University of Florida

Florida Advanced Technological Education Center (FLATE)

PI: Marilyn Barger, Hillsborough Community College

Description: FLATE (Florida Advanced Technological Education Center) is partnering with FESC to develop statewide curriculum frameworks for technical A.S./A.A.S. degree programs supporting existing and new energy business sectors. FLATE will develop and have processed through the FLDOE the industry-validated student competencies of the frameworks. FLATE will also develop new courses required for each new program of study. Additionally FLATE will help state and community colleges implement the new frameworks in their institutions. To support the new curriculum, FLATE will work closely with the FESC Public Outreach and Industry Partnership programs to provide professional development opportunities for teachers and faculty to upgrade and update their knowledge base.

Budget: $300,000

Universities: Hillsborough Community College

External Collaborators:
Brevard Community College
Tallahassee Community College
Central Florida Community College
Polk State College
School District Hillsborough County
Florida Department of Education – Division of Adult and Career Education
West Side Technical School
WFI Banner Center for Energy
Advanced Technology for Energy and Environment Center (ATEEC)
University of West Florida, Dept of Construction Technology
WFI Banner Center for Construction
WFI Banner Center for Alternative Energy
Florida State College at Jacksonville
Madison Area Technical College ATE project for Alternative Energy certifications
Milwaukee Area Technical College Energy Conservation and Advanced Manufacturing Center (ECAM)
Florida Energy Workforce Consortium (FEWC)
TECO
Progress Enegy

Progress Summary

Contract is fully executed as of September 1. FLATE participated and hosted the following related events:
09/22/09 – poster presentation at USF-TECO "Energy Forum with US Senator Mel Martinez" (Tampa, FL)
12/08/08 – FLDOE Greenforce Florida Green Education Inventory Report Draft review (Tallahassee, FL)
02/06/09 – presentation at FESC Community College Summit (Gainesville, FL)
06/30/09 –hosted and participated in NSF ATE National Center for Energy and Environment (ATEEC) Regional Energy Conversation (Tampa, FL)

FESC
Florida Energy Systems Consortium

UNIVERSITY OF FLORIDA
A Low Cost CIGS Thin Film PV Process

PI: Gys Bosman, Tim Anderson
Students: Barrett Hicks, Yige Hu, Chris Muzillo, Vaibhav Chaudhari (Ph.D.)

Description: PV has entered into a period of record growth. Most of the current production is based on crystalline Si technology. However, there are fundamental limits to the ultimate Si costs that may inhibit it from achieving the desired level of contribution to worldwide energy production. In contrast, thin-film PV technology can reach the desired outcome due to fast deposition rates and lower cost. USF, UCF and UF play a lead role in developing these technologies. The world record 16% efficiency for CdTe was set by USF and held for 10 yrs. The time has come to coordinate the leading-edge resources within the SUS and establish a Florida PV industry. To achieve the desired level of energy generation, efficiency has to be >13%, which has been achieved in the laboratory; however, there is an inability to transfer laboratory success into manufacturing success. The transfer process has been the purview of industry, with limited success. What is needed is a fundamental understanding of this process, which can best be done in a university environment with industry cooperation. It is proposed to combine SUS expertise with local industry to develop this foundation. We will build and operate a pilot line that includes all aspects of module fabrication and characterization for the SUS/industry partners to develop manufacturing processes.

Budget: $450,000

Universities: UF

External Collaborators: NA

Progress Summary

Recent advances in the development of high efficiency polycrystalline thin film α-$CuIn_xGa_{1-x}Se$ (CIGS) solar cells have generated considerable excitement as evidenced by the number of CIGS startups in the U.S. In addition to their high cell efficiency, CIGS thin-film solar cells exhibit outstanding long-term outdoor stability, excellent radiation hardness, and the potential for use in a CGS/CIGS tandem arrangement. Needless to state, solar cells based on CIGS show excellent promise for commercialization.

The champion CIGS cell was demonstrated using the 3-stage NREL process by vacuum evaporation. Unfortunately, the 3-stage NREL recipe for high efficiency cells has not been developed for a practical manufacturing process. The goal of this project is to evaluate the feasibility of a countercurrent CVD process to rapidly and efficiently produce CIGS absorber layers. The process uses chlorides of the metal elements to transport In, Ga and Cu while Se transports under its own vapor pressure. It is a continuous rather than a batch process that uses two parallel substrates to form a channel flow reactor. This design minimizes wall area (less waste) and increases substrate area (higher throughput). The proposed process also specifies that the substrates move countercurrent to the gas reactant flow direction. This configuration permits the 3-stage NREL process to be emulated in a continuous manner. The countercurrent, parallel-plate design along with effluent recycling promises highly efficient reactant utilization.

Complex equilibrium calculations were performed to simulate the envisioned process. All four source zones were modeled to determine suitable reaction temperatures and reaction extents. The products of the source reactions were then allowed to equilibrate in the deposition zone to product thin films. Again, this region was modeled using complex chemical equilibrium calculations. The results of this analysis suggest were favorable and a patent has been filed. In parallel to the modeling, work has begun to convert an existing CVD reactor to grow CIGS. This work has included the design of the reactor, including the source zones, modifying the multi-stage furnace assembly, and installing the safety system. Cell fabrication will require deposition of the TCO (Al:ZnO) by sputter deposition and a 50 nm CdS buffer layer by chemical bath deposition. Work was also performed on both of these systems.

Device modeling and simulation of ZnO/CdS/CIGS/Mo solar cells were carried out using the Medici simulation program. Defect morphology in the CdS/CIGS interface is analyzed. Results were obtained for Fermi level pining, carrier recombination rates, current-voltage characteristics and cell efficiency. The simulation showed that moving the electrical junction away from the interface into the CIGS absorber layer improved the efficiency from 16.1 to 16.7%.

In addition, hot carrier solar cells are studied to improve cell conversion efficiency. Phonon dispersion properties are investigated to slow down thermalisation of photon-generated electron-hole pairs in absorber materials. The phonon dispersion of binary materials was simulated and phonon dispersion of ternary CIS will be characterized.

2009 Annual Progress Report

Background and Objectives

Power that is universally available and carbon neutral is becoming an increasingly relevant product. As concerns rise about using coal and natural gas due to their limited geographical occurrence and carbon dioxide emissions, alternative energy products are continuing to claim greater market shares. Photovoltaic (PV) devices are one such promising alternative energy source. First generation technology (crystalline silicon) still dominates the PV market, while second generation thin film PVs are now rapidly penetrating the market.

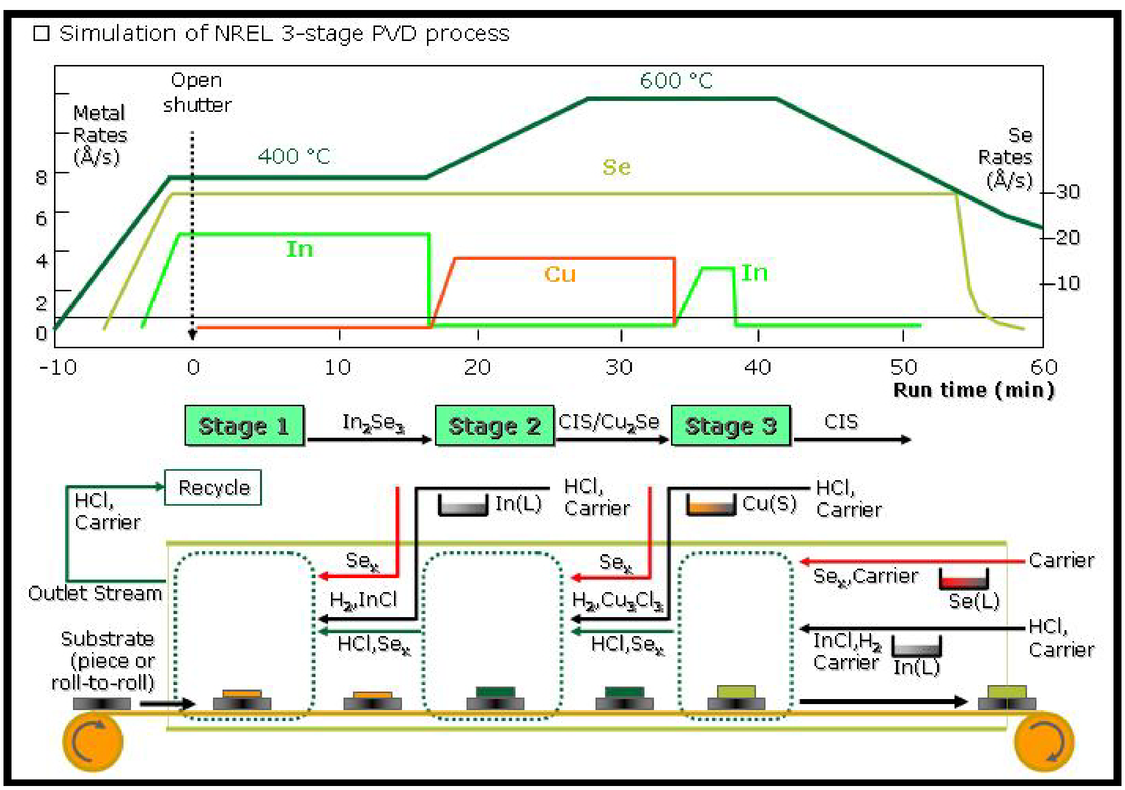
If inexpensive thin film PV manufacturing processes can be developed, they stand to be competitors in the global power market. One of the most promising thin film PV absorber materials is $CuIn_xGa_{1-x}Se_2$ and its related alloys $(Cu,Ag)(In,Ga,Al)(Se,S)_2$, which will be collectively referred to as CIGS. Its unmatched absorption of the visible solar spectrum due to a nearly optimal band gap (Kazmerski 1976), demonstrated long-term module stability (Mitchell 1990), and record laboratory efficiencies of 20% have made CIGS an attractive thin film PV absorber. As a result of these many benefits, there has been a considerable number of new companies (~35) pursuing CIGS PV development. These companies are primarily distinguished on the basis of their absorber synthesis process.

