best pathway to low cost large scale implementation of solar energy. The United States has lost the lead it once had in this technology to Europe and Asia. This has occurred despite the fact that the U.S. has led the way to the development of these technologies that are being commercialized by others. At a local level the state universities in Florida have made significant contributions to these developments, and their professors and laboratories collectively represent one of the most formidable resources in the world for advancing these technologies. In spite of this there is to date no PV manufacturing located in the state. The primary goal of this project is to attract PV operations to the state. This will result in significant job creation as well as enabling the transition of our energy generation to a clean renewable source.

The objectives of the project are:

Establish a world-class thin film PV module capability

Attract PV manufacturing operations to the state

To accomplish these objectives a full capability module fabrication and characterization laboratory will be developed. A key element of this operation will be a processing unit that can deposit state-of-the-art thin film materials in large areas. The design of the unit will be based upon process recipes that have been developed in our research labs. These laboratory scale research activities will continue to support refinement of the module fabrication activity as well as to provide new opportunities for lowering manufacturing costs with new materials and advancing efficiencies with new device structures. Progress in each of these areas will be discussed below.

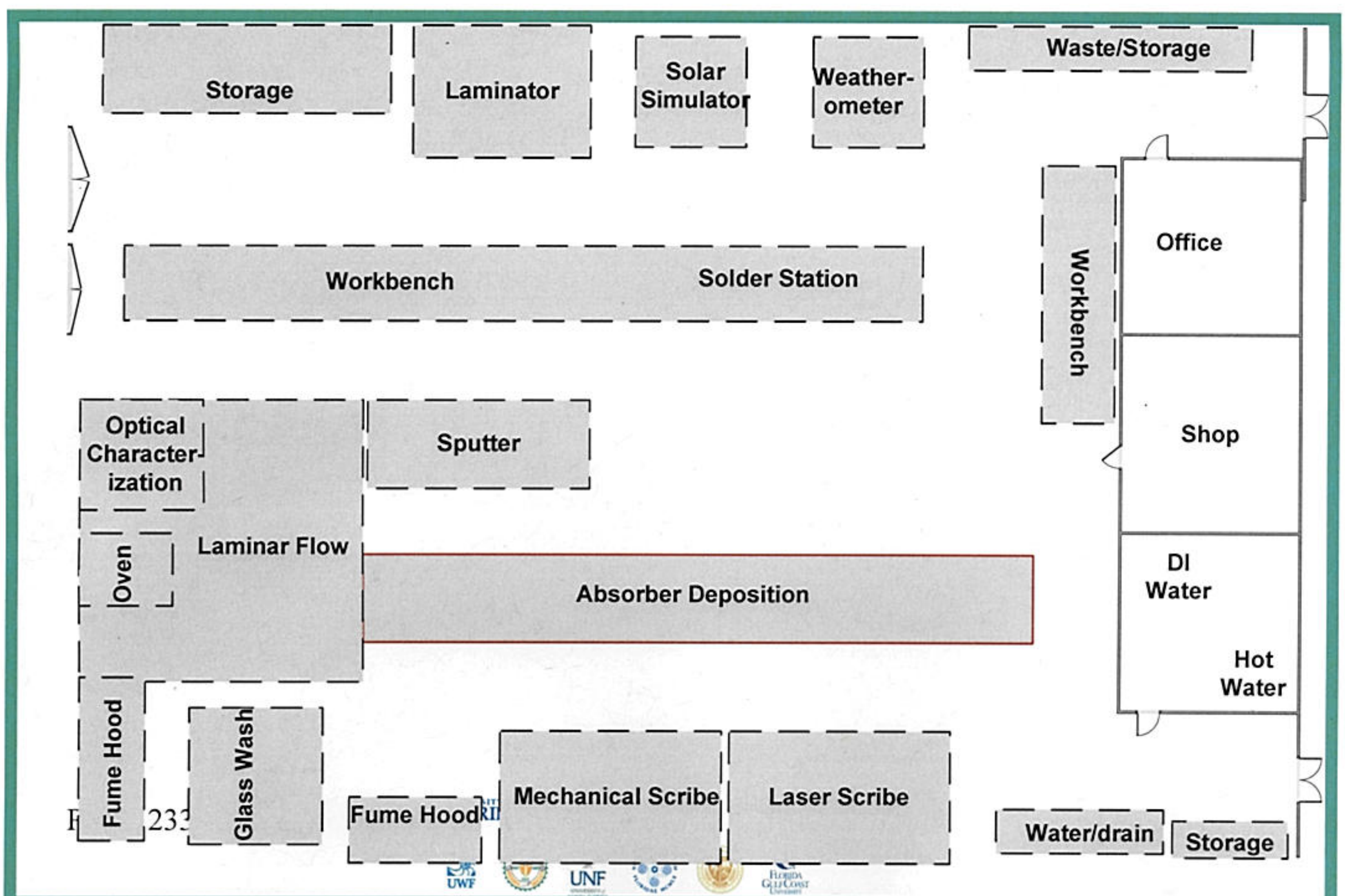
Module Processing Facility

Thin film modules are fabricated using either a glass or a metal foil substrate. The latter is usually supplied from a roll of metal foil that is fed through the process using what is termed a "roll-to-roll" process. Glass substrates are feed through the process as discrete units on a conveyor system. Each of these processes has pros and cons, and both are found in commercial operations. The initial process for our lab will be based upon glass substrates. This choice affects the design of the deposition equipment as well as many other processing and characterization tools. The major process steps for glass substrates are as follows:

Thin film module fabrication steps

Clean glass
Deposit back contact metal layer
Scribe(laser) the back contact into individual cells
Deposit the absorber material
Deposit the junction forming layer
Scribe(laser or mechanical) into separated cells
Deposit the front transparent contact to interconnect cells
Scribe(laser or mechanical) to isolate cell contacts
Solder contacts and lead wires
Encapsulate and frame
Test

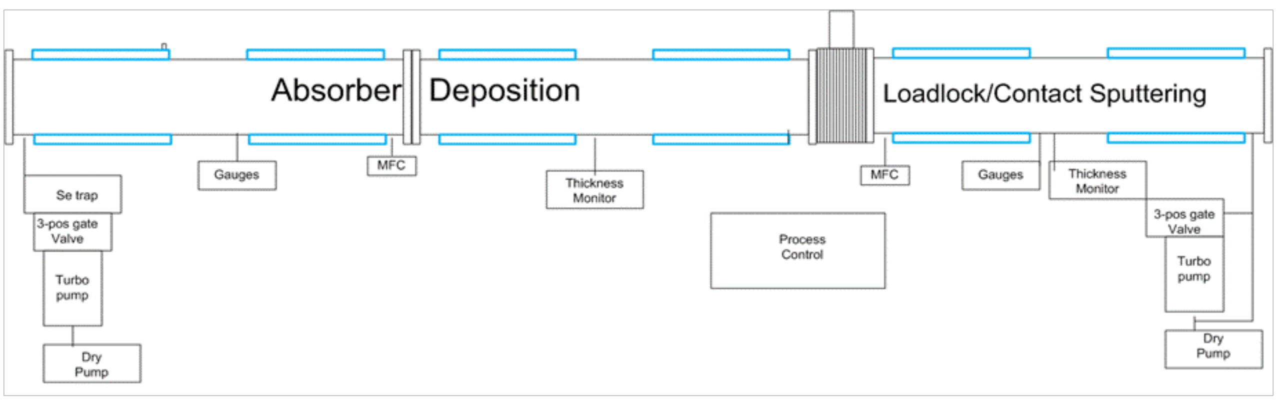
To perform all of these steps requires a fully tooled processing lab. In the figure below we show a schematic of the lab and the location of the processing tools. As a result of the budget cutbacks the entire lab will not be outfitted in this budget cycle. Emphasis will be placed on the front end of the process which is the most critical. The key element of the process is deposition of the absorber material.



Discussion of this tool will be provided in the next section of this report. The lab infrastructure has been planned out and is now in final check and approval.

Absorber Deposition

All steps of the module fabrication process have to be performed flawlessly to have a successful commercial process. The most important of these steps is the deposition of the absorber. This is the semiconductor material that absorbs the sunlight and converts it into electrical energy. The rest of the process steps are somewhat generic and can be used to support different thin film technologies. While we have expertise in all of the leading thin film technologies, we will be focusing on copper indium gallium diselenide (CIGS) during the start up phase. This material has exhibited the highest efficiency(20%) at the laboratory scale and has the best chance at competing with the currently dominant crystalline silicon technology. Unfortunately, it is also the most complex of the thin film materials, and this has slowed its commercialization. However, faculty at the three key universities of USF, UCF and UF have extensive expertise with this material, and by joining forces under this project we expect to develop processes that will enable successful commercialization. As a compound semiconductor composed of four elements, CIGS has a complex phase space and equally complex and varied deposition space in which to make it. While devices with efficiency greater than 15% have been routinely made at the laboratory cell level, the best performing devices are made with processes that are not easily scaled up. This has led to the failure of several commercialization efforts. With this in mind we are carefully designing our absorber deposition unit to accommodate two considerations. On the one hand the unit has to be versatile enough to test the various deposition pathways that can produce good performance. On the other hand once a pathway is chosen, the unit has to be able to demonstrate the rigors required for commercialization including throughput and yield. A schematic for the design of the unit is shown in the figure below. An overarching



aspect of the design is that the sputtering unit and the absorber unit are combined. This again is done to get the most out of the current available funding for the project. By combining the two deposition chambers through a gate valve as shown, the sputtering chamber can serve two purposes. It can be used as a sputtering chamber for deposition of the contact materials, and it can also be used as a load lock for the absorber deposition chamber. Ideally, as shown in the laboratory schematic these should be separate units, and in the future they will be. For now, however, this approach enables more to be done at the price of a bit of added inconvenience.

The chamber design allows for handling of glass substrates 1’ wide and up to 2’ long. The approach taken is such that these dimensions can easily be scaled in a commercial system in both dimensions to accommodate the largest glass substrates.

The sputtering chamber is designed to handle up to four sputter guns. Sputtering is a proven technology for large area thin film deposition. All of the contact layers for our modules will be deposited by sputtering. It is necessary to heat the substrate for achieving optimal performance from these layers. Both the sputtering and absorber chambers will be outfitted with heater assemblies capable of heating the glass substrates uniformly and rapidly.

The most challenging step of the process is the absorber deposition. The best laboratory cells are fabricated by simultaneously depositing the four elemental constituents by evaporation. While this works for small areas, it is very difficult to scale up evaporation processes for large areas. Stoichiometry control over large areas for long periods of time is a daunting challenge. As indicated above, sputtering is a proven commercial technology for large areas. Unfortunately it has been difficult to find a suitable source of Se that can be deposited by sputtering. This has led to alternative pathways for deposition including deposition of metal precursors by sputtering followed by a separate selenization step. The most promising of these to date is a process in which the precursor is selenized in hydrogen selenide gas. A shortcoming of this process, however, is that the selenization step is rather slow. A variation of this process is one in which selenization is accomplished by an evaporation source. We had such a process under development in our lab for several years and have an issued patent (*Method of manufacturing CIGS photovoltaic devices*, Patent Application Number 6258620, Inventor: Morel, Don Louis; Zafar, Syed Arif) covering this approach. It is one of the deposition pathways that we will explore for our large area system.

To accommodate the various process recipes that fall within the realm of physical vapor deposition the absorber deposition unit is designed to accommodate both sputtering and evaporation type sources for the constituent elements. Sputtering itself has many dimensions that have to be considered. While planar magnetrons are generic designs used by most applications, vendors also have advanced designs such as rotating magnetrons that can provide added dimensions to the tool. In addition, target composition and design are key variables that must be carefully included in developing a process. As indicated above, the system will be able to accommodate these advanced designs, and we are working with the vendors to determine which offer the best pathway to meeting our process requirements. If it is not feasible to accomplish selenization through a sputtering approach, it will be necessary to provide the Se through some other mechanism compatible with sputtering. We are currently working on the design and testing of novel Se sources to address this likely need.

Although we will consider the deposition pathway covered by the above issued patent, we have developed others in considering the design of the processing unit. *A patent application is presently being prepared by our Patents and Licensing division to protect these ideas.* This is important in that *we are also working with a Florida based company that has expressed strong interest in participating in our program*. An initial meeting has been held with our Sponsored Research Division, and an agreement is currently being drafted.