The cost of a solar cell is largely determined by the cell conversion efficiency and the cost of manufacturing. Although CIGS absorbers can be synthesized by a number of reaction pathways, the cell efficiency depends on the details of the synthesis scheme. Unfortunately, the record 20 % (AM1.5) efficient CIGS device results from the NREL 3-stage process that takes approximately a full hour to complete. The batch processing characteristic along with the long times required for evacuation, heating, and cooling as well as synthesis makes this a low throughput approach. A high throughput adaptation of this process could make it industrially economical if it were to achieve <2 μm/min CIGS synthesis rate.

The overall objective is then to develop a high throughput CIGS deposition process that provides device quality absorber layers with scale-up flexibility. The detailed problems and tasks to achieve the overall objective are as follows:
Design and construction of a chemical vapor deposition (CVD) system utilizing chloride chemistry
Thermochemical simulation of the CVD process to estimate optimal process windows
Experimental growth to demonstrate the feasibility of the newly developed CVD process
Characterization of the grown films and feedback of the results to improve the process
Investigate scale-up routes to extend laboratory results to factory scale continuous processes
Develop optimal process conditions and apply to the absorber formation
Fabricate CIGS solar cells using the new method and characterize the cell
Perform device modeling and simulation to better characterize the cells.

Major Achievements and Planned Activities

The figure below is a graphical representation of the planned CVD process, and its relation to the prescribed NREL 3-stage physical vapor deposition (PVD) process.



To intelligently design practical, robust processes for deposition of CIGS films, it is important to first grasp the thermodynamics of the material system. A complete thermodynamic assessment of CIGS is desirable, but very little experimental data is available for the ternary and quaternary systems. Studying the simpler binary systems within CIGS offers a tractable route to fully model the thermodynamics of the most promising alloy therein, $Cu(In,Ga)Se_2$. A recent thermodynamic assessment of Cu-Ga-Se (unpublished results) and an older assessment of Cu-In-Se have been completed by Shen et al. (Shen 2006). These databases allow our group to perform thermodynamic calculations using the Thermo-Calc software and its self-consistent SUB94 database with unprecedented accuracy (Sundman 1985).

The thermodynamic feasibility of CVD of CIGS has been studied. Based on the equilibrium models, a chloride based CVD process was proposed that would emulate the 3-stage NREL record efficiency process. A reactor was designed and constructed to simulate separate stages in the continuous CVD process. The process requires HCl gas reacting with the pure elemental metals (Cu, In, and Ga) to form volatile chloride species, which are then deposited downstream under Se overpressure. The reactor can hold the four pure elemental sources in separate chambers at three different temperatures. New furnace controllers are being installed to more precisely hold temperatures in different sectors of the reactor (i.e. Se source zone, In and Ga source zones, Cu source zone, and deposition/mixing zone). Nominal furnace temperatures will also be correlated to a temperature profile at the axial centerline of the reactor under N_2 carrier gas flow.

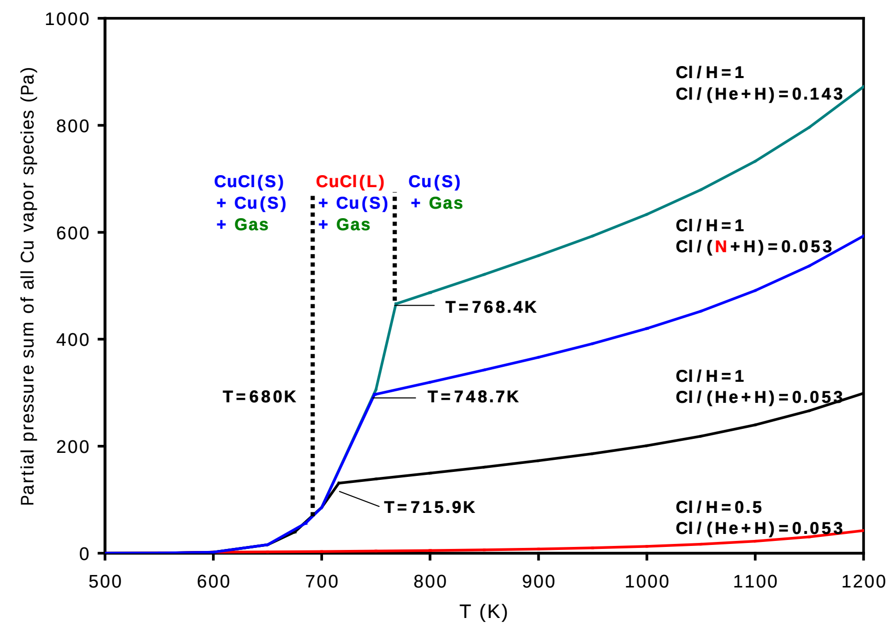
First, HCl transport gas diluted by N_2 will be passed over each of the pure Cu, In, and Ga sources and the exhaust chloride gases bubbled into water to measure their relative individual transport rates. This will be done once the newly installed reactor is entirely free of substantial leaks, which may require the modification of fittings or other joints. Targeted temperatures and carrier gas flow rates may be altered based on these results, as the process kinetics may not approach equilibrium. It is also possible that the pure Cu source may need to be replaced by CuCl if the HCl does not efficiently transport Cu species. However, complications would then be introduced because of the highly hygroscopic nature of CuCl.

As an example of the complex equilibrium calculations, the figure below shows the sum of the calculated partial pressures of the equilibrium Cu vapor phase species as a function of temperature in the Cu-Cl-H-inert system. In these calculations, He is used as an inert species. Four cases were studied, each with an excess of Cu. The base simulation (black line) assumed that HCl in a He carrier (H:Cl:He atom ratio of 1:1:18) reacted with the excess Cu at atmospheric pressure. As can be seen HCl reacts with the Cu to form solid CuCl, which melts at 680K. The liquid CuCl remains until the temperature exceeds 748.7K, at which temperature the vapor pressure of CuCl exceeds the partial pressure leaving only a gas and the excess solid Cu. The dominant vapor species is the trimer $(CuCl)_3$. Above this temperature the total Cu species partial pressure varies only slightly with temperature, and for this reason it is the preferred minimum operating temperature. The difficulty with this approach is that the transport efficiency (moles of Cu transported per mole of Cl introduced) is only about 10% (HCl is more stable than $(CuCl)_3$). More concentrated Cu transport can be achieved by increasing the HCl concentration (changing Cl/(He+H) from 0.053 to 0.143 (green line)), but the efficiency does not increase appreciably. Another approach is to reduce the H content for example by using a reducing agent (blue line substitutes reactive N for He, to compete with Cl for the H (forms NH_3 at equilibrium), thus freeing more Cl for reaction with Cu). Adding more H to the system (red line) takes the transport efficiency in the wrong direction.

The individual stages will be proved by forming In_2Se_3, Cu_2Se, and finally $CuInSe_2$. These experiments allow Se to encounter the H_2 gas product resulting from the oxidation of HCl. Extreme care must be undertaken to safely abate any toxic H_2Se produced and to detect any possible leaks. The reactor must therefore be equipped with hydride and acid gas resins that act as dry scrubbers for the exhaust stream. The exhaust then will be bubbled through nonvolatile, inert halocarbon oil. This is to prevent the further downstream wet scrubber (water) from introducing water vapor into the reactor. Furthermore, continuous toxic gas monitoring specifically for 20 ppb H_2Se detection will be in the lab at several points to ensure operator safety.

Once Cu(In,Ga)Se_2 can be successfully grown the operating conditions may be optimized to produce smooth, homogenous thin films on Mo-coated soda lime glass in a single deposition experiment. To fully demonstrate the absorber film's quality CdS will then be deposited by chemical bath deposition, followed by ZnO sputtering, and finally Al contact metallization. Thus real photovoltaic devices can be fabricated and their efficiencies measured in-house.

Significant progress has been made toward the demonstration of CIGS CVD. The theoretical work has been completed with promising results. There is much experimental work to be performed, yet once the system is running results will come quickly.



Equilibrium Cu-source calculations for the Cu-Cl-H-N-inert system.

Progress has also been made on the device modeling task using the Medici package. This is a 2D device simulator that models the electrical, thermal and optical characteristics of semiconductor devices. It simulates internal device operations through potential, electric field, carrier, current density and recombination and generation rate distributions. It is used in the project for modeling the ZnO/CdS/CIGS/Mo solar cell. Performance parameters and photo-J-V curves of the CIGS cells with different uniform band-gap profiles were obtained. Single junction CIGS cells with varying thickness of the CdS buffer layer were simulated.

Next, the Medici software was applied to study the effects of defect morphology in the interface of CdS and CIGS, where possible migration of Cu^+ induces the diffusion of Cd^{2+}. As a result, the charged difference between Cd^{2+} and Cu^+ converts p-type CIGS to n-type at the surface. This transfer process is simulated by Medici and the carrier recombination rates, current-voltage characteristics and cell efficiency were calculated and presented at the 2009 FESC Summit.

A second effort is to study the thermalisation problem that limits single bandgap solar cells. Hot carrier solar cells are designed to collect high energy electron and holes before they are thermalised to the bandgap energy level. The lifetime of the hot carriers is increased by blocking the decay of optical phonons into acoustic phonons, which is the principle energy decay mechanism for hot photo-generated carriers. Phonon dispersion of a GaAs/AlAs superlattice was simulated. Phonon dispersion of ternary CIS will be investigated with the focus on collecting the hot carriers efficiently so that higher open-circuited cell voltage values may result.

Patents

"Chemical Vapor Deposition of $CuIn_xGa_{1-x}(Se_yS_{1-y})_2$ Thin Films and Uses Thereof," T.J. Anderson and W.K. Kim. U.S. Patent Application No. PCT/US2008/065400 filed May 30, 2008. Application pending.

Presentations

Muzzillo, C. P., T. J. Anderson (2009). "High rate chemical vapor deposition of $Cu(In,Ga)Se_2$." Poster presentation at the Florida Energy Systems Consortium Summit, Tampa, FL.

Hu, Y., G. Bosman, T.J. Anderson (2009). "Device simulation of ZnO/CdS/CIGS/Mo solar cell using Medici." Poster presentation at the Florida Energy Systems Consortium Summit, Tampa, FL.

References

Kazmerski, L. L., F. R. White and G. K. Morgan (1976). "Thin-film $CuInSe_2$/CdS heterojunction solar cells." Applied Physics Letters **29**(4): 268-270.

Mitchell, K. W., C. Eberspacher, J. H. Ermer, K. L. Pauls and D. N. Pier (1990). "$CuInSe_2$ cells and modules." Electron Devices, IEEE Transactions on **37**(2): 410-417.

Shen, J., W. K. Kim, S. Shang, M. Chu, S. Cao and T. J. Anderson (2006). "Thermodynamic description of the ternary compounds in the Cu-In-Se system." Rare Metals **25**(5): 481-487.

Sundman, B., B. Jansson and J.-O. Andersson (1985). "The Thermo-Calc databank system." Calphad **9**(2): 153-190.

UNIVERSITY OF FLORIDA

Solar Thermal Power for Bulk Power and Distributed Generation

PI: David Hahn
Students: Richard Stehle (PhD); Michael Bobek (PhD); Kyle Allen (PhD); Justin Dodson (PhD)

Description: While there are many different approaches to hydrogen generation, the most attractive means is to split water molecules using solar energy. The current approach is to develop highly reactive metal oxide materials to produce intermediary reactions that result in the splitting of water to produce hydrogen at moderate temperatures (<1000 K). It is envisioned that the metal oxide reactors will ultimately be mounted within a solar concentrating reactor, and irradiated via heliostats. This Task is structured toward the overall goals of solar-driven, thermochemical hydrogen production, with associated efforts toward the enabling surface science, catalysis, particle science, material synthesis, nano-structures, multiscale-multiphase physics modeling, and process simulation that will enable the realization of solar hydrogen-based fuels to power the transportation economy. Successful efforts as targeted in this project are a critical step toward increased renewable-resource based fuels and energy, reduction of GHG emissions, and establishment of a new power industry in Florida.

Budget: $446,400

Universities: UF

Progress Summary

Efforts to date have focused on two primary tasks, namely, construction of two laboratory-scale reactors for fundamental studies of the reactor processes and surface chemistry for hydrogen production. The first reactor is a monolithic configuration that is specifically designed to allow for fundamental measurements of surface kinetics during hydrogen production from reduced ferrous surfaces. This reactor is powered by resistance heating to enable precise temperature control. Real-time species measurements will be made with on-line mass spectrometry using a heated gas capillary to sample directly from the reactor stream. The second reactor design is configured around the concept of a fluidized bed to achieve high efficiency with actual reactors. Ultimately, this configuration will be extended to magnetically-assisted fluidized bed configurations. As a laboratory system, this reactor will also be configured with resistance heating to allow precise control. Ultimately, we will move toward pilot-scale radiatively heated reactors using solar simulator lamps. However, for fundamental studies, the electrically heated reactors are most efficient.

The current work has focused on the use of ferrous metals, primarily elemental iron as the reduced material. Upon exposure to water vapor under the correct temperatures, the iron is oxidized primarily to hematite and magnetite, generating hydrogen. The goals of the above described facilities are to measure the fundamental reaction kinetics of the oxidation states, and to explore the final state of oxide, as well as gage process efficiency under highly dispersed powderized reactants. Assessment of oxidized states will be done through a combination of surface analysis tools, including micro-Raman spectroscopy for speciation, and depth analysis using a focused-ion beam (FIB), which will enable detailed analysis about the penetration of the oxide layer into the bulk iron substrate.

At present, the monolithic reactor is undergoing final assembly. All fabrication and acquisition of the necessary heating elements, reactor housing, process controllers, flow controllers, and gas-sampling interfaces have been completed. The primary power is via a series of four high-temperature 400 W heater coils. These are formed around a concentric-tube annular flow reactor, designed to provide an isothermal reactor test section. Within the month of October, the system will be fully functional and initial testing and benchmarking of the system performance will be initiated. It is fully expected that hydrogen generation will be initiated in November/December of this year.

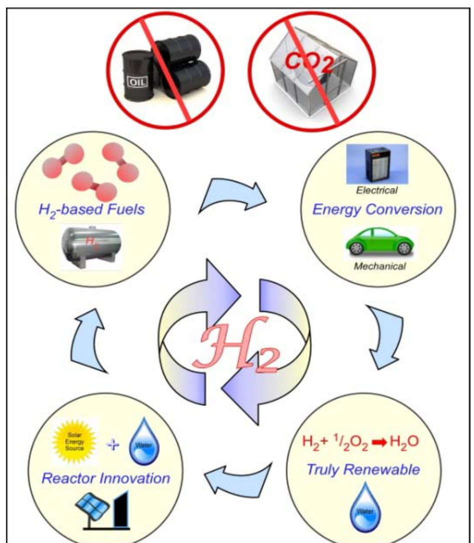
At present, the fluidized bed rector is also undergoing final assembly. The reactor was constructed about a high-temperature tube furnace to provide uniform process heat. A reduced iron-oxide power will be used for assessment of the reactor performance. The time-frame is similar to the monolithic reactor, with initial testing and benchmarking of the fluidization process expected to be completed in October/November, and hydrogen-generation activities initiated in the November/December time-frame. Parallel efforts are in place with regard to magnetically-assisted fluidization.

Additional efforts have focused on understanding of surface reaction processes and the relationships between surface properties and functionality, specifically on correlating catalyst properties with water splitting activity and thermal reduction, and clarifying mechanistic details of the surface reactions.

Graduate students have been hired and are all fully integrated into the project. If is expected that additional graduate students will be hired in the coming months to complement the experimental efforts by focusing on computational modeling of the heat and mass transfer. These activities will be focused on the fluidized bed, in which critical transport phenomena remain to be addressed with regard to scaling to larger processes or to solar-driven processes.

2009 Annual Progress Report

Our project efforts to date have focused on direct hydrogen splitting from water in support of our overall mission to conceive, design, and develop advanced reactor technologies that utilize concentrated solar energy and highly reactive materials to produce low cost hydrogen. These activities directly align with the National Academy of Engineering Grand Challenge and published DOE strategic goals.
High temperature thermochemical production of hydrogen that uses concentrated solar radiation for process heat has been suggested as a candidate technology for renewable hydrogen. This process entails a two step approach where endothermic dissociation of a metal oxide is driven in a solar furnace. The liberated metal (or reduced metal oxide) is mixed with water vapor, and the resulting exothermic reaction liberates hydrogen molecules and re-oxidizes the metal. The metal oxide decomposition requires very high temperatures, on the order of 1500 C. The advantage of the two-step process is that the high-temperature separation of H_2 and O_2 is avoided and no explosive H_2 and O_2 mixtures are formed, since the H_2 and O_2 are formed in different steps. Recent work has reported metal oxide decomposition at temperatures of ~1300°C and hydrogen liberation at temperatures at 500°C. Such temperatures are very well suited for a tower type solar concentrator that can yield energy fluxes on the order of 1000 suns, and can potentially yield high quantities of hydrogen at low cost.

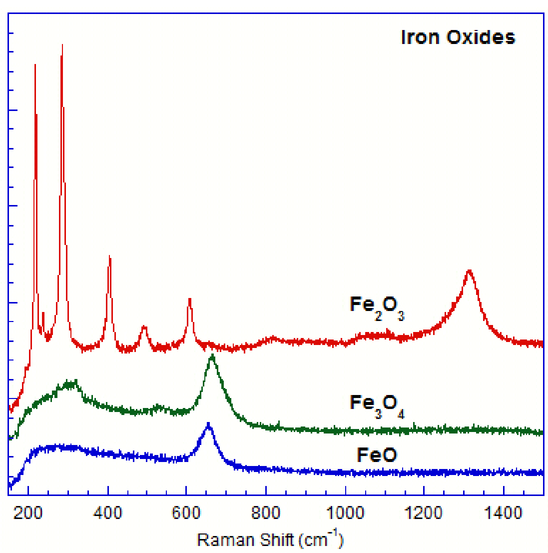


Carbon-neutral solar-driven hydrogen production

The theoretical basis for the multi-step water splitting reaction paths are well established, and the process has been demonstrated at the laboratory and pilot scale by various investigators using a variety of reactive materials. At this time ferrous, cerium, and zinc based materials show the most promise for implementation within prototype reactors. In order to achieve our goal of inexpensive hydrogen production (<$1.50/kg), the efficiency of the process will need to be substantially enhanced. The technological hurdles to achieving this goal are the high operating temperatures needed to achieve reasonable reaction kinetics, cyclic stability of the reactive material, non-uniform transient heating, and recuperation of thermal energy lost through high temperature operation. In order to overcome these technological hurdles, our FESC team has specifically initiated a plan to revolutionize thermochemical reactor design through the development of magnetically fluidized bed reactors. There are many technological advantages to operating such a reactor including, very high reaction surface area to yield rapid kinetics at more moderate operating temperatures (<1000 K), more spatially uniform temperature distribution during transient heating, and substantial control over the fluidization characteristics of the bed using magnetic fields. For the reactor temperature operating regime, the most likely phase transition during the iron oxidation process is a conversion of iron powder to magnetite. Both have excellent magnetic properties and are easily fluidized using electromagnets.