Laboratory Scale Experiments:
The unit size of modules made in the large area system will initially be 1 ft^2. This is a large sample size for a university lab, so it is important that the process recipe be well established before launching on module fabrication. To this end we will be running supporting laboratory scale experiments in our existing labs. We have completed the needed upgrades to our deposition units to be able to run the targeted process recipes. The lead deposition unit has been outfitted with four evaporation sources and is currently being automated to allow the type of process control needed to match the performance of the large deposition system. Stoichiometric films of CIGS are currently being deposited on glass substrates. Experiments are under way to determine the effect of growth rate on phase formation as determined by X-ray diffraction. It is known that the presence of secondary phases affects the performance of devices, and

a key issue for commercialization is to speed up the deposition process while not introducing harmful levels of these secondary phases. A correlation among growth rate, phase formation and performance will be determined by making complete devices under the same deposition conditions. Once this is sorted out, the more difficult aspect of point defect formation will be addressed.

Another important aspect for commercialization is the availability and cost of feedstock materials. For CIGS, Indium and Gallium are of concern when multi-gigawatt scale production is under way. In recognition of this issue researchers have been experimenting with reducing the thickness of the CIGS layer. We have also worked on this issue, and like others are having some success but are also finding that the whole process must be retuned to the reduced thickness. In developing new process recipes in the lab units we will keep an eye to those which offer the best potential for minimizing materials use. Another approach that is being taken is to find substitute materials for In and Ga that can produce absorbers with equivalent performance. We will also be exploring this pathway in our second laboratory scale system.

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

PI: Yogi Goswami, USF; **Co-PI's:** Lee Stefanakos, Mohammed Rahman USF, D. Hahn,UF, R. Reedy, FSEC

Abstract

This project targets to develop a solar thermal power technology that will lead diverse energy resources in Florida and reduce greenhouse emissions by utilizing renewable sources. Also, there will be economical impacts with the establishment of 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 and codes for the proven solar thermal power technologies in combination with bio or fossil fuels 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 based on new thermodynamic cycles.

Task 1: Development of simulation and design methodology for parabolic trough and parabolic dish

The objective of the task one is to develop a simulation and design methodology for the parabolic trough and parabolic dish based technologies for Florida conditions. Solar radiation, solar collector and thermal storage topics are the subtasks, and following progresses have been made during the period.

Solar radiation

Daily integration (DI) approach was used to obtain the hourly solar radiation for any location and tracking mode [1]. Monthly global and diffuse solar radiations are inputs for the radiation model. These values were obtained from Surface meteorology and Solar Energy Database (NASA) [2]. The solar radiation obtained in Florida for north south tracking mode is shown in Fig. 1.

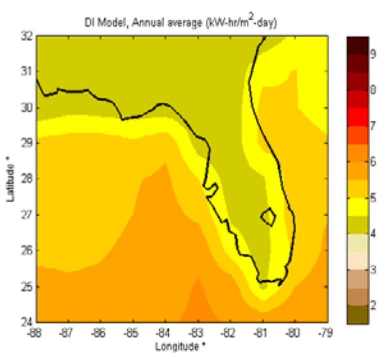


Figure 13 Solar radiation for Florida. North-south tracking (DI Model [1])

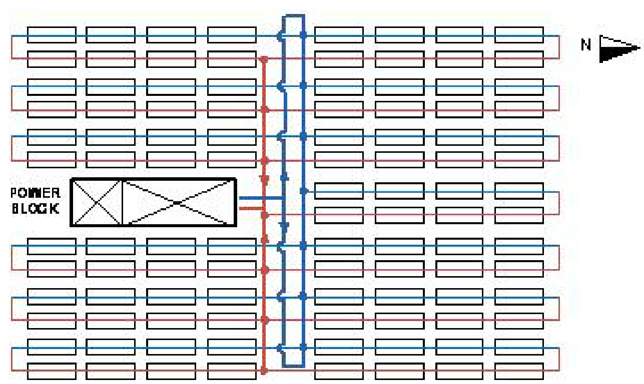


Figure 14 Solar field layout proposed for equal pressure drop trough solar collector circuit

Solar collectors

The solar field layout and the energy model of solar receiver for parabolic trough, which are shown in Figures 2 and 3 respectively, have been under investigation for the project. In this model, a more detailed solar radiation loss is being analyzed and the effect of no uniform solar flux around the receiver is being studied.

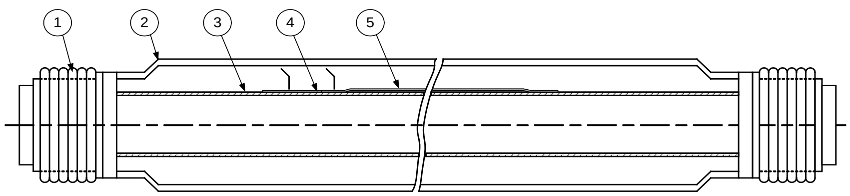


Figure 15 Solar Receiver components [3]

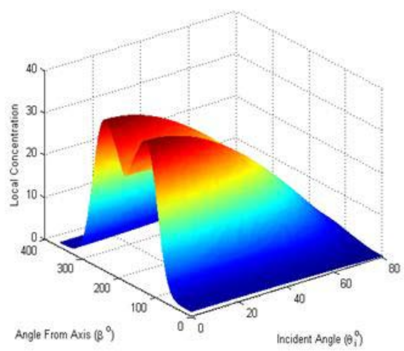


Figure 16 Local concentration distribution around the solar receiver

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 and dish 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 Experimental studies and improvement of the components of the cycle

The experimental Goswami cycle setup, which is shown in Fig. 5, is under modification during the period. Various components in the cycle are currently being under improvement such as piping, absorber heat exchanger, and strong solution pump.

Heat Exchanger (HEX)

The heat exchanger inside the absorber had a leaking problem; the previous design had a weak brazing connection at the header tubes. In order to prevent mixing of ammonia-water mixture with the chiller fluid, a new heat exchanger is designed and manufactured; the new design has a larger heat transfer area compared to the previous one. The previous and the new heat exchangers are shown in Fig. 6.

2.1.2 Strong Solution Pump

A magnetic coupled positive displacement pump is bought and will be used in the new studies; the new pump is shown in Fig. 7. The previous pump has a cavitation problem due to low net positive suction head (NPSH). The positive displacement pump does not require a NPSH, and also no mechanical seal is needed. It also provides a non-pulsing flow which will produce stable experimental results.

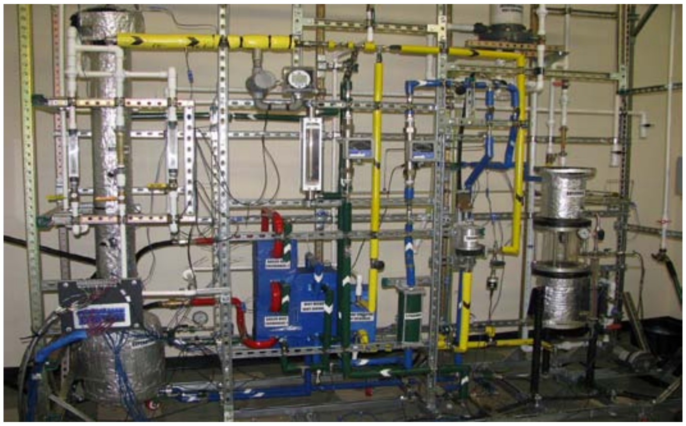
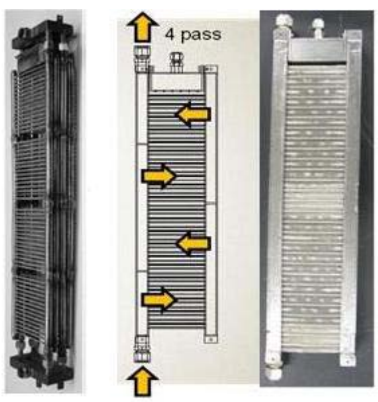


Figure 5 Experimental Setup of the Goswami Cycle



PreviousHE New HEX

Figure 6 Modification of Absorber Heat Exchanger

Figure 7 Positive Displacement Pump

2.2 Expander analysis for low temperature heat sources

A scroll expander is currently being implemented to the cycle. Scroll machines have some unique advantages like simplistic design (i.e. fewer moving parts), low friction, low torque pulsation, and compliance. A scroll compressor is modified by removing the motor and the copper wiring inside the compressor unit. The compressor will work in reverse direction to serve as an expander. A generator is also coupled with the expander so that power output will be measured directly from the experimental setup; the new scroll expander is shown in Figure 8.

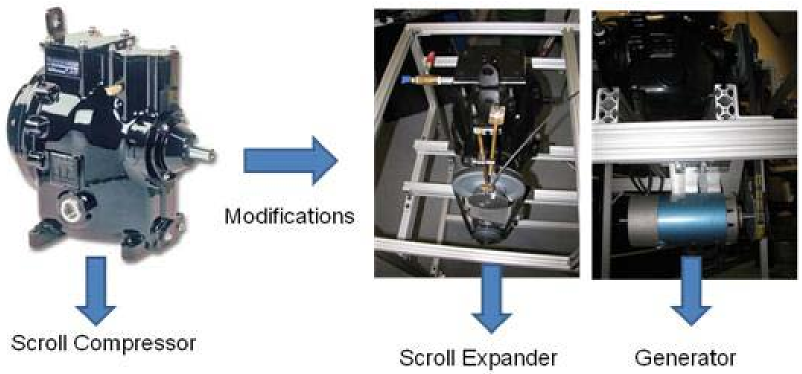
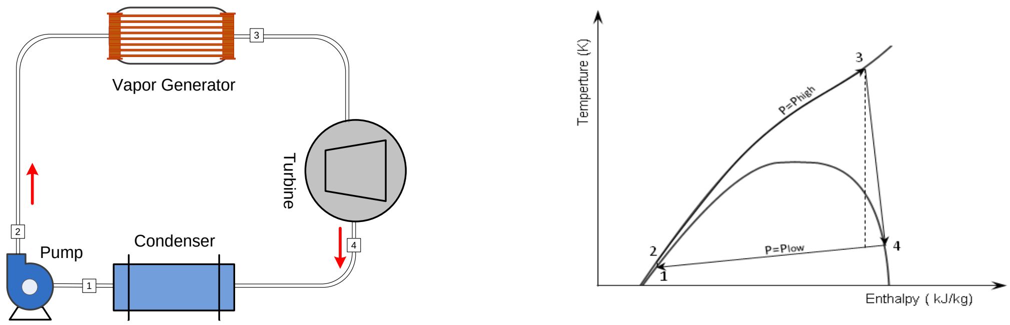


Figure 8 Scroll Expander



(a) Configuration of the supercritical cycle (b) Process of the cycle in a T-s plane

Figure 9 Configuration and process of a zeotropic mixture supercritical Rankine cycle

Table 1 Comparative study between the organic Rankine cycle and the supercritical Rankine cycle

Working fluid & Thermodynamic cycle	R134a, ORC	Zeotropic mixture, SRC*
Average First Law Efficiency (%)	10.06	13.44
Average Second Law Efficiency (%)	30.53	40.60
Condensing process exergy Efficiency (%)	66.55	81.64
Heating process exergy Efficiency (%)	82.64	88.67
System total exergy efficiency (%)	16.79	29.39

* zeotropic mixture of R134a and R32, 0.7/0.3, mass fraction

Task 3: Development of new technologies based on the novel thermodynamic cycle

The final task includes the development of new technologies based on the novel thermodynamic cycle for combined power and cooling developed by Goswami, in cooperation with industry for commercialization.

3.1 Power generation from low-grade heat using supercritical Rankine cycle

The configuration and process of a supercritical Rankine cycle is shown below in Fig. 9. Comparing to an organic Rankine cycle, a supercritical Rankine cycle does not pass two phase region during the heating process, which needs no boiler and simples the cycle configuration. The performance of supercritical cycles for the conversion of low-grade heat is studied numerically. A comparative study between an organic Rankine cycle and a supercritical Rankine cycle showed that the efficiency is improved up to 30% by adopting supercritical Rankine cycle.

We screened over 30 components that can be potentially used as the working fluids of supercritical cycles and achieve favorable efficiencies. Based on the screened components, zeotropic mixtures are further introduced to supercritical cycle to improve the thermal matching and reducing the irreversibility during the heat transfer process, which further improves the cycle efficiency. Our comparative study showed that the exergy efficiency of the cycle can improve as high as 75% compared to conventional organic Rankine cycle. The results of a comparative study between an organic Rankine cycle using R134a as the working fluid (R134a, ORC) and a supercritical Rankine cycle using the zeotropic mixture of R134a and R32 as the working fluid working (Zeotropic mixture, SRC) at the same condition are shown in Table 1.