In support of these goals, our efforts to date have focused on two primary tasks, namely, construction of two laboratory-scale reactors for fundamental studies of the reactor processes and surface chemistry for hydrogen production. The first reactor is a monolithic configuration that is specifically designed to allow for fundamental measurements of surface kinetics during hydrogen production from reduced ferrous surfaces. This reactor is powered by resistance heating to enable precise temperature control. Real-time species measurements will be made with on-line mass spectrometry using a heated gas capillary to sample directly from the reactor stream. The second reactor design is configured around the concept of a fluidized bed to achieve high efficiency with actual reactors. Ultimately, this configuration will be extended to magnetically-assisted fluidized bed configurations. As a laboratory system, this reactor will also be configured with resistance heating to allow precise control. Ultimately, we will move toward pilot-scale radiatively heated reactors using solar simulator lamps. However, for fundamental studies, the electrically heated reactors are most efficient.

Our current focus is on the use of ferrous metals, although future work will examine doped metals using ferrous, cerium and zinc-based reactive materials. Important questions are the specific transformations of elemental under oxidizing conditions. Therefore, the monolithic reactor has been designed to allow precise temperature control under a wide range of process flow conditions, enabling direct assessment of the chemical states upon hydrogen production. Various analytical tools will be examined, including micro-Raman spectroscopy for speciation, and depth analysis using a focused-ion beam (FIB), which will enable detailed analysis about the penetration of the oxide layer into the bulk iron substrate. We have done preliminary assessment of micro-Raman spectroscopy as a means for analysis of surface iron oxide states. The right figure depicts Raman spectra for three different expected iron oxide states, showing the unique bands for each. Additional spectral features have been noted at higher vibrational energies, which will also be explored. For design of a fluidized reactor, critical questions involve the optimal powder size, both from a fluidization point of view as well as from an available iron volume for oxidation. Hence the monolithic reactor studies will also enable careful examination of the



oxide layer penetration distance as a function of temperature and time using the FIB and depth analysis. Therefore, future studies will make use of the monolithic reactor for generation of this data.

The monolithic reactor was configured as an annular tube design, making use of a 0.25” diameter iron rod as the monolithic reactor core. Resistance heating is used for the overall design, as implemented with a 1600-W electrical heater coil array. High-temperature Inconel coils were purchased in combination with a stainless-steel reactor housing, enabling an effective maximum reactor temperature of 1255 K. Mass flow controllers will be used for gas flow control, while a precise syringe pump will be used for water introduction into the steam generator. Overall, precise control of all reactor parameters (temperature and mass flow) will be realized. On-line mass spectrometry (Hiden residual gas analyzer) will be used for real-time assessment of products during hydrogen production, thereby allowing accurate assessment of process kinetics. The monolithic reactor is undergoing final assembly. All fabrication and acquisition of the necessary heating elements, reactor housing, process controllers, flow controllers, and gas-sampling interfaces have been completed. The primary power is via a series of four high-temperature 400 W heater coils. These are formed around a concentric-tube annular flow reactor, designed to provide an isothermal reactor test section. Within the month of October, the system will be fully functional and initial testing and benchmarking of the system performance will be initiated. It is fully expected that hydrogen generation will be initiated in November/December of this year.

The fluidized-bed reactor was configured around a tube furnace to provide the process heat, making use of a 1” diameter quartz tube as the reactor core. Resistance heating is used for the overall design, as implemented with a 1000-W tube furnace with 1400 K maximum temperature range. A steam generation system has been constructed to provide the necessary process steam for fluidization and hydrogen generation. Overall, precise control of all reactor parameters (temperature and mass flow) will be realized. On-line mass spectrometry (Hiden residual gas analyzer) will be used for real-time assessment of products during hydrogen production, thereby allowing accurate assessment of process rates and overall efficiency. All fabrication and acquisition of the necessary heating elements, reactor housing, process controllers, and flow controllers have been completed. Analytical instrumentation will be added in the near future, making use of leveraged funds from our recent DOE funding, to share gas analysis equipment. The time-frame is similar to the monolithic reactor, with initial testing and benchmarking of the fluidization process expected to be completed in October/November, and hydrogen-generation activities initiated in the November/December time-frame. Parallel efforts are in place with regard to magnetically-assisted fluidization.

Advances in the application of mixed-metal oxides for hydrogen production require fundamental understanding of surface reaction processes and the relationships between surface properties and functionality. Efforts have focused on correlating catalyst properties with water splitting activity and thermal reduction. The first part of this task involves synthesis of high surface-area mixed metal-oxides and characterization of their reactivity. Substituted ferrites (e.g. $M'FeO_x$) will be deposited onto oxide supports exhibit favorable characteristics for thermal hydrogen production, thus efforts to date have focused on synthesizing oxide-supported substituted ferrites. Our initial work involves Fe supported on nano-particle ZrO_2 as this is a promising combination, and we have investigated the redox (reduction-oxidation) properties of the Fe/n-ZrO_2. Future work will involve the addition of Ni to prepare a nickel-ferrite and adding Al_2O_3 as a structural support.

The modeling effort thus far has been led by Renwei Mei, with efforts directed toward formulating the computation framework for transport within a fluidized bed. Graduate students will be added in the coming months as the modeling effort accelerates.

Presentations:

1) FESC Summit in Tampa, Florida (October 29, 2009). Poster presented by R. Stehle, M. Bobek, J. Klausner, H. Weaver, R. Mei, and D.W. Hahn. Solar thermal chemistry for carbon-free hydrogen production.

UNIVERSITY OF FLORIDA

Joint Optimization of Urban Energy-Water Systems in Florida

PI: James P. Heaney
Student: Miguel Morales (M.E.)

Description: Urban water infrastructure systems for providing water supply, collecting and treating wastewater, collecting and managing stormwater, and reusing wastewater and stormwater require major energy inputs. End users of the water require even more energy to heat this water for showers and baths, clothes washing, cooking and other uses. Increasingly, cities will rely on alternative water supplies such as desalination that require much more energy per gallon of water produced. Conservation is the ideal way to save energy and water by managing the demand for these precious commodities. Major strides have been made in reducing indoor water use from about 75 gallons per person per day to as low as 40 gallons per person per day. However, these gains are being offset by concurrent increases in outdoor water use for irrigation that range from 30 to 300 gallons per person per day depending on irrigation practices and the size of the landscape. From a water use perspective, perhaps the greatest challenge will be the expected growing competition for water if certain energy options are implemented in order to reduce our current dependence on foreign oil. Several recent national studies warn of this impending energy-water crisis. This project will build on our extensive experience in evaluating urban water conservation options to include the implications for energy use and to develop integrated energy-water management systems that are compatible.

Budget: $72,000

Universities: UF

External Collaborators: NA

Progress Summary

Water use analysis is typically done using utility-wide data since it is to difficult to organize and evaluate customer level attribute and water billing data. A major breakthrough in the research of the CFWC has been the acquisition and use of customer level attributes including land use information, and utility level monthly water use data for every utility in the State of Florida. Florida, is unusual, if not unique, in making parcel level information public as part of its open government and public records laws. Thus, annually updated attribute and GIS data are available for nine million parcels in Florida and can be downloaded from the Florida Department of Revenue (FDOR) web site (ftp://sdrftp03.dor.state.fl.us/). Each of Florida's 67 counties has a property tax assessor's (CPTA) database that contains information that is included in the FDOR database and other attributes that are of interest in that county. For example, Alachua County reports which parcels have irrigation systems. The information in the county databases varies from county to county but the county data can be linked to the state database with a Unique Parcel Number. This information is of high quality since it is the basis for estimating property taxes. The key land use information for a parcel is its impervious and pervious areas. This information can be extracted directly from the FDOR/CPTA databases. The type of land use is available for about 90 land uses based on an FDOR land use code. Population information can be obtained from US Census data at the Census Block level of aggregation. Water utility service areas may not be contiguous with the political boundaries of the cities. Fortunately, the three largest of the five water management districts have developed GIS coverage that enables one to assign parcels to the appropriate utility. These data sources can be combined to estimate the long-term trends in attributes of interest.

All utilities in Florida are required to submit Monthly Operating Reports (MORs) that include information on daily water supplied by each treatment plant, water quality data, and information on the population served and the number of connections. Ten years of monthly water use data are available for each utility from the FDEP web site (http://www.dep.state.fl.us/water/drinkingwater/download.htm). This information can be used to evaluate historical trends and to project future growth patterns.

A detailed, customer level analysis of monthly water use, has been done for SFRs in Gainesville Regional Utilities using data for a recent year. A customer's water use pattern provides a signature of the nature of their water use. The vast majority of customers have a single meter that records their total water use. Our research indicates that indoor water use is constant throughout the year whereas outdoor water use varies widely based on the lot size, type of irrigation system, and customer preferences. Thus, it is possible to partition the total water use signal into its indoor and outdoor components.

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2009 Annual Progress Report

Impact

Florida seeks to be a leader in developing innovative energy systems that will reduce our dependence on foreign oil and generate energy related jobs. The Florida Energy Systems Consortium will develop numerous innovations to address our needs for more energy. Concurrently, we face unprecedented challenges to meet our growing needs for more water. Florida is blessed with a relative abundance of high quality water, especially ground water. These water sources have been a major component of the economic engine that has nurtured Florida's development over the past century. However, beginning in 2013, Florida water users will not be allowed to tap traditional low cost, high quality, water supply sources to meet their new needs because their supply has dwindled to low levels. Thus, we are running out of low cost energy and water at about the same time. Worse yet, many of the newer energy and water sources require more intensive use of these two resources, e.g., desalination of sea water is much more energy intensive than pumping from a nearby groundwater source; biofuel production requires far greater amounts of water to grow the crops and support the conversion process. National studies warn of the impending energy-water conflict (Cohen et al. 2004, Electric Power Research Institute 2003, National Research Council 2008, Navigant Consulting 2006, Sandia 2007, Webber 2008). Facing such dire circumstances, attention is shifting to developing more efficient systems and reducing our demands, where possible, through conservation. This project addresses how to evaluate energy-water linkages and find better ways to manage the demands for energy and water as a cost-effective way to reduce our future needs. It is essential for Florida to understand these water-energy trade-offs so that it can avoid myopic solutions that address one problem to the detriment of the other.

This two year study beginning July 1, 2009 will be conducted to integrate energy evaluations into our ongoing Conserve Florida Water Clearinghouse (CFWC) project that is addressing water use efficiency and conservation. CFWC already has a network of state agencies, water management districts, water utilities and professional water organizations. Its current funding level is $425,000 per year. Many of these water utilities also provide energy services, e.g., Jacksonville Electric Authority, Gainesville Regional Utilities. These utilities will be targeted for more in-depth evaluations of energy and water use since they already have in-house expertise in both areas. The results of this study will be disseminated in the form of software tools and technical support to allow users to do accurate integrated evaluations of water and energy systems.

Description

Statement of the Purpose and Objectives of the Program

Water and energy are fundamental necessities of modern civilization (Webber 2008). People can survive without water for a few days. Contemporary people are totally dependent on energy to grow food, run computers, or power homes, schools or offices. Demand for energy and water continues to increase due to growing population and affluence. Energy is a vital input to water infrastructure systems and vice versa and major tradeoffs exist. The overall purpose of this program is to develop new ways to integrate the evaluations of energy and water systems that recognize the tradeoffs that exist in satisfying needs in both areas with emphasis on better utilization of the these resources through improved efficiency and conservation.

Background and Significance

The energy-water nexus for Florida is shown in Table 1. Water use for power generation is a large user of fresh surface water and the dominant use of saline surface water. Agriculture is the largest user of fresh water and this use could grow significantly to support biofuel initiatives. All public water supply and most other water uses require that the water be delivered under pressure. Public water supplies consume about 4% of the nation's electricity (Sandia 2007). Per capita energy demands for supporting water supplies in Florida are expected to increase since cities are being required to meet future increases in water demand from energy intensive alternative sources such as desalination and reuse.

[Compiled by the U.S. Geological Survey, Tallahassee; all values in million gallons per day]

Florida 2000	Freshwater			Saline Water		
	Ground	Surface	Total	Ground	Surface	Total
Public Supply	2,199.36	237.43	2,436.79	0.00	0.00	0.00
Domestic self-supplied	198.68	0.00	198.68	0.00	0.00	0.00
Commercial-industrial self-supplied	430.70	132.60	563.30	0.00	1.18	1.18
Agricultural self-supplied	1,989.95	1,933.06	3,923.01	0.00	0.00	0.00
Recreational irrigation	230.45	181.28	411.73	0.00	0.00	0.00
Power generation	29.53	628.73	658.26	3.82	11,950.82	11,954.64
TOTALS	**5,078.67**	**3,113.10**	**8,191.77**	**3.82**	**11,952.00**	**11,955.82**

Table 1. Total water withdrawals in Florida by category in the year 2000 (Marella 2004).

All electric vehicles are estimated to withdraw ten times as much water and consume up to three times as much water per mile as gasoline powered vehicles (Webber 2008). Biofuels have an even bigger impact on water supplies due to increases in irrigation water demand, and crop processing for conversion to biofuels can consume 20 or more times as much water for every mile traveled than the production of gasoline (Webber 2008). Low cost irrigation water is no longer available in most parts of the United States. Nonpoint pollution associated with irrigated agriculture is also a significant additional cost to control. For example, excess nitrogen in the Mississippi River system is a major cause of the oxygen starved "dead zone" in the Gulf of Mexico. Nonpoint pollution from agriculture is a major component of this problem (National Research Council 2008).

Examples of the interrelationships between energy and water are shown in Figure 1. Energy use for supporting public water supply activities can be divided into two major components: 1) the energy needed to deliver the water to the end user; and 2) the additional energy use by the end user for water heating, clothes washing and drying. Energy use at the end use level is the greater of the two components in California accounting for 14% of California's electricity consumption and 31% of its natural gas consumption, mostly in the residential sector (Electric Power Research Institute 2003).

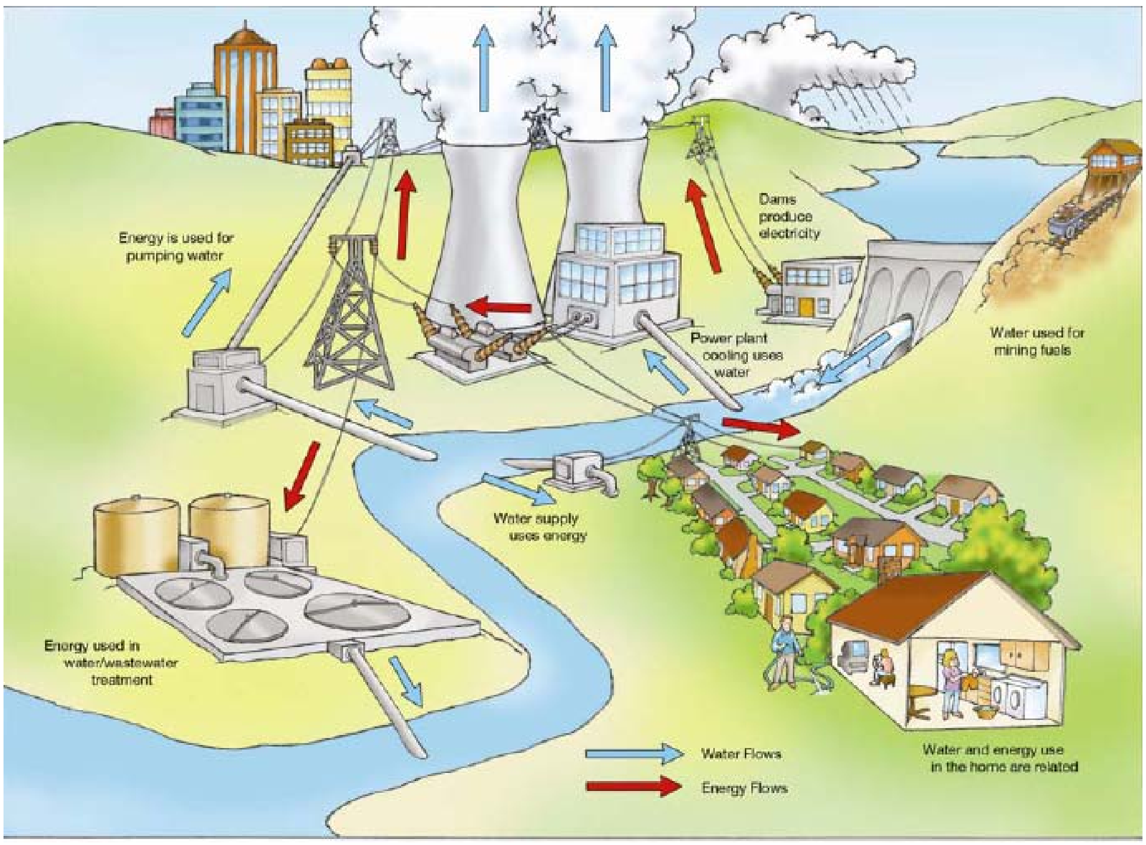

Figure 1. Examples of interrelationships between water and energy (Sandia 2007).

Project Plans

Project plans and activities

The four project activities are described below. The key deliverable will be a public domain energy and water evaluation model that reflects Florida conditions and that can be used to do integrated evaluations of energy and water programs. Two manuscripts will be submitted for publication in archival journals. These manuscripts will provide detailed descriptions of the methods used and the key results.

Literature review

The literature review will focus on assembling the results of previous energy-water studies that have been done at the national level and in other states, most notably California. The literature review will include a focus on developing energy and water use coefficients for various key activities. Available models for analyzing water-energy systems will be included in the review. The output of the literature review will be a recommended modeling approach for Florida.

Energy-water efficiency simulation model

We have developed an urban water conservation evaluation model for Florida called EZ Guide as part of ongoing research. EZ Guide evaluates urban water conservation programs in the following steps:

Using historical daily and monthly water use records for the past several years and a water use data base and activity sizes obtained from the Florida Department of Revenue database, calibrate EZ Guide to provide the best estimate of recent water use patterns at the end use level. The calibrated model includes the impacts of historical interventions by the water utilities such as outdoor water use restrictions during droughts.

Using the calibrated end use model, project future water use without intervention by the utility as a base case.

Using a library of water conservation options, their expected effectiveness and costs, prioritize among the available water conservation options using optimization techniques.

Find the optimal blend of conservation practices by comparing the cost of the conservation program with the utility's alternative cost for the next increment of water supply.

Implement the conservation program, track its actual performance, and adapt the program as needed.

The current funding does not provide support to include energy considerations in an in-depth manner. The funding from this project will allow us to add this critical element. The key additional elements for adding an energy component to EZ Guide are to incorporate energy utilization and cost information into the existing EZ Guide to allow joint evaluation of water and energy systems.

Energy-water efficiency optimization model

The Energy-Water Efficiency Simulation Model (EWESM) provides the essential detailed process information for evaluating the nature of water and energy use in urban areas. The inclusion of an optimization capability will allow us to go from *what if* to *what's best* evaluations. Key additional inputs for the optimizer are cost-performance relationships that provide the basis for doing trade-off analysis. A spreadsheet platform will be used for the simulation and optimization models to allow easy access to powerful traditional optimization tools like linear and nonlinear programming as well as newer evolutionary algorithms that can solve more complex optimization problems.

Model testing and utilization

Several detailed test bed case studies have been developed as part of ongoing Conserve Florida Water Clearinghouse activities. These detailed datasets for a given urban utility are used to provide a benchmark for testing the validity of simpler models that are often used for estimating water use patterns. These databases include a large amount of the essential information that is needed to evaluate energy systems as well as water systems including parcel size, detailed information regarding the physical features of the property (from the County Tax Assessor's database), climatic data for estimating water and energy use. The existence of this extensive water and demographic data warehouse for every parcel in the State of Florida provides a unique opportunity to do advanced energy-water evaluations.