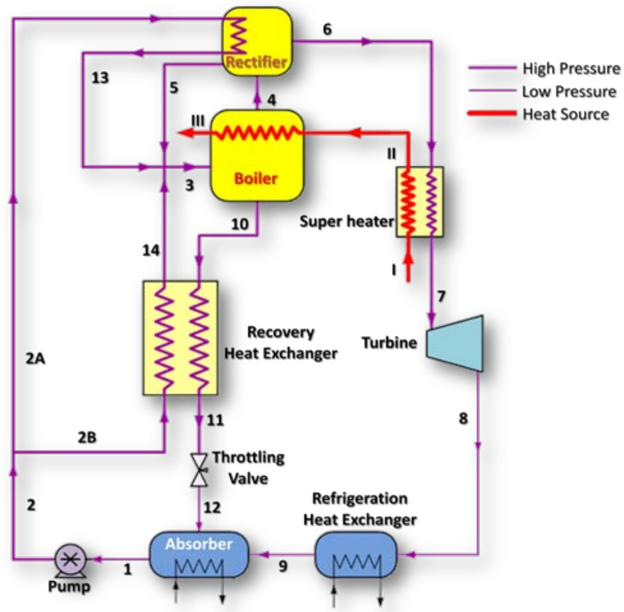


Figure 10 Schematic Drawing of Goswami Cycle

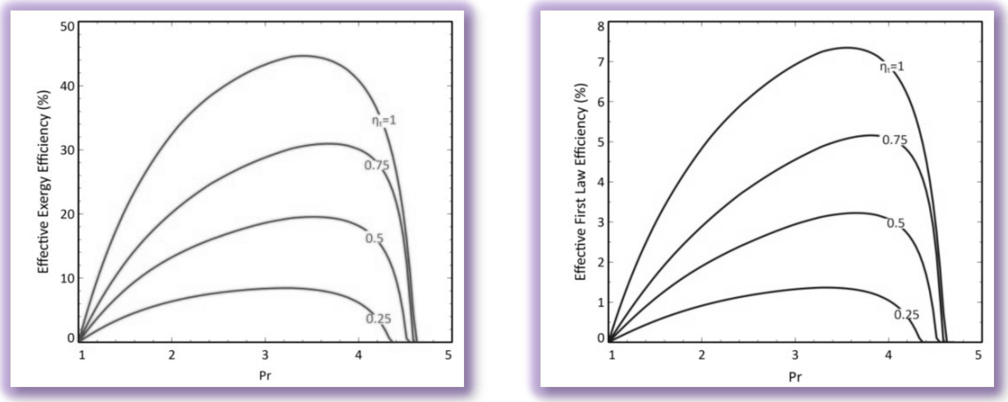
3.2 Optimization of Goswami Cycle

The schematic drawing of the cycle is given in Fig. 10. Optimization studies are performed by the Chemcad (2008) process model, the simulation model was used to perform parametric studies for different boiler pressures and expander efficiency. The effective first law and exergy efficiencies are given by Equations 1-2, and the results are shown in Figure 7 for two different boiler temperatures. The optimization studies are continuing for temperatures higher than 125 ^{o}C.

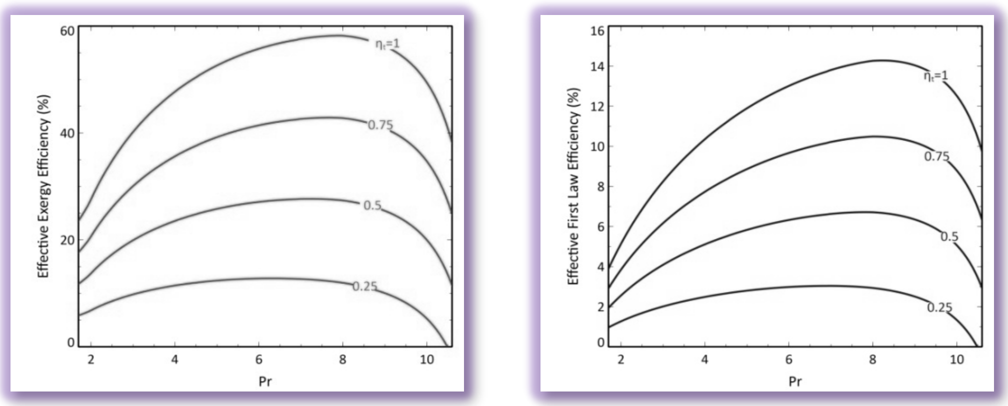
$\eta_{I,eff}=(W_{net}+E_c/\eta_{II,eff})/Q_h$ (Eq. 1)

$\eta_{exergy,eff}=(W_{net}+E_c/\ \eta_{II,eff})/(E_{hs,in}-E_{hs,out})$ (Eq. 2)

Where $E_c=(h_{cf,in}-h_{cf,out}-T_o(s_{cf,in}-s_{cf,out})$ (Eq. 3)



Boiler temperature is 83.40 ^{o}C.



Boiler temperature is 125 ^{o}C

Figure 7 Effect of pressure ratio and η_t on effective exergy and first law efficiencies.

Conclusions

A state of the art solar thermal power test and demonstration facility is targeted for evaluation, improvement and optimization of Florida specific Solar Thermal Power technologies. In order to fulfill the project goals, several subtasks have been identified under the main tasks of the project. A solar radiation method based on Daily Integration method is developed and an analytical model for heat loss in a solar collector is modeled and a local concentration distribution around the solar collector is found. Experimental setup of the combined cycle has been under modification at various points, such as piping, absorber heat exchanger, and strong solution pump. A scroll compressor is modified to work as an expander. A comparative study between an organic Rankine cycle and a supercritical Rankine cycle showed that the efficiency is improved up to 30% by adopting supercritical Rankine cycle. Optimization of the Goswami cycle for two different boiling temperature shows that a $\eta_{I,eff}$ of 6-10% and a $\eta_{exergy,eff}$ of 25-40% with 50-75% expander efficiency could be achieved for a boiler temperature of 125^{o}C.

References

[1] C. Gueymard, "Prediction and Performance Assessment of Mean Hourly Global Radiation," Solar Energy, vol. 68, Mar. 2000, pp. 285-303.
[2] Surface meteorology and Solar Energy. http://eosweb.larc.nasa.gov/sse.
[3] R. Forristall, Heat Transfer Analysis and Modeling of a Parabolic Trough Solar Receiver Implemented in Eng. Equation Solver, Golden Col.: National Renewable Energy Laboratory, 2003.

[4] Goswami, D., 1995. “Solar Thermal Power: Status of Technologies and Opportunities for Research”. In Proc. of the 2nd ISHMT-ASME Heat and Mass Trans. Conf., Tata Mc-Graw Hill, New Delhi, pp. 57–60.
[5] Goswami, D. Y., 1998. “Solar thermal power technology: Present status and ideas”. Energy Sources, 20, pp. 137–145.
[6] Chemcad, 2008, version 6.1.2.

Published/Submitted Papers

Gokmen Demirkaya, Ricardo Vasquez Padilla, D. Yogi Goswami, Elias Stefanakos, Muhammad M. Rahman, “Analysis of a Combined Power and Cooling Cycle for Low Grade Heat Sources”, Submitted to International Journal of Energy Research, 2009

Ricardo Vasquez Padilla, Gokmen Demirkaya, D. Yogi Goswami, Elias L. Stefanakos, “Parametric Study of a Combined Power and Cooling Thermodynamic Cycle for Low Temperature Heat Sources”, Proceedings of Proceedings of the 2009 ASME International Mechanical Engineering Congress and Exposition Conference, IMECE2009, November 24-28, 2009, Lake Buena Vista, Florida, USA

Huijuan Chen, D. Yogi Goswami, The conversion of moderate temperature heat into power and refrigeration, 2009 AIChE Annual Meeting, Philadelphia, Penn. Nov.,2008
Huijuan Chen, D. Yogi Goswami, Thermodynamic cycles and working fluids for the conversion of low-grade heat. Ready for submission.

Huijuan Chen, D. Yogi Goswami, A supercritical Organic Rankine cycle using difluoromethane for low grade heat recovery. Ready for submission.

Huijuan Chen, D. Yogi Goswami, A supercritical Rankine cycle using zeotropic mixture working fluids for the conversion of low-grade heat into power. Ready for submission.

Patents
D. Yogi Goswami, Huijuan Chen, Elias Stefanakos, Method and system for generating power from low- and mid temperature heat sources.Patent application submitted.

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UNIVERSITY OF SOUTH FLORIDA

Beyond Photovoltaics: Productionizing of Rectenna Technology for Conversion of Solar Radiation to Electrical Energy

PI: S. Bhansali, USF; **Co-PI's:** L. Stefanakos, Y.Goswami, J. Wang, USF
Students: Rudran Ratnadurai, Electrical Engineering, Ph.D.
Michael Celestin, Chemical Engineering, Ph.D.
Samantha Wijewardane, Electrical Engineering, Ph.D.

Description: The main objective of the proposal is to commercialize and scale up a new technology, rectenna to convert waste heat energy to electricity. Although the prediction of highly efficient (~85%) solar rectennas was published almost 30 years ago, serious technological challenges have prevented such devices from becoming a reality. Since the ultimate goal of a direct optical frequency rectenna photovoltaic power converter is still likely a decade away, we plan to convert optical solar radiation to thermal radiation (~30 THz regime) using an innovative blackbody source. Leveraging the research efforts of the world-class team members, we plan to further develop the rectenna technology that is within reach of efficient radiation conversion at 30 THz. A fully integrated, blackbody converter and 30 THz rectenna system will be capable of converting at least 50% of solar and thermal energy into usable electrical power, clearly demonstrating a truly transformational new technology in the renewable energy technology sector. It is strongly believed that this technology can reduce the present solar cost of production from $/watt to ¢/yard of flexible solar panels.

Budget: $598,500

Universities: USF

External Collaborators: BGS Technologies, Idaho National Laboratory

Progress Summary

Objectives:
The research objective of this project is to develop rectennae to convert thermal radiation to electrical energy through,

Fabrication, characterization and testing of Metal-Insulator-Metal tunnel junction,
Design, Fabrication and testing of antenna,
Determination of various cost point of rectenna manufacturing, and,
Integration of antenna and MIM junction.

Approach:
Develop a self-aligned Metal-Insulator-Metal (MIM) junction using a novel cross-hair layout using E-beam lithography process.
Characterize the insulator layer to yield uniform and thin film.
Investigate various techniques for depositing thin film insulator for MIM application.
Design and optimize antenna structure for receiving the electromagnetic radiation.
Analytical study and development of an engineered thermal emitter. Characterize and test the intensity of the emitter

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Accomplishments:

MIM junctions were fabricated with (a) 1 μm x 1 μm and (b) 0.5 μm x 0.5 μm contact area with a cross-hair layout to assure alignment during the e-beam lithography process. The electrical behavior of the diodes was evaluated by measuring the current-voltage characteristic.

The roughness, thickness and composition of the insulator layer were measured using Atomic Force Microscopy, X-Ray Reflection, and X-Ray Diffraction. The thickness of the insulator was determined to be 1.3 nm.

Thin film insulators in the MIM junctions such as HfO_2, Polyaniline and 1,6 hexanedithiol were deposited with 1 nm thickness using Atomic Layer Deposition, Langmuir-Blodgett process and Self-Aligned Monolayer deposition process, respectively.

The antenna structures were redesigned to be packaged to improve the measurement procedure.

Fabrication of engineering thermal emitters based on the analytical study. Emitter surface was fabricated using micromachined silicon substrate coated with Ni to emit a narrow band of blackbody radiation.

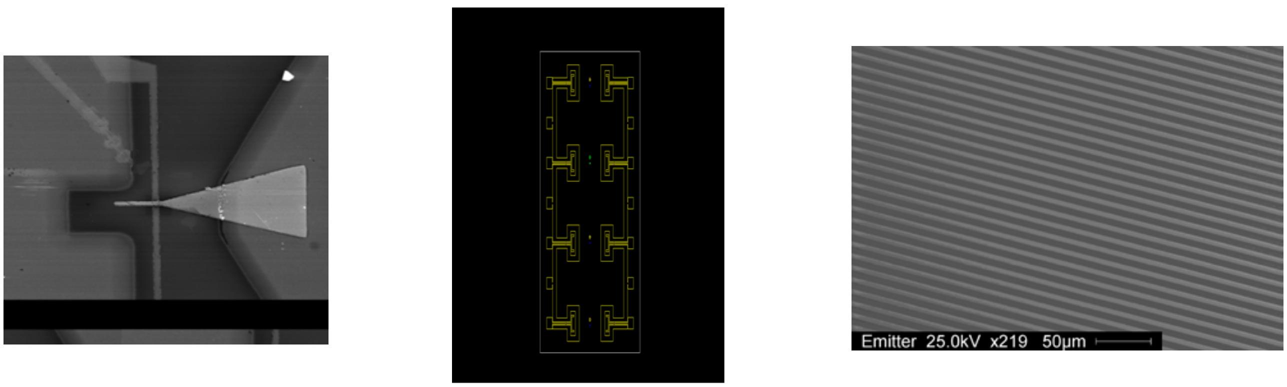


Figure 1: *Micrograph images showing (a) MIM junction with a self-aligned pattern, (b) redesigned antenna structure for packaging and testing, and (c) top view of an engineered thermal emitter.*

2009 Annual Progress Report

Introduction:

The development of a photovoltaic device with high efficiency and cost-effective process is indeed essential for supplying the ever-increasing energy demand. The world's main source of power is still generated by fossil fuels, which account for over 85% of total power consumption globally. Among the various renewable energy sources, solar radiation provides unlimited supply of clean and renewable energy. However, a widespread commercial usage of solar energy is very rarely seen, principally because of low conversion efficiencies. In order to meet the higher demands, considerable improvements are needed beyond photovoltaic technology. Various research groups have investigated *rectifying antenna or Rectenna* for the past three decades for energy conversion applications. Although the theoretical efficiency of the rectenna was determined to be ~ 85% [1], serious technological challenges have prevented such devices from becoming a reality. In this project, we propose to convert the Infrared (IR) electromagnetic radiation from the sun to electricity using an engineered blackbody thermal emitter and rectenna elements.