Existing collaborations

This project is made feasible by the research efforts during the past three years by the Conserve Florida Water Clearinghouse (CFWC) that is directed by Professor Heaney, the P.I. on this project. CFWC receives $425,000 per year in support from the Florida Department of Environmental Protection, three water management districts and a professional water supply organization. Details about CFWC can be found at our web site (www.conservefloridawater.org). CFWC provides a variety of resources including a library on water conservation, databases of key information, the EZ Guide Model, and links to information about water conservation. The scope of activities is on water use and energy has not been a funded component of our studies to date. The support from this project will allow us to expand our activities to incorporate the critical energy-water nexus that needs to be an integral part of evaluations of both water and energy options.

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FESC
Florida Energy Systems Consortium

UNIVERSITY OF FLORIDA

Outreach Activities for the Florida Energy Systems Consortium

PI: Pierce Jones

Description: The Program for Resource Efficient Communities (PREC) promotes the adoption of best design, construction and management practices that measurably reduce energy and water consumption and environmental degradation in new residential community developments. Our focus extends from lot level through site development to surrounding lands and ecological systems. We support the implementation of these practices through direct training education and consulting activities, applied research projects/case studies, and partnering with "green" certification programs. As the Energy Extension Service, and through the cooperation of the Extension offices in each county in Florida, we provide and deliver continuing education courses and associated certifications for professionals involved in the design, construction, and operation of residential community developments, including "Build Green & Profit" and "Low Impact Development (LID) Practices for Florida: Stormwater." Through this network and with the assistance of our diversified faculty, we will deliver outreach activities for the Florida Energy Systems Consortium (FESC) in the areas of Energy/Climate Awareness Factsheets, demand side management programs, continuing education modules on applied energy efficient technologies, collaboration with demonstration houses throughout the state and alternatively fueled vehicle research and data collection. By working collaboratively with the FESC universities, we can help the citizens and communities of Florida make informed decisions on energy use and stimulate economic opportunities in the alternative energy and energy efficiency services sector.

Budget: $497,671

Universities: UF

Progress Summary

Energy/Climate Awareness Fact Sheets -

Contributed nine fact sheets available under "More Information on Home Energy Issues" including: *Caulking & Weather-Stripping*; *Dishwashers*; *House Design & Room Location*; *Radiant Barriers*; *Refrigerators & Freezers*; *The Roof*; *Swimming Pools*; *Ventilation*; and, *Whole-House Systems Approach to Energy Efficiency*. Additional fact sheets are under development.

Energy Extension Service (EES) –

Faculty is serving on both the UF/IFAS Sustainable Housing and Home Environment and the Climate Variability and Change Focus Teams. One of our faculty members developed the Climate Variability and Change Shared Materials site for county and state faculty (Sharepoint site).

As a major outreach activity we made 19 presentations regarding different aspects of energy efficiency at a number of functions and conferences, some of which included: county extension faculty in-service trainings, planning & zoning commissions, Florida municipal energy efficiency committee, Gulf Coast Energy Network, Edgewater City Commission, Orange County EcoNomic Living Expo, Florida Tech's International Sustainability Conference, Florida Housing Coalition Conference, Association of Florida Community Developers, DOE Southeast Regional Workshop, Farm Foundation, Florida Environmental Resources Agencies Conference, and Southeast Builders Conference. These meetings, activities, and conferences were held around the state and included Lake Buena Vista, Tampa, Edgewater, Gainesville, Orlando, Melbourne, Plant City, and Sarasota with an additional presentation made in Little Rock, Arkansas.

Developed tentative agenda for *Emerging Energy Issues and Topics* in-service training scheduled for March 18, 2010, in Gainesville. Online registration is underway through IFAS' Program Development and Evaluation Center dedicated website for County Faculty.

Demand Side Management (DSM) –

Under demand side management, worked with Gainesville Regional Utilities, St. Johns River Water Management District, Osceola County Extension Service, and Neutral Gator on a number of grant-related and other projects to compare household energy use based on consumptive use, to quantify carbon emission reductions from local weatherization programs, etc.

Continuing Education (CE) –

Developed and will soon offer *Greenhouse Gas Reduction and Energy Conservation I: Comprehensive Planning under Florida's HB 697* continuing education course for **5 AICP-CM credits for Planners (pending), 6 PDHs for Professional Engineers,** and 6 CEUs for Landscape Architects. This one-day class, from 9:30 am to 3:30 pm is scheduled on October 27th in Broward County, October 28th in Palm Beach County, and October 29th in Miami-Dade County with **the** goal of presenting to local officials,

planners and development professionals new growth management regulations as enacted in Florida HB 697, along with ways and means for addressing the new requirements.

In addition, collaborating with Sarasota, Manatee and Pinellas counties to develop and deliver continuing education classes targeting built environment professionals.

Demonstration Houses (DH) –

Working with Pinellas County to design and specify products for use in an energy-efficient demonstration house to be built at the County Extension Service offices. Working with Orange County to design and install a solar PV demonstration system to be built at the Orange County Extension Service offices and to be used in conjunction with educational programs.

Workforce Development (WD) –

Exploring collaborative opportunities for grant funding.

Alternatively Fueled Vehicles (AFV) –

Working with Progress Energy to evaluate performance of PHEV using converted Toyota Prius equipped with GPS tracking system and software to monitor performance; had discussions with TECO on natural gas powered vehicles; met with Publix to discuss fuel efficiency data from their fleet of 180+ hybrid vehicles. Made three presentations on alternatively fueled vehicles.

Collaboration on New Initiatives –

Prepared nine FESC-Related Grant Applications in 2009, of which two are funded and the decision is pending on three.

Energy/Climate Awareness Fact Sheets (FS) –

Developed tentative list of fact sheet titles and met with FESC group on August 25th to discuss.

Sent nine fact sheets to be included on FESC website under the proposed title of *More Information on Home Energy Issues* and included: Caulking & Weather-Stripping; Dishwashers; House Design & Room Location; Radiant Barriers; Refrigerators & Freezers; The Roof; Swimming Pools; Ventilation; Whole-House Systems Approach to Energy Efficiency.

Additional fact sheets under development.

Energy Extension Service (EES) –

9/3 Presented information about FESC to approximately 80 state and county faculty members during the Climate Change in-service training, Lake Buena Vista; in addition, served on panel discussion during same training

Kathleen Ruppert is a member of the IFAS Sustainable Housing and Home Environment and the Climate Variability and Change Focus Teams. Barbra Larson developed the Climate Variability and Change Shared Materials site for county and state faculty (Sharepoint site)

9/29 – 30 Attended, participated and presented (*FESC Education and Outreach Efforts*) in the FESC Summit, Tampa.

Developed tentative agenda for *Emerging Energy Issues and Topics* in-service training scheduled for March 18, 2010, in Gainesville. Online registration is underway through IFAS' Program Development and Evaluation Center dedicated website for County Faculty. Plan is to bring county faculty up-to-date on activities in support of the Florida Energy Systems Consortium and to increase their knowledge on specific energy related topics of current and future interest to them and their clientele.

Presentations by Dr. Pierce Jones:

1/14 Restoration Development Order Recommendations - Edgewater Planning & Zoning Commission

1/16 Energy & Housing in Florida - Florida Municipal Energy Efficiency Committee (Gainesville)

1/23 Energy & Housing in Florida - Gulf Coast Energy Network (Ft Walton Beach)

1/26 Restoration Development Order Recommendations - Edgewater City Commission

2/2 Restoration - Edgewater City Commission

2/3 Energy & Housing in Florida – Baker & Hostetler (Orlando)

2/4 FESC Outreach Overview - FESC Steering Committee (Gainesville)

2/7 Environmental Challenges to Florida's Future - Orange County EcoNomic Living Expo

2/18 Community Development and Climate Change – UF/IFAS in-service (Plant City)

3/4 Reduced Impact Practices at "Restoration" – FIT's International Sustainability Conference (Melbourne)

4/30 Green Building and Construction - Florida Housing Coalition Conference (Orlando)

5/22 Monetizing Energy in Resource Efficient Communities - Association of Florida Community Developers (Orlando)

5/27 Resource Efficient Master Planned Communities - DOE SE Regional Workshop (Orlando)

6/30 Extension Resource Efficiency Programs - Farm Foundation (Little Rock, AR)

7/30 Compact Urban Form and GHG Emissions - Florida Environmental Resources Agencies Conference (Sarasota)

7/31 Bright Ideas to Build On - Southeast Builders Conference (Orlando)

8/20 HB 697: Carbon Credits for Measured Performance – TREEO Continuing Education Workshop (Gainesville)

Demand Side Management (DSM) –

Current activities include:

Working with GRU on American Public Power Association, Demonstration of Energy Efficient Developments Grant to compare households based on consumptive use and identifying households with low energy use/carbon emissions;

Working with GRU and the St John's River Water Management District on Soil Moisture Sensor pilot program where households will be compared on potable water use. The program targets measurable reductions that can be leveraged for alternative water supply funding;

Working with Osceola County Extension to quantify energy reductions from various weatherization programs in the area;

Working with Neutral Gator (local non-profit) to quantify potential for carbon emission reductions from local weatherization programs;

Developing energy, water and carbon baseline standards for use in various county, utility, non-profit, and industry programs.

Continuing Education (CE) –

Greenhouse Gas Reduction and Energy Conservation I: Comprehensive Planning Under Florida's HB 697 continuing education course developed and to be offered for **5 AICP-CM credits for Planners (pending), 6 PDHs for Professional Engineers,** and 6 CEUs for Landscape Architects. This is a one-day class, from 9:30 am to 3:30 pm.

Classes scheduled to date:

October 27 - Broward County / Ft. Lauderdale Research and Education Center, Davie (http://fl rec.ifas.ufl .edu/directions.shtml)

October 28 - Palm Beach County / Okeeheelee Nature Center, West Palm Beach (http://www.co.palm-beach.fl .us/parks/nature/ okeeheelee_nature_center/)

October 29 - Miami-Dade County / Extension Office, Homestead (http://directory.ifas.ufl .edu/Dir/searchdir?pageID=2&uid=A23)

Course Description: With the recent emergence of greenhouse gas (GHG) reduction and energy efficiency requirements in the comprehensive planning scheme through HB 697, comprehensive planning has entered a new era in Florida. The new statutory requirement to address greenhouse gas and energy efficiency in local comprehensive plans will pose challenges for local governments who must embrace new scientific and technological concepts and incorporate them into their local land use regulatory schemes. Similarly, land owners and developers will need to work with local governments to comply with these new statutory requirements. This one-day workshop will explore the implications of HB 697

as a comprehensive planning matter and examine issues and best practices from other states with GHG regulations.
Course Goal: The goal is to present local officials, planners and development professionals with the new requirements of growth management regulations as enacted in Florida HB 697, along with ways and means for addressing the new requirements.