Approach:

Based on the research objective, during the phase I of the project, the various elements of the Rectenna (Rectifier, Antenna and Emitter) were designed and characterized. Initially, antenna structures were developed with a slot structure resonating at 94 GHz. The slot antennas were also designed with a tuning stub to improve the bandwidth of the device. The antenna was designed in a co-planar waveguide configuration, which enables the testing of antenna parameters using a ground-signal-ground wafer probes. The antennas were redesigned to be fabricated on a package with MIM junctions at its feed point.

A scaled prototype of the rectifier was also designed and fabricated. As a preliminary approach, the rectifier (Metal-Insulator-Metal tunnel junction) will be fabricated with Nickel-Nickel Oxide-Chromium. During the course of rectifier fabrication, certain characterization challenges were tackled. *(1) The materials, specifically the insulator layer used in fabricating the MIM junctions were deposited using different techniques and characterized using various metrology techniques.* Several insulator layers such as HfO_2, Polyaniline and Thiols were considered and deposited using Atomic Layer Deposition, Langmuir-Blodgett Technique, and Self-Assembled Monolayer deposition process to form MIM sandwich structures. Nickel-oxide layer was typically deposited using reactive sputtering process and the thickness of the film was determined using X-Ray Reflectometry technique. *(2) The method of manufacturing a nanoscale junction was optimized using e-beam lithography techniques.* The preliminary design used for fabricating nanoscale MIM junction exhibited several manufacturing challenges and alignment issue in lithography. To address this, a self-aligned structure was designed and fabricated using a bi-layer e-beam lithography process. This enabled the use of a thicker metal layer, while ensuring a good alignment of subsequent layers. The electrical response of the fabricated tunnel junctions was evaluated by measuring its DC current-voltage characteristics.

Analytical study of an engineered thermal emitter was performed and determined the use of a grating structure or a metal patch structure as a thermal emitter source. The emitter was designed to be fabricated on a silicon substrate, which could be micromachined to obtain the desired surface. It was determined from the Wien's blackbody radiation plot that the IR emission occurs when a surface is heated to 60C. This approach will enable the grating surface to emit the IR radiation. The emissivity from the engineered surface will be measured using a commercial IR detector, kept at a lower temperature. The temperature differential between the detector and the source will show the intensity of the source. The grating size will be optimized based on this initial test result.

Results:

Characterization of Nickel Oxide layer:

In this one-year project timeline, we have explored the use of different insulator material to be used in the MIM sandwich structure for high asymmetry and current. Initially, MIM junctions were fabricated with NiO as the insulator layer. Figure 2(a) shows the schematic of the MIM design used for characterizing the NiO layer. Typically NiO was deposited on the base Ni electrode using a reactive sputtering process. The gas ratio was maintained at 1:2 O_2: Ar at a 100W DC power. The deposition rate of the process and therefore the thickness of the deposited film were determined by X-Ray Reflectometry measurements. Figure 2(b) shows the XRR plots and the humps represents the layers of NiO. The smooth humps represent the smoothness of the films. Typically, the thickness of the film is determined by measuring the intensity of the humps plotted against Braggs' function,

$$2d \text{ sine } (\theta) = n\lambda$$

hus the rate of deposition using the reactive sputtering technique was determined to be 1.3 nm/min. Based on the XRR result, MIM junctions were fabricated with 1.3 nm NiO layer.

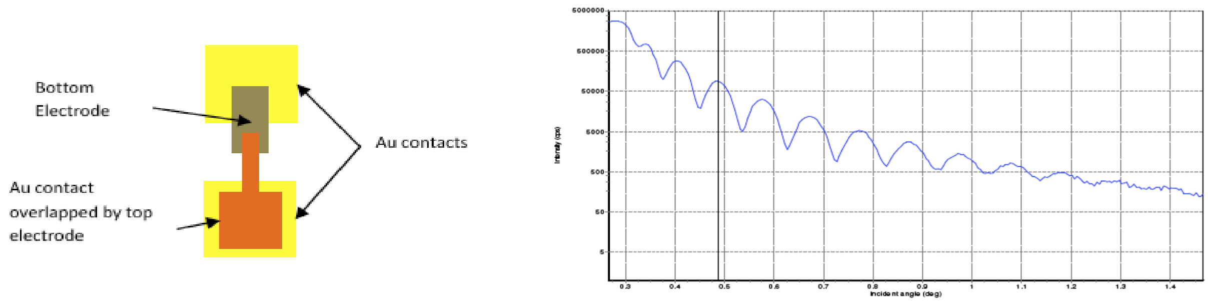


Figure 2: *(a) A Schematic of MIM design used for characterizing the insulator layer, (b) XRR pattern to determine the thickness of the insulator layer.*

(b) Design of Self-Aligned MIM Pattern:

The MIM design was refined to yield good alignment of layers during the lithography process. Due to the complexity involved in the previous design (Figure 3(a)) in aligning the layers in e-beam lithography, a novel design was prepared. This design uses a self-aligning pattern, which facilitates easier alignment of MIM layers during the lithography process. This design also improves the probability of the contact with bottom electrode. Figure 3(b) shows the preliminary design and fabrication of the self-alignment pattern with 1 μm^2 contact area. This test pattern allowed making smaller contact areas with much ease than the previous design.

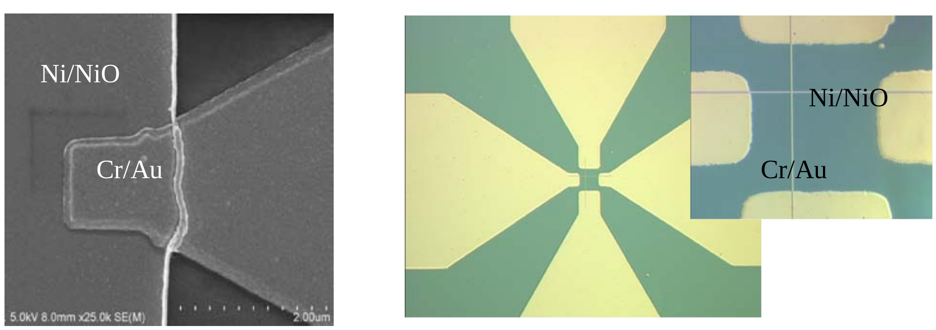


Figure 3: *Micrograph image showing (a) the previous MIM junction layout and (b) the newly redesigned cross-hair structure*

This design was further refined to incorporate in an actual rectifier design capable of measuring the DC and RF performance of the device. Figure 4(a) shows the cross-hair MIM pattern fabricated with a 0.25 μm^2 contact area. The DC I-V characteristics of the junctions were measured using a semiconductor parametric analyzer. The voltage was swept from -1V to +1V and the corresponding current output was measured. Figure 4(b) shows the I-V characteristics measured for the fabricated tunnel junction. The tunnel junctions were also observed to undergo a voltage annealing process, wherein the applied voltage seems to anneal the device, thereby increasing the breakdown voltage of the device. The tunnel junction was determined to withhold bias voltage up to 2.3 V before breakdown. Furthermore, the asymmetry of the junction was pronounced with a maximum rectification ratio of 7 at 1V bias (Figure 4(c)).

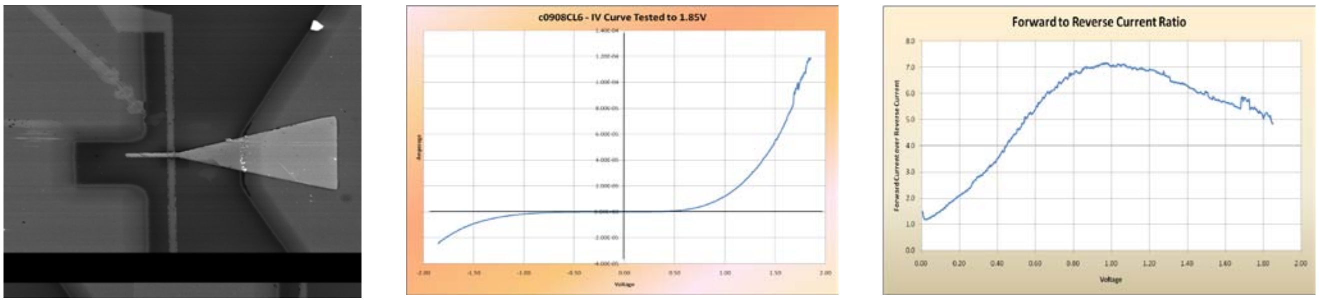


Figure 4: *(a) Micrograph of a 0.25 μm² MIM junction, (b) I-V characteristics of the MIM junctions and (c) Rectification ratio of the tunnel junctions*

(c) MIM junctions with different insulators:

Typically, MIM junctions are fabricated with a native oxide layer as the insulator layer, e.g. NiO. In this approach a non-native insulator layer as well as organic insulator layer was used to estimate the performance of the MIM junction. The non-native oxide used was HfO_2, deposited using Atomic Layer Deposition (ALD) technique. The I-V characteristics of the MIM junction fabricated using HfO2 insulator layer is shown in Figure 5(a). The thickness of the insulator layer was determined as 1 nm. The contact area was varied from 4um2 to 10000 μm². Although the device exhibited asymmetric characteristics, the current output was lower than the conventional MIM junction. This suggests that the non-native oxide still needs to be characterized.

In the next approach, organic films were used as the insulator layer. The main advantage of using an organic layer is the ability to control the film thickness in sub-nm level. Initially, polyaniline (PANI) was selected as the insulator layer due to its ability to change the permittivity by varying the doping concentration. Hence, an undoped PANI was used to take advantage of its insulating property. A monolayer of PANI was deposited using Langmuir-Blodgett (L-B) process. MIM junction with 10000 μm² contact area was coated with a monolayer of PANI using the L-B process. The I-V characteristics of the PANI based MIM junction is shown in Figure 5(b).

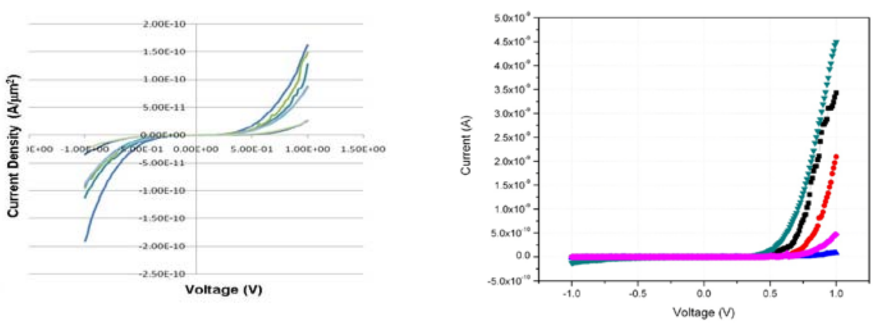


Figure 5: *I-V characteristics of MIM junctions fabricated with (a) Ni-ALD-HfO_2-Cr and (b) Ni-PANI-Cr*

From the figure it can be observed that the I-V characteristics is highly asymmetric. However, the current output is similar to the ALD-HfO_2 (in the nA range). These organic as well as non-native oxide have been deposited on a layer of Ni, which forms a thin native oxide layer when exposed to ambient condition. This might have formed a dual insulator layer causing the current to decrease. Hence further optimization is required to achieve higher current.

(d) A scaled prototype of the antenna:

Initially, antenna structures were developed with a slot structure resonating at 94 GHz, shown in Figure 6(a). The slot antennas were also designed with a tuning stub to improve the bandwidth of the device. The antenna was designed in a co-planar waveguide configuration, which enables the testing of antenna parameters using a ground-signal-ground wafer probes. The antennas were redesigned to be fabricated on a package with MIM junctions at its feed point. A schematic of the new design is shown in Figure 6(b,c). This design will enable bonding the wafer to an external chip carrier, which can be mounted on a test set-up for RF testing.