Registration forms available at http://buildgreen.ufl.edu/cecampus/

With sponsorship funding from block grants FESC is collaborating with Sarasota, Manatee and Pinellas counties to develop and deliver continuing education classes targeting built environment professionals.

Demonstration Houses (DH) –

Working with Pinellas County to design and specify products for use in an energy-efficient demonstration house to be built at the County Extension Service offices. We are facilitating collaboration with the FSU Off-Grid, Zero Emissions Building researchers to provide plans and design guidance.

Working with Orange County to design and install a solar PV demonstration system to be built at the Orange County Extension Service offices and to be used in conjunction with educational programs. FESC will coordinate development of supporting educational materials.

Workforce Development (WD) –

Exploring collaborative opportunities for grant funding.

Alternatively Fueled Vehicles (AFV) –

Working with Progress Energy to evaluate performance of PHEV using converted Toyota Prius equipped with GPS tracking system and software to monitor performance; had discussions with TECO on natural gas powered vehicles; met with Publix to discuss fuel efficiency data from their fleet of 180+ hybrid vehicles.

Targeted Presentations by Dr. Pierce Jones:

1/25 *Alternative Transportation in Florida* - Alachua County Library - Hawthorne Branch Library

1/30 *Plug-in Hybrid Electric Vehicles: Initial Thoughts* - Lakeland South Rotary

3/16 *Plug-in Hybrid Electric Vehicles: Initial Thoughts* - FISE Seminar (Gainesville)

Collaboration on New Initiatives –

FESC-Related Grant Applications, 2009:

EPA, Indoor Environments: Reducing Public Exposure to Indoor Pollutants. Sept. 14, 2009. Project title: *Integrated Indoor Environmental Air Quality Training for Building Professionals* (includes training on HVAC systems and other IAQ practices that have energy connections.) Budget request of $240,565. Decision pending.

Florida Department of Community Affairs. Public Awareness and Outreach Campaign for American Recovery and Reinvestment Act Weatherization Assistance Program. September 10, 2009. Budget request of $411,065. Not funded.

Department of Labor, American Recovery and Reinvestment Act of 2009; Energy Training Partnership Grants. Sept. 4, 2009. Applicant was Florida Green Building Coalition. PREC/FESC was included as a collaborator, with a sub-contractor budget request of $301,605. Decision pending.

Department of Energy, Recovery Act: Community Renewable Energy Deployment DE-FOA-0000122. Sept. 3, 2009. Applicant was Babcock Ranch Independent Special District. FESC / UF (PREC and

PURC) included as collaborators, with a total sub-contractor budget request of $278,027 and match contribution of $118,357. Decision pending.

Florida Department of Community Affairs. Weatherization Construction Contractor Training for Implementation of American Recovery and Reinvestment Act (ARRA) Funding for the Weatherization Assistance Program (WAP). August 21, 2009. PREC's proposal was a collaborative effort involving the Florida Solar Energy Center at UCF; Florida Housing Coalition; Disasters, Strategies and Ideas Group, LLC; and Conceptual Arts, Inc. Budget request of $ 2,040,337. Not funded.

EPA, Climate Showcase Communities. July 22, 2009. Project title: *Optimizing GHG Emissions Reductions in Master Planned Communities through Florida's Growth Management Process*. Applicant was the East Central Florida Regional Planning Council. PREC was included as a collaborator, with a sub-contractor budget request of $315,033 (total project request of $702,781). Not funded.

EPA, Pesticide Registration Improvement Renewal Act (PRIA 2) Partnership Grants. June 1, 2009. Project title: *Providing the Foundation for Resource Efficient Communities: A Strategy for Reducing Pesticide Risk in Master Planned Residential Development* (included training on building practices that serve to reduce both energy consumption and pest issues). Budget request of $247,209. Not funded.

American Public Power Association (APPA), Demonstration of Energy Efficient Developments (DEED) grant. November 1, 2009. Project title: *Assessing the Potential for Residential Energy Efficiency in Carbon Markets.* This project is a collaboration with Gainesville Regional Utilities and serves as an analysis of potential demand side management programs linked to carbon markets. Budget request of $15,000. Funded.

Alachua County, Energy Conservation Strategies Commission. August 1, 2009. Project Title: *10,000 Home Weatherization Initiative: Phase 1 Feasibility Analysis.* This project is a collaborative effort between PREC and the Alachua County Office of Sustainability. Funded $10,000 with request of additional $10,000 for Phase 2.

UNIVERSITY OF FLORIDA

Clean Drinking Water using Advanced Solar Energy Technologies

PI: James Klausner
Students: Fadi Alnaimat/ Ph.D

Description: Availability of fresh water is a major societal problem facing the world. The state of Florida is vulnerable to fresh water shortages. Moreover, Florida ground water is contaminated in many locations from leaky underground tanks, agricultural pesticides, and other chemicals. Although it is possible to desalinate sea water, conventional systems are energy intensive. Solar energy can provide the needed energy, and solar vacuum (USF), humidification/dehumidification (UF), and solar still (UF) desalination systems are being investigated 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 to remove contaminants and integrate these technologies with solar PV for complete water supply systems.

Budget: $252,000

Universities: UF

Progress Summary

A theoretical model is developed to describe the heat and mass for the solar diffusion desalination process from the basic principles of mass and energy conservation. The developed model takes into account the transient variations in the water, air, and packing bed temperatures when it is subjected to a variable heat source such as solar collector.

The transient theoretical model has been solved numerically using a finite difference scheme. The numerical results obtained from the transient model are compared against the results obtained from the DDD steady state model using the same operating conditions. A satisfactory agreement is achieved.

Solar DDD facility is constructed such that the validity of the developed theoretical model can be investigated. To harvest solar energy, a solar collector is simulated using an electric heater to deliver energy to the distillation process. A set of experiments with different operating conditions are required. Experiments are currently ongoing to test the model.

2009 Annual Progress Report

Project (1) - Solar Diffusion Driven Desalination

Water and energy scarcity poses a future threat to human activity and societal development around the world. Supplying sufficient quality water is essential to the development of any country. Seawater desalination offers an excellent option to meet freshwater needs. However, all of the conventional desalination technologies are energy intensive. Non-renewable energies, such as fossil fuel, are increasingly depleting, and extensive technological development for harnessing renewable energy is the only solution for energy and water shortage problems. Solar energy utilization for seawater distillation is a promising option for solving fresh water shortage problems.

This research concerns a transient analysis of Solar Diffusion Driven Desalination process (Solar DDD). This low-temperature distillation process uses solar energy harvested with a flat plat collector, and separate salt from seawater using direct contact evaporation and condensation. The DDD which consists of two main components, namely: diffusion tower and direct-contact condenser. The diffusion tower and the direct-contact condenser entail a nozzle mounted at the top of the packing and used to spray water over the packing material. A schematic diagram of the Solar DDD system is shown in Figure 1. The principle of the DDD is to humidify an air stream using a hot seawater. The seawater, heated via the solar collector, enters the diffusion tower chamber at a relatively high temperature and sprayed on packing bed that has a high surface area to improve the evaporation process. The air exits the diffusion tower chamber humidified; it then enters the direct-contact condenser, where cold fresh water is sprayed on another packed bed in the condenser, whereby water vapor condenses to produce freshwater. Clean freshwater is collected in a basin and sent to a freshwater tank.

In order to optimize the utilization of solar energy for seawater distillation, it is necessary at first to understand the heat and mass transfer between the liquid, air and the packed bed in the diffusion tower, as well as the direct-contact condenser. The theoretical modeling enables physical understanding of the underlying physics relating to heat and mass transfer between the working fluids and the packed bed. This enables improving the evaporation and condensation process. A theoretical model is developed for the diffusion tower and the condenser from the basic principles of mass and energy conservation. The developed models takes into account the transient variations in the water, air, and packing bed temperatures when it is subjected to a variable heat source such as solar collector. Figures 2 and 3 depict, respectively, the differential control volume of the diffusion tower and the direct contact condenser. In the transient modeling of the heat and transfer in the diffusion tower and the condenser, the thermal inertia of the packed bed is taken into account. In the diffusion tower, the heat flows from the liquid side to the air side, which results in water evaporation. Furthermore, the heat flows from the liquid to packed bed due to conduction. Due to the high heat transfer between the liquid and the packed bed, it is expected that the temperature of the packed bed is higher than the air. As a result of that, in some areas where the packed bed is not fully wetted, it is expected that heat will transfer from the packed bed to the vapor. A similar model is also obtained for the direct contact condenser; however, heat will transfer from the air side to the liquid and packed bed. Furthermore, since the solar DDD operates in the re-circulating mode, the mass and temperature of the seawater in the storage tank varies as time proceeds. Thus conservation of mass and energy is applied to the storage tank to predict the variations of the mass and temperature of the seawater. The size of the seawater in the storage tank is an important parameter in optimizing the solar DDD process.