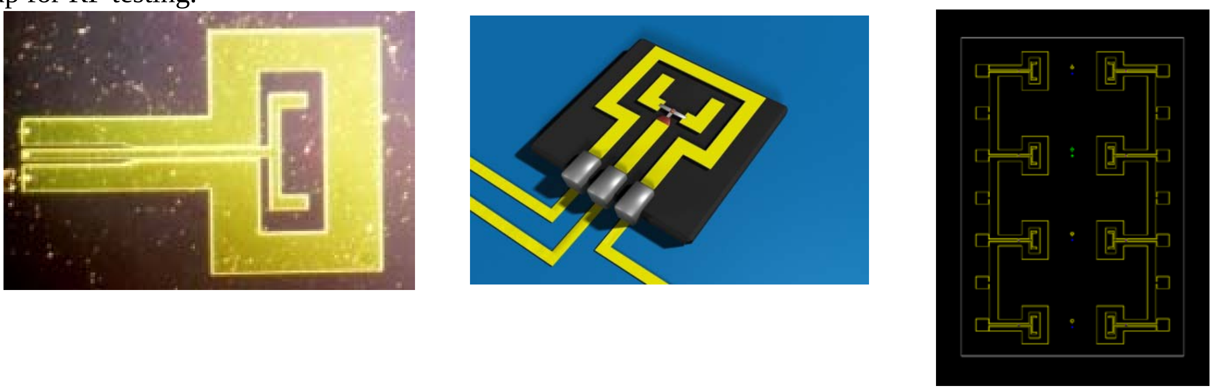


Figure 6: *Schematic showing (a) a fabricated 94 GHz antenna, (b) a scaled prototype with diode in the feed point and (c) antenna array for packaging*

(e) Engineered Thermal Emitter:

Thermal sources are considered as the epitome of incoherency and the archetype of isotropic source, which emits radiation in all directions. The reviews done for exploring the possibilities to modify the emission to suit the requirements revealed that the emission properties could be tuned by structuring the surface in the order of interested wavelength scale (micro/nano scale). One approach for the optimization of the structure is by numerical simulations. The Rayleigh hypothesis is used commonly for modeling the space at the metal (grating) / air interface, but many have argued the validity of this hypothesis especially at higher depths. Even though there exist other methodologies, such as the Chandrasekhar method, no methodology is capable of handling the complex structures with good accuracy. Although for a simple analytical surface profile, such as a sinusoidal profile, the simulation and experimental results agree with a reasonable accuracy, for profiles with triangular or square type cross sections there is a considerable discrepancy between theory and experiment. In practice no profile can be made perfectly smooth and this secondary roughness, other than the grating pattern, produces second harmonics with waves causing deviations from the computed values. The roughness, the consistency and the accuracy of the profile are functions of the fabrication process, quality control, etc., and it is hard to quantify these factors in the simulation program. As our requirement is to build an efficient pragmatic source, the experimental approach for optimizing the grating parameters is considered as the most appropriate. With the constraints regarding the width and depth, and with the knowledge of the outcome from literature, initial values were assumed and the thermal emitters were designed and fabricated.

Samples were fabricated on a silicon wafer using typical lithographic techniques. The gratings were fabricated using dry etching process. Then, a thin layer of Nickel was deposited on the surface as shown in the Figure 7. Emission tests are set-up, which will reveal the optimum parameters for the grating with respect to the materials used and the fabrication process. Changing the fabrication process within the capability of our facilities and taking into consideration possible costs involved in each process and finally by quantifying the emitter performance, we will be able to determine an optimal design for the emitter.

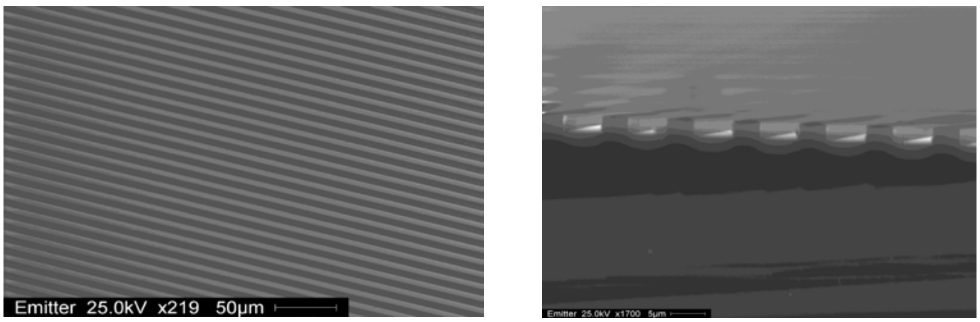


Figure 7: *A micrograph image showing the top and cross-sectional view of the fabricated thermal emitter*

Summary and Future work:

MIM junctions were fabricated with different insulators and interesting electrical characteristics were observed. Ni-NiO-Cr junctions have been well characterized to form a reproducible thin film of uniform thickness. A novel phenomenon of voltage annealing was also observed in these tunnel junctions, leading to higher breakdown voltage. In the next phase, the MIM junctions will be thermally annealed to ensure uniform film. Initial studies indicate better electrical characteristics at 250°C. In addition, MIM junctions with self-assembled monolayers will be explored. The antenna structures have also been redesigned to have a MIM junction in its feed point, packaged in a chip carrier. This will ensure proper device handling during testing the device. The thermal emitter fabricated in silicon substrate will be tested using a commercial IR detector and then optimized for rectenna operation. Thus in phase 2 of the project a simple prototype array of IR rectenna will be fabricated along with an IR emitter and tested for its efficiency.

Other Synergistic Activities:

(a) Publications:

S. Krishnan, Y. Emirov, E. Stefanakos, Y. Goswami, S. Bhansali, "Thermal Stability Analysis of Thin Film Ni-NiOx-Cr Tunnel Junctions," Thin Solid Films, 2009, doi: 10.1016/j.tsf.2009.10.021

S. Krishnan, S. Bhansali, E. Stefanakos, Y. Goswami, "Thin Film Metal-Insulator-Metal Junction for Millimeter Wave detection," Procedia Chemistry, 1, 2009, 409-412.

S.Krishnan, R.Ratnadurai, S. Bhansali, E.Stefanakos, Y.Goswami, "Polymer Tunnel Junctions: Fabrication and Characterization of Ni/Polyaniline/Au Organic device" (under submission) 2009.

M.Celestin, S.Krishnan, S. Bhansali, E. Stefanakos, Y. Goswami, "Tunnel Diodes Fabricated using Self-Assembled Alkanethiol Films on Au," (Under submission) 2009.

R. Ratnadurai, S.Krishnan, S. Bhansali, E. Stefanakos, Y. Goswami, " Characterization of Nickel oxide films prepared by sputtering technique for MIM tunnel junctions," (under submission) 2009.

(b) Proposals:

Title: Nanoscale Rectenna for converting solar and thermal radiation to electricity; **Organization:** DOE-ARPA-E; **PI**: Elias Stefanakos; **Co-PI**: Shekhar Bhansali, Yogi Goswami, Steve Novack (INL), Steve Wix (SNL), Mark Gordon (BGS)

Title: Modeling and Simulation of Nanoscale Rectenna; **Organization:** DOE-EERE; **PI: Dale Kotter**; Co-PI: Yogi Goswami, Elias Stefanakos, Steve Novack (INL)

UNIVERSITY OF SOUTH FLORIDA

Energy Efficient Technologies and The Zero Energy Home Learning Center

PI: Stanley Russell, USF; **Co-PI:** Yogi Goswami, USF

Description: The project is to create and evaluate an affordable residential scale Zero Energy building that will function as an exhibition of energy efficiency and Zero Energy Home [ZEH] technology on or near the University of South Florida campus. The project will feature the most cost-effective combination of renewable solar energy with high levels of building energy efficiency. The building will incorporate a carefully chosen package of the latest energy-.efficiency technologies and renewable energy systems to achieve the most successful and reliable results.

The building will utilize Photovoltaic solar electricity and solar domestic hot water heating systems using the grid as an energy storage system, sending excess power to the grid during the day and taking power back from the grid at night. Plug-in hybrid automobile technology offers a promising means of providing distributed energy storage for such homes but has not been sufficiently tested. Using a systems approach to couple zero energy home technology with PHEVs we will explore opportunities to develop marketable products that meet Florida's energy and environmental goals.

Budget: $344,600

Universities: USF

Progress Summary

The Energy Efficient Technologies and The Zero Energy Home Learning Center task began with research into the current state of Zero Energy House technology in the World, the U.S., and the hot humid climate of southern Florida. Data from Case studies of Zero Energy and Near Zero Energy Houses built in a hot humid climate were compiled for reference. A list of technologies used for various building components will act as a ZEH Database to draw from during the design phase of the Learning Center. For the center's educational aspect, we also looked at facilities like the Florida House Learning Center in Sarasota built with a similar purpose of educating the public about energy efficiency in buildings.

Meetings with energy efficiency and ZEH experts at FSU, UF, Sarasota, the FSEC, and housing makers in Japan, were a springboard for our research and have helped us formulate strategies for the design of the Zero Energy Home Learning Center. During this preliminary research period we have established several collaborations with members of the academic and professional communities.

As new technological innovations continue to arise on a daily basis it is important to delve beyond what has already been done to look at the emerging technologies that will influence ZEH in the future. We have begun a list of emerging technologies that we will continue to edit as information becomes available. Conferences are a valuable source of information and input about energy efficiency and ZEH technology. I have submitted abstracts and been accepted to three international conferences where I will present our research and discuss the Zero Energy Learning Center. I will also attend a Zero Energy Building Conference in NYC in October to network with other professionals in the field and potential industry partners.

Based on our research we are currently developing our own proposals for innovations in ZEH technology. This year's research will involve designing, building and testing prototypes of innovative ideas that we will incorporate in the ZEH learning center. Designing and building prototypes will require the assistance of industry partners. To date we have verbal commitments from the following companies:

Insulation
***Acoustiblok* International Headquarters** 6900 Interbay Boulevard Tampa, Florida U.S.A. 33616
Windows
Pilkington Group/ Nippon Sheet glass Spacia Vacume insulated glass windows
Photovoltaics *Kyocera Solar, Inc.* Headquarters 7812 East Acoma Dr. Scottsdale, Arizona 85260
System Photonics Via Ghiarola Vecchia, 73 41042 Fiorano (MO)
Structural Insulated Panels
PermaTherm, Inc. 269 Industrial Park Road Monticello, GA 31064
Gramatica Group 13926 Clubhouse Drive Tampa, Fl 33618
Housing Manufacturers
Misawa Homes Tokyo Japan
Sekisui Haimu Chiba Japan
Palm Harbor Homes Plant City, Florida
Others
In addition, we are currently talking with Cisco about smart connected building technology and Trane about Mechanical systems.

2009 Annual Progress Report

Before beginning design on the ZEH Learning Center it was necessary to study existing buildings that have aimed at zero energy or near zero energy status. Many of the precedents sited are projects implemented by The Florida Solar Energy Center® (FSEC), a research institute of the University of Central Florida. It is the largest and most active state-supported renewable energy and efficiency institute in the United States. Since 1998 with funding from the department of energy's building America program the FSEC has built and monitored several zero energy and near zero energy houses in the State of Florida. We also visited the recently completed *Off Grid Zero Energy Building* [OGZEB] at Florida state university an off grid zero energy test house which is just beginning to yield data. In addition to Photovoltaic panels, the OGZEB also incorporates hydrogen fuel cells for storage and production of electric power. We studied the *Florida House Learning Center* in Sarasota Florida which, like the proposed ZEH Learning Center, was established to showcase sustainable building technologies to builders and the general public. The Florida House contains exhibits of various green building products and the building itself has explanatory text in various locations to describe the technologies at use. I traveled to Japan in June and met with engineers at two of Japan's largest housing manufacturers Misawa Homes and Sekisui Haimu. Misawa Homes produced its first Zero Energy House Model in 1998 and since then has sold thousands throughout Japan. Both companies take a systems approach to life cycle cost, energy use and CO_2 emissions with their highly efficient manufacturing processes.

We looked at Vernacular Florida architecture built before mechanical systems became popular as precedents for passive cooling, heating and daylighting. The approach to building design in Florida changed considerably with advancements in mechanical systems in the mid- 20th century. Up until that time houses typically had wide overhangs to shade the walls and windows, pitched ceilings with roof vents and crawlspaces under the floor to induce natural ventilation. After air conditioning became popular houses were built to close out the heat with smaller windows, compartmentalized interiors, and low flat ceilings. Passive solar design was experimented with extensively during the energy crisis of the 1970s and many of the lessons learned during this period are once again relevant in the current movement toward sustainable building. Because the thermal comfort range of the average American has changed since the proliferation of air conditioning, it would be difficult for most to live in a passively cooled home especially in Southern Florida. Regardless, the principles of vernacular buildings and passive solar design can compliment advances in highly efficient mechanical systems to greatly reduce the energy consumption of buildings. There is also evidence that comfort levels can be gradually altered when standards are placed on heating and cooling levels in buildings. South Korea for example, has set a standard of not less than 26c [79f] in the summer for air conditioning and not more than 20c [68f] in the Winter for heating. In Japan, air conditioning in public buildings is mandated at not less than 28 [82f] degrees in the summer season which reportedly triggered a new fashion in Japan and boosted the textile and cloth industries.

In addition to documenting what has already been accomplished in the field of building energy efficiency we also feel that it is important to know about the emerging technologies that will transform Zero Energy Building design in the near future. Some of these are already beyond the testing stage and in commercial production but are expensive compared to more conventional alternatives. This is often a function of supply and demand and in many cases it can be assumed that an increased demand for these products will lead to lower prices. We see raising public awareness to increase demand for products as one important function of the Zero Energy House Learning Center. Technologies like Aerogel insulation, Vacume insulated glass, electrochromic glass, Building integrated photovoltaic materials and OLED lighting will revolutionize building design and construction when they reach an affordable level. Advances in Mechanical systems like Liquid Dessicant Solar Cooling also show promise for the next generation ZEH in the hot and humid southeast. Liquid Desiccant solar cooling systems, the end products of a seven year, $5 million development program funded by the Department of Energy's SBIR program and the National Renewable Energy Laboratory can convert hot water from solar thermal panels into cooling and dehumidification.

We are also interested in the interface between buildings and other related systems. The key to energy efficiency in the future will undoubtedly lie in smart grids that will regulate the flow of electricity to and from buildings according to peak and low demand periods. The plug-in hybrid electric vehicles, soon to be released by several auto makers, will be key elements in regulating this flow and storing energy for the grid and will be considered as an integral part of the ZEH Learning Center design.

The Solar Decathlon is an event held every other year on the Mall in Washington DC to showcase the latest advances and emerging technologies for energy efficient buildings. Ten Teams are chosen from a pool of applicants to design and build energy efficient buildings on the Mall. The RFP for the 2011 Solar Decathlon has been issued and I have assembled a team from FSU, UF, UCF and USF to make a proposal by the deadline in November. The ZEH learning center will be a modular design that can be disassembled, transported to Washington DC, and reassembled on the Mall for the 2011 Solar Decathlon. The ZEH Learning Center Task is particularly challenging in that the final product will be a built structure that will require significant support from industry partners. We are in the process of rallying Industry support and to date we have verbal commitments from the following companies:

Insulation
***Acoustiblok* International Headquarters** 6900 Interbay Boulevard Tampa, Florida U.S.A. 33616
Windows
Pilkington Group/ Nippon Sheet glass Spacia Vacume insulated glass windows
Photovoltaics *Kyocera Solar, Inc.* Headquarters 7812 East Acoma Dr. Scottsdale, Arizona 85260
System Photonics Via Ghiarola Vecchia, 73 41042 Fiorano (MO)

Structural Insulated Panels
PermaTherm, Inc. 269 Industrial Park Road Monticello, GA 31064
Gramatica Group 13926 Clubhouse Drive Tampa, Fl 33618
Housing Manufacturers
Misawa Homes Tokyo Japan
Sekisui Haimu Chiba Japan
Palm Harbor Homes Plant City, Florida
Others
In addition, we are currently talking with Cisco about smart connected building technology and Trane about Mechanical systems.

We have established the following collaborations:

FSU- Justin Kramer- OGZEB Project director
UF- Robert Rees- School of Building construction, Solar Decathlon Europe entry
UCF/Florida Solar Energy Center- Subrato Chandra- Director, Stephanie Thomas- Architectural researcher, David Click Photovoltaic researcher
USF- Delcie Durham- Engineering, Jennifer Isenbeck- Mechanical Engineer
Professionals-
Terry Osborn- Architect, Osborn Sharp Associates
Dr. RAM A. GOEL- Project Engineer, Soney FM LLC

Our research to date has been submitted for peer review to 3 International conferences on sustainability and energy efficiency. One abstract was accepted for the International Conference on Building Science and Engineering in Johor Bahru Malaysia and the full paper is currently under peer review. A second abstract was accepted to the Eco-Architecture 2010 conference in La Coruna Spain and the final paper is due in December. A third abstract was accepted to the International Conference on Sustainable Architecture and Urban Design 2010 in Penang Malaysia. I attended the Net-Zero Energy Buildings Conference II in New York City in October and was able to connect with several potential industry partners and fellow researchers. I have been invited to submit a paper for peer review to Faces of Urbanized Space Journal in Poland to be published later this year and will continue to submit papers to journals and conferences as the research develops.

UNIVERSITY OF SOUTH FLORIDA
Energy Delivery Infrastructures

PI: Alex Domijan, USF; **Co-PI:** Arif Islam, USF

Description: The Power Center for Utility Explorations (PCUE) proposes to simulate the effects of a renewable energy generation system in a microgrid context to the distribution grid system. The proposed project is to simulate the combination of renewable distributed generation and a battery system to assess the effects during critical conditions such as power system peak.

A research opportunity is to investigate how existing tools can be applied to properly representing dynamic and transient behaviors of microgrids. Therefore, in this project we propose using simulation tools to model a microgrid and investigate how well we can reproduce its measured behavior in the field.

Budget: $485,184

Universities: USF

External Collaborators: N/A

Progress Summary

We are in the stage of identifying simulation tools and different software's which will be useful for analysis of microgrids.

An important aspect of microgrid is to find a suitable control strategy that will advantage of the inherent scalability and robustness benefits of distributed energy. This gives an opportunity to investigate how existing tools can be applied to properly represent dynamic and transient behaviors of microgrids.

PSS®E is an integrated, interactive program for simulating, analyzing, and optimizing power system performance. It provides the user with the most advanced and proven methods in many technical areas, including:
Power Flow
Optimal Power Flow
Balanced or Unbalanced Fault Analysis
Dynamic Simulation
Extended Term Dynamic Simulation
Network Reduction

EDSA (Paladin DesignBase$^{TM)}$: Features of the software include
Fault Analysis: - calculate the effects of flowing faults in three-phase, single-phase and DC power distribution systems.
Power Flow Analysis: - Enable users to conduct balanced three-phase and single phase load flow studies on almost any network configuration imaginable. Power Quality Analysis and Mitigation, Dynamic Behavior Simulation, Sizing Optimization.
PSCAD/EMTDC: Power Systems CAD is a powerful and flexible graphical interface to the world-renowned, EMTDC solution engine. Contingency studies of AC networks relay coordination, transformer saturation effects, Investigation of new circuit and control concepts.

SimPower Systems: Simulink tools power flow analysis.
Mathematical computation, analysis, visualization, and algorithm development
Hardware connectivity and data analysis for test and measurement applications.

Next Step:
Plan to collect various parameters related to the simulation.

FESC
Florida Energy Systems Consortium

UNIVERSITY OF SOUTH FLORIDA

Creation of Carbon Sequestration Data, Technologies and Professional Cohorts for Florida

PI: Mark Stewart, USF; **Co-PI's:** Jeffrey Cunningham, Maya Trotz, USF
Students: Shadab Anwar (Post-doctoral researcher)
Drupatie Latchman (MS, Chemical & Biomedical Engineering)
Roland Okwen (PhD, Civil & Environmental Engineering)
Douglas Oti (PhD, Civil & Environmental Engineering)
Tina Roberts-Ashby (PhD, Geology)
Mark Thomas (MS, Civil & Environmental Engineering)

Description: Rising concerns over increasing levels of green house gases, especially carbon dioxide, have led to suggestions to capture carbon dioxide at fixed sources, such as fossil fuel power plants, and sequester the carbon for millennia by injecting it underground. Florida overlies many thousands of feet of carbonate rocks which may be suitable for geologic sequestration of carbon dioxide. This project will investigate the potential for geologic sequestration of carbon dioxide in Florida, the physical and chemical changes that may occur as a result of injection, assess the potential for escape of injected carbon dioxide, determine the risk, if any, to aquifer systems used for water supplies, develop methodologies for Florida utilities to predict the performance and risks of proposed sequestration projects, and educate a cohort of geologic sequestration professionals to create a carbon sequestration industry in Florida.

Budget: $80,133

Universities: USF

External Collaborators: Tampa Electric Company (TECO)

Progress Summary

We have made significant progress with our analysis of the physics and chemistry of supercritical CO2 injection into deep saline aquifers, with particular application to the Cedar Key-Lawson formations, the principal geologic carbon sequestration reservoirs identified in Florida. Results of numerical simulations with the TOUGH2 code suggest injection rates up to 8 million tons per year (Mt/y) may be possible with a single vertical injection well. Horizontal injection wells allow for a higher injection rate under pressure-limited conditions. We used the tool TOUGHReact (Lawrence Berkeley National Laboratory) to investigate chemical effects at flow rates up to 20 Mt/y. Model simulations suggest solution of supercritical CO2 in native brine lowers pH, which induces solution of dolomite and calcite and precipitation of gypsum. However, the volumes of minerals dissolved and precipitated are a very small fraction of the aquifer volume, and have very little effect on aquifer porosity or permeability, suggesting that long-term injection of supercritical CO_2 is feasible.

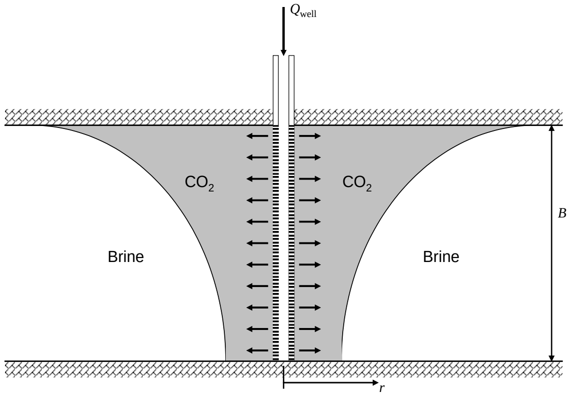
Major progress was made on evaluation of the South Florida Basin (SFB) for geologic sequestration and enhanced oil recovery (EOR). Our analysis shows that the SFB meets the criteria for EOR, and has significant carbon dioxide storage potential beyond the oil-producing zones. The results will be presented at the Geological Society of America national meeting in November, and a journal article is in preparation. Three trips were made to the Florida Geological Survey in Tallahassee to obtain geologic data for a State-wide evaluation of carbon sequestration potential which will be completed in early 2011. Early analysis suggests that Florida has very significant carbon sequestration resources, possibly the largest resources in the Southeast. A major proposal was submitted to DOE ($5.9 million) in cooperation with Tampa Electric, Florida Geological Survey, and the Electric Power Research Institute.

The effects of injected streams of aqueous waste water, supercritical CO2 or mixtures of the two into deep aquifers pose questions that relate to water quality and well clogging. Will chemical precipitates clog injection wells? Can the solubility of CO_2 be enhanced through co-injection with aqueous waste? Will injection adversely affect water quality in the receiving formation? We are using Geochemist Workbench for simulating potential effects of injection of an aqueous waste stream which could be co-injected with a CO2 injection stream or injected in a nearby well. This arrangement has the potential to increase the solubility of CO2 in deep aquifers and hence significantly increase storage capacity. Simulated waste streams were tested and sensitivity analysis conducted using two thermodynamic databases, Thermo.dat and Thermo_minteq.dat. Based on the thermodynamic results, above ground treatment would be necessary to limit well clogging from carbonate precipitates. Simulations are currently being undertaken to look at injection of a supercritical CO2 stream and an aqueous waste stream in close proximity to each other.

Large-scale carbon sequestration requires an efficient and economic system for capture of carbon dioxide. We are investigating a high-efficiency carbon capture system that uses a metallic oxide to carbonate capture progress. A thin film of calcium or calcium-magnesium oxide is placed on a ceramic cloth substrate. Carbon dioxide is captured by conversion of the oxide to carbonate, and released by thermally converting the carbonate back to oxide. Our research is focusing on increasing the thermal efficiency of the system and increasing the cycle lifetime of the thin oxide film.

Physical Modeling of Injection of Supercritical CO2

We used the software package TOUGH2/ECO2N (developed by Lawrence Berkeley National Laboratory) to predict how the candidate repository would respond to steady injection of CO_2 via a single vertical injection well.

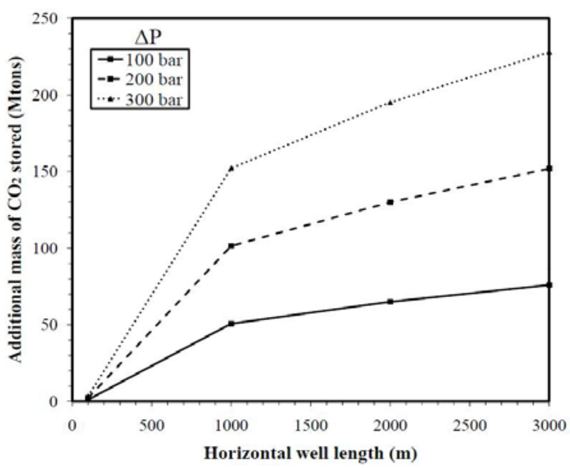


Time (Years)	Flow rate (million tons/year)		
	4	8	12
	r_{max} (km)	r_{max} (km)	r_{max} (km)
1	1.1	1.4	1.7
10	3.7	4.9	5.7
100	12.2	16.2	19.0

Model simulations were based upon assumed geologic parameters available from previous investigations. Model simulations suggest that steady *injection of CO_2 at rates up to 8 million tons/year (Mt/y) should be technically feasible.* Injection rates of higher than 12 Mt/y may require injection pressures that are too high, leading to potential fracturing of overlying cap rocks and subsequent leakage of CO_2. If CO_2 is injected at a rate of 8 Mt/y for 100 years, the tip of the CO_2 plume would travel about 16 km (10 miles) from the injection well. Based on simulations conducted as part of this project, the extent of the CO_2 plume can be estimated using the relationship $r_{max} = 0.351\{Qt\}^{0.5}$, where r_{max} is the maximum radius of the CO_2 plume in miles, Q is the injection rate in millions of tons of CO_2 per year, and t is the injection time in years. We have assessed the sensitivity of the model simulations to key assumptions and input variables. The pressure response in the formation is highly sensitive to the formation's permeability; if the actual permeability is a factor of 10 lower than current estimates, then CO_2 injection rates may be limited to about 1 Mt/y. Also, the results suggest that gravity has a significant impact on model predictions, and should not be neglected as has been done in some previously published example problems. Predictions of plume extent are sensitive to the residual (irreducible) brine saturation, S_{res}. Therefore, this parameter must be reasonably estimated or determined if an accurate estimate of plume extent is required.

Injection of Supercritical CO2 in Horizontal Wells

Effects of well orientation and length on the storage of CO_2 in deep saline aquifers were evaluated and quantified by conducting numerical simulations with TOUGH2. Simulations of CO_2 injection into confined, homogeneous, isotropic, saline aquifers were conducted for both vertical and horizontal wells. The metrics used in quantifying the performances of different strategies included changes in pressure near the well, mass of CO_2 dissolved into brine, fraction of injected CO_2 dissolved into brine, and storage efficiency, all evaluated over a simulated injection period of 50 years. These metrics were quantified as functions of well length and CO_2 injection rate. When equal injection rates and well lengths were compared, there was not a significant difference between the performances of horizontal wells and vertical wells. However, the length of a horizontal well may exceed the length of a vertical well, because the length of the horizontal well is not constrained to the vertical thickness of the geologic formation. As the length of the horizontal well was allowed to increase, the geologic formation could receive a significantly higher injection rate of CO_2 without exceeding a maximum allowable pressure. This results in a higher CO_2 storage efficiency in the formation, because storage efficiency increases with injection rate. These results suggest that horizontal wells could be utilized to improve CO_2 storage capacity in confined aquifers, especially under pressure-limited conditions.

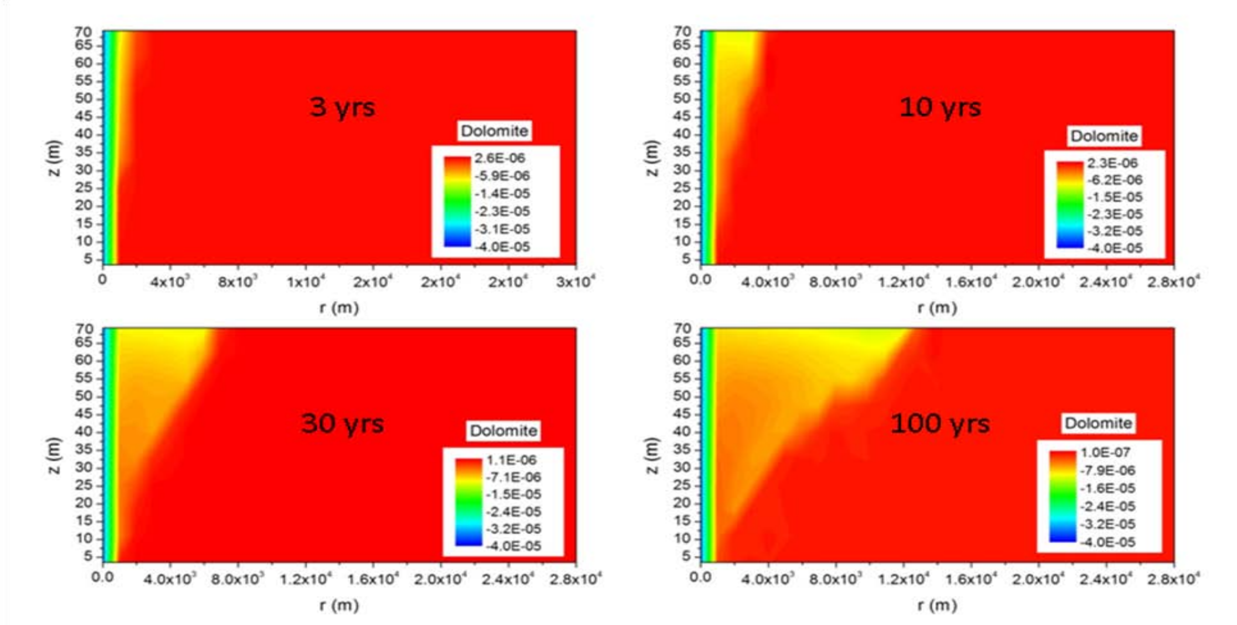


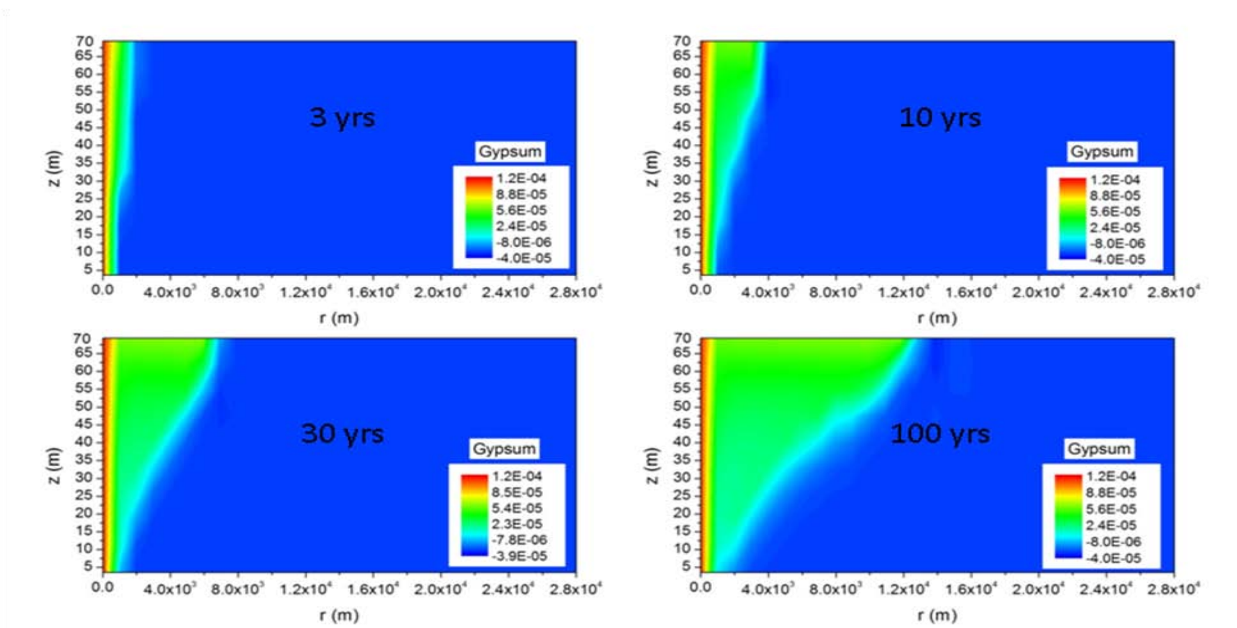
Chemical Modeling of Injection of Supercritical CO_2

Injection of CO2 into carbonate saline aquifers lowers pH, and can cause dissolution of carbonate minerals and precipitation of gypsum (calcium sulfate). We used the software package TOUGHReact (developed by Lawrence Berkeley National Laboratory) predict the geochemical response to steady injection of CO_2 via a single vertical injection well. We assume initial equilibrium with the rock matrix, which consists of dolomite, calcite, and gypsum. Results show that as CO2 moves radially outward, CO2 dissolves into the brine, and pH of the brine drops. This causes dissolution of dolomite (MgCa(CO3)2) and calcite (CaCO3). The increase of Ca(2+) ions successful implementation of CO2 injection in Florida. in solution then causes gypsum (CaSO4•*n* H2O) to precipitate. However, the changes in formation porosity due to both the dissolution and the precipitation are predicted to be very small, on the order of 10^(–4) or lower (i.e., 0.01% or lower), even assuming a CO2 injection rate of 20 Mt/y for 100 years.

Florida Energy Systems Consortium

Chemical dissolution and precipitation should not prevent successful implementation in Florida.





Evaluation of Potential Geologic Reservoirs for Carbon Sequestration in Florida

Use of anthropogenic carbon dioxide for enhanced oil recovery (EOR) reduces the cost of sequestration through the added value of the recovered oil. Successful EOR projects much meet several criteria. Our study determined that the Sunniland oil field of the South Florida Basin meets the five EOR criteria

Criterion 1: High CO_2 density

The effectiveness of the CO_2 sweep increases as the density of the supercritical CO_2 injected increases. The density is a function of injection pressure and bottom-hole temperatures. High injection pressures and low temperatures increase CO_2 density. The recommended density is 400 – 750 kg/m^3. The expected bottom-hole temperatures at a depth of 11,400 ft in the Sunniland Trend are about 40-45^{o}C. Hydrostatic fluid pressure at this depth is about 345 bar. At these pressures and temperatures, the minimum CO_2 density for CO_2 injected at 11,400 ft would be about 750-800 kg/m^3.

Criterion 2: Minimum API density

Tzimas et al. (2005) recommend a minimum API density of 22^o. Reported values for upper Sunniland Limestone oils range from 24^o to 28^o API. While the Sunniland Limestone oils are heavy oils, they meet the CO_2-EOR criterion for oil density.

Criterion3: Relatively thin production zones

The injected CO_2 is only about 80% as dense as the formation waters, resulting in a buoyancy effect. This can lead to the CO_2 front overriding the formation waters, leaving residual oil behind, and creating early breakthrough of CO_2 at the production well. This effect increases with increasing thicknesses of the producing or 'pay' zones. The pay zones in the Sunniland Trend oil fields are relatively thin, 15- to 30-ft thick, which encourages an efficient CO_2 sweep.

Criterion 4: Remaining oil in place exceeds 50-60%

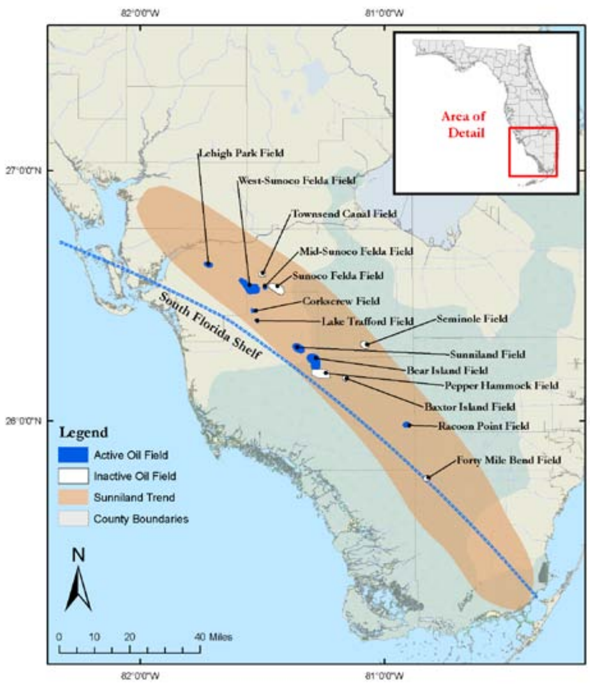
After water flooding, recovery ratios of produced oil to OOIP at Sunniland Trend oil fields range from about 0.3 to 0.5. This implies that 50-70% of the OOIP is still present (Lloyd, 1996).

Criterion 5: Uniform intergranular porosity

If the porosity and permeability of the producing zone is not uniform, or if significant fracture porosity is present, the CO_2 plume will form fingers instead of a more uniform front. The fingering will bypass much of the residual oil, reducing the effectiveness of the CO_2 injection. The producing zones in the Sunniland Trend oil fields have relatively simple intergranular porosity created by the original shell hash, later weathering, and some dolomitization. With the exception of production from the Lower Sunniland Limestone at Lake Trafford Field, the producing zones do not appear to have significant fracture porosity.

Summary of criteria:

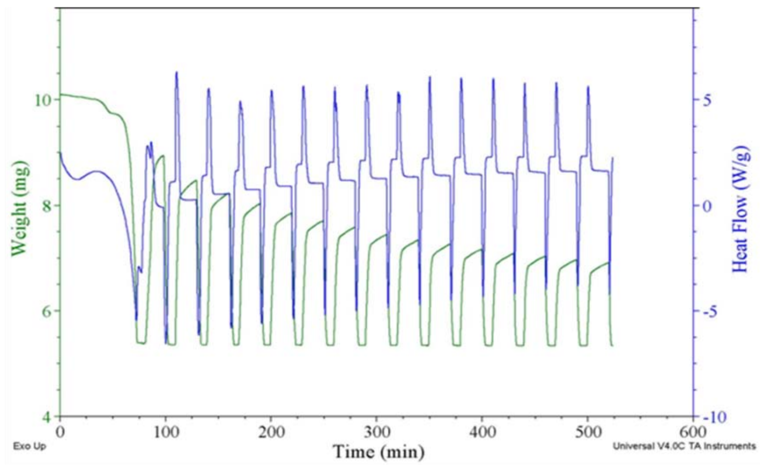
The Sunniland Trend appears to meet the five technical criteria for EOR with CO_2. The principal concerns and unknowns at the moment for Sunniland EOR are the cost of the delivered CO_2, the economics of EOR in the Sunniland Trend given a CO_2 price, and the volumes of CO_2 which can effectively be used in an EOR project.



Preliminary evaluation of geophysical and geologic well log data from the Florida Geological Survey suggests that The Cretaceous-Paleocene Cedar Keys-Lawson Formations have very significant storage potential, in excess of 800 million tons of CO_2 in central Florida alone, and perhaps several billion tons in central and south Florida combined. The injection zone lies at depths of 5000 to 6000 feet under all of central and south Florida. In addition, well logs suggest that the 5000 ft thick interval between the Sunniland Limestone and the Cedar Keys-Lawson injection zone contains several potential carbonate sequestration reservoirs. The Florida Peninsula may have the largest carbon sequestration potential in the Southeast.

The effect of injected streams (whether aqueous waste water, supercritical CO2 or mixtures of the two) into deep aquifers pose multiple questions that relate to water quality: Will the injected fluid clog the wells? How will the injected fluid impact the water quality of the deep aquifer? How will the injected fluid impact the water quality of the aquifers above? Will the injected fluid form precipitates or dissolve rock minerals thereby change aquifer porosity? Geochemical modeling software can be used to identify some of the potential impacts provided enough data exists for both the injected stream and the aquifer material. To date we have used Geochemist Workbench for simulating potential effects of injection of an aqueous waste stream which could potentially be co-injected with or close to a CO2 injection stream. This type of arrangement has the potential to increase solubility of CO2 in deep aquifers and hence increase storage capacity. Simulated waste streams were tested and sensitivity analysis conducted using two thermodynamic databases, Thermo.dat andThermo_minteq.dat. Based on the thermodynamic results, above ground treatment would be necessary to limit well clogging due to carbonate precipitates. Simulations are currently being undertaken to look at injection of a supercritical CO2 stream and an aqueous waste stream in close proximity to each other.

Carbon sequestration requires a reliable, efficient, and economical method for capture of CO_2. USF is investigating the use of calcium-magnesium oxide deposited as a thin film on a ceramic cloth substrate. Conversion of the oxide to carbonate captures CO_2 and heating converts the carbonate back to the oxide, releasing CO_2. Current research is focused on improving the thermal efficiency of the carbonation-calcination cycle, and increasing the number of cycles before regeneration is necessary.



UNIVERSITY OF SOUTH FLORIDA

Clean Drinking Water using Advanced Solar Energy Technologies

PI: Lee Stefanakos; **Co-PI's:** Yogi Goswami, Matthias Batzill, Maya Trotz, Sesha Srinivasan
Graduate Students: M. Abutayeh, K. Dalrymple

Description: Availability of fresh water is one of the biggest problems facing the world and Florida is one of the most vulnerable states to fresh water shortages. Moreover, Florida ground water is contaminated in many locations from leaky underground tanks, agricultural pesticides, and other chemicals. Although possible to desalinate abundant sea water, conventional systems are too energy intensive. Solar energy can provide the needed energy, and innovative new solar vacuum (USF) and humidification/dehumidification (UF) desalination systems can provide adequate fresh water for the state's needs. Systems will be developed for both bulk water desalination and small community needs/disaster response. We will also develop photocatalytic disinfection systems to remove contaminants and integrate these technologies with solar PV for complete water supply systems

Budget: $220,664

Universities: USF

External Collaborators: NA

Project Summary

This project report is composed of two components: (A) solar desalination and (B) solar photocatalytic disinfection.

Solar Desalination: The objective of this project is to develop an economically–viable and an environmentally–friendly desalination system that requires less energy and uses renewable energy for its operation. The most common desalination technique, multi–stage flash, will be modified to have its system vacuum created passively and its thermal energy requirements provided by solar radiation. The proposed modifications are expected to further the feasibility and broaden the applicability of the desalination process. A thorough literature review was conducted to assess the work that has been reported on conventional and sustainable desalination systems to date. A preliminary theoretical analysis was conducted to help design a pilot unit. Experimental simulations were carried out using a lab-scale indoor pilot unit under varying conditions. A detailed computer model is being developed to simulate the proposed desalination method. The model is built based on the original theoretical model and the obtained experimental results.

Solar Photocatalytic Disinfection: The objective for this task is to develop an economically–viable and an environmentally–friendly desalination system by lowering its energy demand and employing renewable energy to drive its operation. The most common desalination technique, multi–stage flash, will be modified to have its system vacuum created passively and use solar energy. A thorough literature review was conducted to assess the work that has been reported on the modeling of photocatalytic disinfection systems to date. The rationale for this study is that the development of a mechanistic model for photocatalytic disinfection will allow scientists and engineers to develop design and analytical tools to optimize photocatalytic disinfection systems so that their efficiency. A series of experiments were set up to test the hypothesis that overall disinfection rate is dependent on the rate of lipid peroxidation. Important parameters, which have an effect on the peroxidation rate, were varied and the overall inactivation rate for *E. coli* was observed. The bench-scale experiments are still ongoing. To ensure that our model can translate to the design of real systems, a pilot-scale system was proposed. The design of the system has been complete. Two systems will be used. One such system is already in operation and the other system is under construction. Both systems are capable of being used under solar conditions in outdoor.

2009 Annual Progress Report

This project report is composed of two components: (A) solar desalination and (B) solar photocatalytic disinfection.

Solar Desalination

Natural Vacuum Solar Flash Desalination:

Objective

Develop an economically–viable and an environmentally–friendly desalination system that requires less energy and uses renewable energy for its operation. The most common desalination technique, multi–stage flash, will be modified to have its system vacuum created passively and its thermal energy requirements provided by solar radiation. The proposed modifications are expected to further the feasibility and broaden the applicability of the desalination process.

A.1 Achievements

Literature review

A thorough literature review was conducted to assess the work that has been reported on conventional and sustainable desalination systems to date. The following tasks were completed under the literature review:
Review conventional desalination methods
Review sustainable desalination methods
Review combined desalination methods
Publish a literature review paper (1 peer-reviewed article in progress)

Theoretical Analysis

A preliminary theoretical analysis was conducted to help design a pilot unit. The following tasks were completed under the theoretical analysis:

Develop a detailed process flow diagram
Develop a comprehensive theoretical model
Present theoretical analysis results (1 invited presentation + 2 conference papers + 4 posters)
Publish theoretical analysis papers (2 peer-reviewed articles)

Experimental Simulations

Experimental simulations were carried out using a lab-scale indoor pilot unit under varying conditions. The following tasks were completed under the experimental simulations:

Design and build an experimental unit

Run experiments and collect data
Present experimental simulations results (1 invited presentation + 1 conference paper)
Publish experimental simulations papers (1 peer-reviewed article in progress)

Model Development

A detailed computer model is being developed to simulate the proposed desalination method. The model is built based on the original theoretical model and the obtained experimental results. The following tasks are being performed under the model development:

Revise and modify the theoretical model
Run simulations using the optimized model
Present the experimentally validated model results (in preparation)
Publish the experimentally validated model results (in preparation)

A.2 Short-Term Prospects

The short-term prospects will be performed upon the completion of the model development tasks above. The following tasks represent the short-term prospects of this project:

Perform a feasibility analysis
Write a conclusion and make recommendations
Produce a final manuscript for commencement

A.3 Long-Term Prospects

The long-term prospects will be performed by a future graduate student or a post-doctoral researcher. The following tasks represent the long-term prospects of this project:

Modify experimental unit to generate passive vacuum
Modify experimental unit to utilize heated brine
Run experiments and collect data for modified unit
Present experimental simulations results for modified unit
Publish experimental simulations papers for modified unit
Revise and modify the theoretical model for modified unit
Extend the theoretical model for modified unit to represent multi-stage
Run simulations using the optimized model for modified unit
Present the experimentally validated model results for modified unit
Publish the experimentally validated model results for modified unit
Perform a feasibility analysis for modified unit
Write a conclusion and make recommendations for modified unit
Produce a final manuscript for modified unit

Solar Photocatalytic Disinfection

Background

Drinking water requires disinfection to remove pathogens (bacteria, viruses and protozoa). It is estimated that 1.2 billion episodes of waterborne infections occur worldwide every year. The US has a reputation for high drinking water standards, but severe outbreaks have occurred (*e.g. Milwaukee 1993*

Cyptosporidium outbreak). The number of food and waterborne disease outbreaks in Florida averages about 300/yr. Chlorine is the most common disinfection method, but forms potentially carcinogenic byproducts (e.g. trihalomethanes). Regulations limit the amount of disinfection byproducts in drinking water.Alternative disinfection methods are available, but many are energy intensive and require expensive chemicals and equipment.

Objective

The objective for this task is to develop an economically–viable and an environmentally–friendly desalination system by lowering its energy demand and employing renewable energy to drive its operation. The most common desalination technique, multi–stage flash, will be modified to have its system vacuum created passively and use solar energy.

B.1 Achievements

Literature review

A thorough literature review was conducted to assess the work that has been reported on the modelling of photocatalytic disinfection systems to date. The following tasks were completed under the literature review:

Review available information on water disinfection
Review history of disinfection model development
Review the proposed inactivation pathways of photocatalysis
Prepare comprehensive review paper for publication - paper pending submission

Model development

The rationale for this study is that the development of a mechanistic model for photocatalytic disinfection will allow scientists and engineers to develop design and analytical tools to optimize photocatalytic disinfection systems so that their efficiency.

The following tasks were completed toward developing the model:

Establish the steps in photocatalytic inactivation
Develop mathematical relationships

Bench-scale experiments

A series of experiments were set up to test the hypothesis that overall disinfection rate is dependent on the rate of lipid peroxidation. Important parameters, which have an effect on the peroxidation rate, were varied and the overall inactivation rate for *E. coli* was observed. The bench-scale experiments are still ongoing.

The following tasks were accomplished:

Set up lab-scale experiments
Perform experiments

Pilot-scale experiments

To ensure that our model can translate to the design of real systems, a pilot-scale system was proposed. The design of the system has been complete. Two systems will be used. One such system is already in operation and the other system is under construction. Both systems are capable of being used under solar conditions in outdoor.

Design and build pilot-scale test system

B.2 Project Output Summary

Work presented at FESC Summit at USF September 30, 2009
Literature review completed
Bench-scale experiments still ongoing
Pilot system designed

B.3 Targets for the Next 3 Months

The following tasks will be completed within the next three months:

Test model with preliminary data
Complete construction of pilot-scale system
Commence testing on pilot-scale system and collect data
Complete bench-scale experiments and summarize data
Publish review paper in peer-reviewed journal