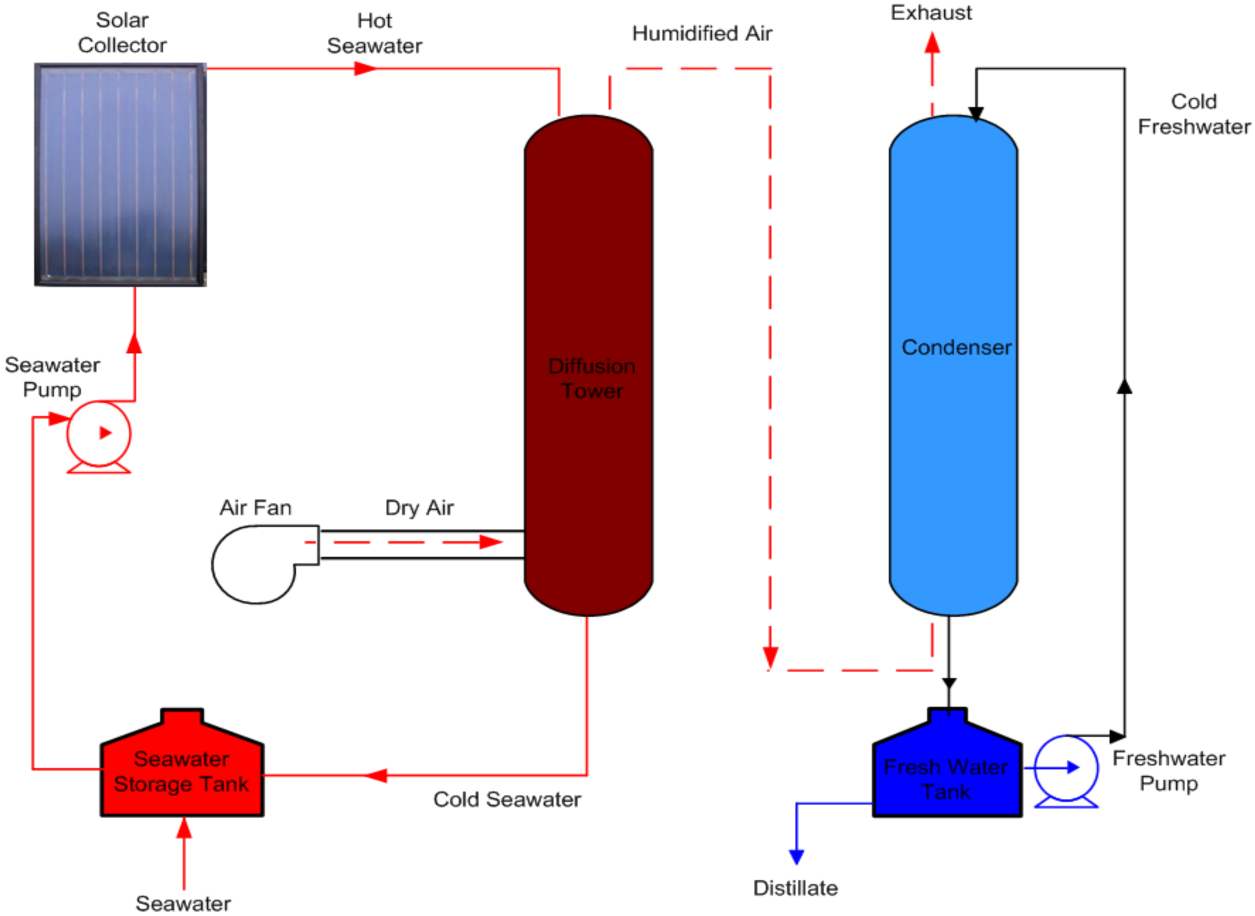

Figure 1 Solar Diffusion Driven Desalination

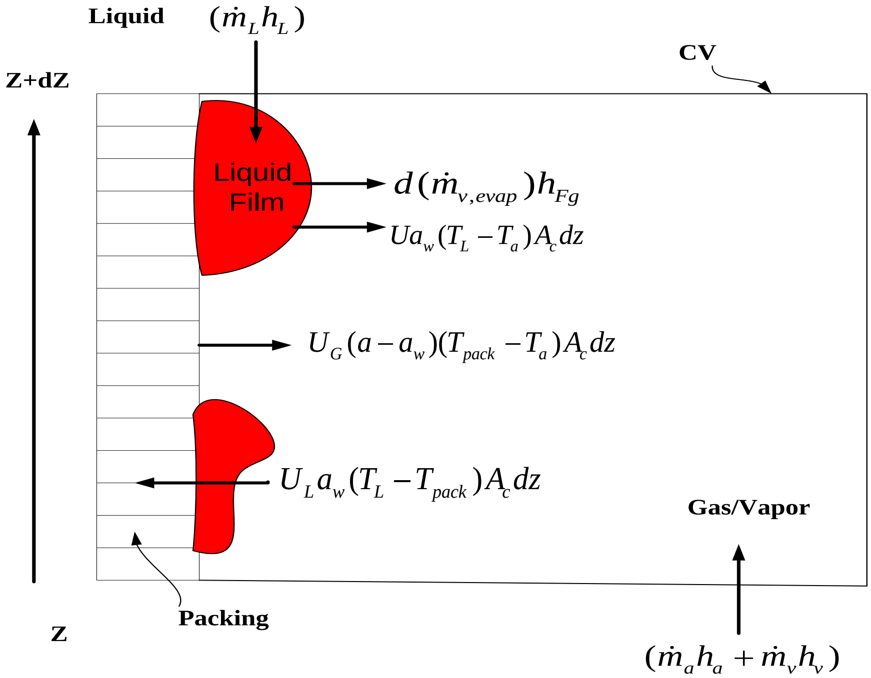

Figure 2 Differential control volume for liquid/vapor heat and mass transfer within diffusion tower

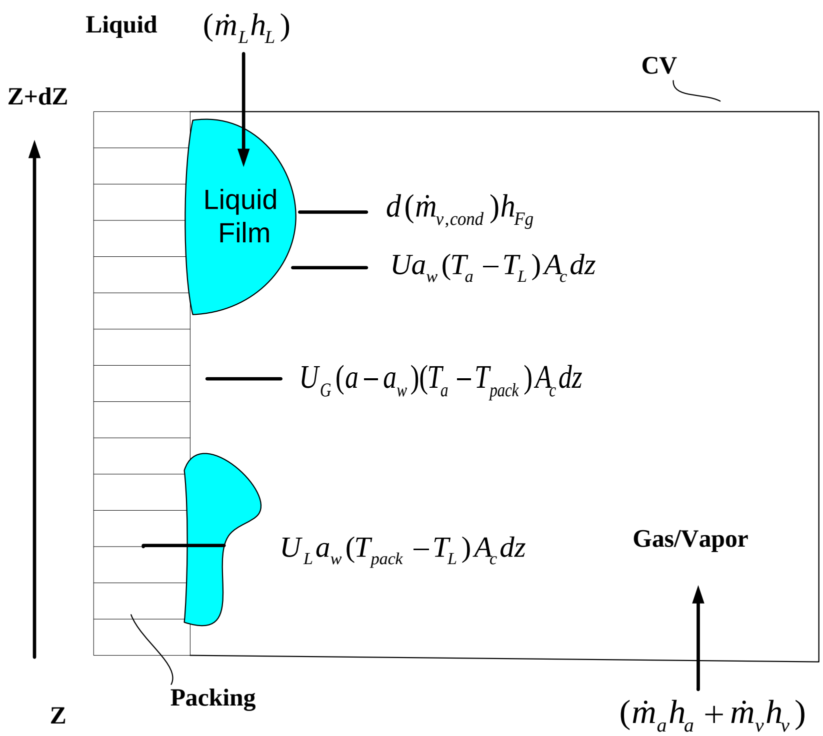

Figure 3 Differential control volume for liquid/vapor heat and mass transfer within direct contact condenser

The theoretical model has been solved numerically using a finite difference scheme. Spatial and temporal temperature distribution of the water, air and the packed bed is obtained for the diffusion tower and the direct-contact condenser. Furthermore, a flat plate solar collector is modeled and implemented into the numerical code. Solar data for a typical summer day is used in the simulations. Thus, this modeling enables testing the performance of solar DDD for different influencing parameters such as the solar intensity, water and air flow rates, and size of seawater in the storage tank.

In order to test the validity of the transient model as well as to verify the results obtained numerically, a comparison was made between the temperature profiles obtained using the transient model and the steady state model [1], [2]. Using a constant water temperature entering the diffusion tower and the direct-contact condenser, the predicted results using the transient model are in satisfactory agreement with results obtained using steady state model. Figures 4 and 5 compare the water and air temperature profiles along the diffusion tower, obtained using the developed transient model and the steady state model. It is found that the transient model has an excellent prediction capability in determining the evolution of the temperature profile within the diffusion tower and the condenser. A set of simulation runs were performed and the following conclusions are highlighted:

The result indicates that the time required to reach the steady state is considerable. The time required to reach a steady state depends on the water to air mass flow ratio. Higher liquid to air mass flow ratio results in lower time required to reach the steady state.

The temperature of the packing is very close to the water temperature. This agrees with the steady state model assumption in which a fluid film was assumed to exist at the packing and have the same temperature of the packing.

The temperature of the water drops sharply at the entrance of the diffusion tower which is due to the sudden exposure to the air at lower temperature. Also, the air experience a large temperature gradient at the entrance and this is also due to the large heat transfer at the entrance region. In addition, it is found that the temperature of the air approximately increases linearly within the middle portion of the diffusion tower.

This study gives better understanding of the evolution of the water, air/vapor, and packing temperature in the diffusion tower as time progress. The transient model is of prime significance because it allows the performance of the solar DDD to be simulated, which operates in a re-circulation mode and is inherently unsteady. In the recirculation mode, the saline water exiting the diffusion tower enters the storage water tank and gets mixed with the water in the tank. Then the water is pumped again through the solar collector to raise its temperature. Therefore the temperature of the liquid continuously changes as time proceeds, and such a transient model is required. Further, an experimental work is required to validate the theoretical models and to investigate the validity of the obtained numerical results. A laboratory scale Solar DDD system is designed and fabricated to study the feasibility of utilizing solar collector to power DDD process. The solar collector is simulated via an electric heater, which is controlled via Pulse-Width Modulation (PWM) method, by which heat is delivered to the seawater in a way similar to the solar cycle. A set of experiments is required for different operating conditions. Experiments are currently ongoing to test the model.

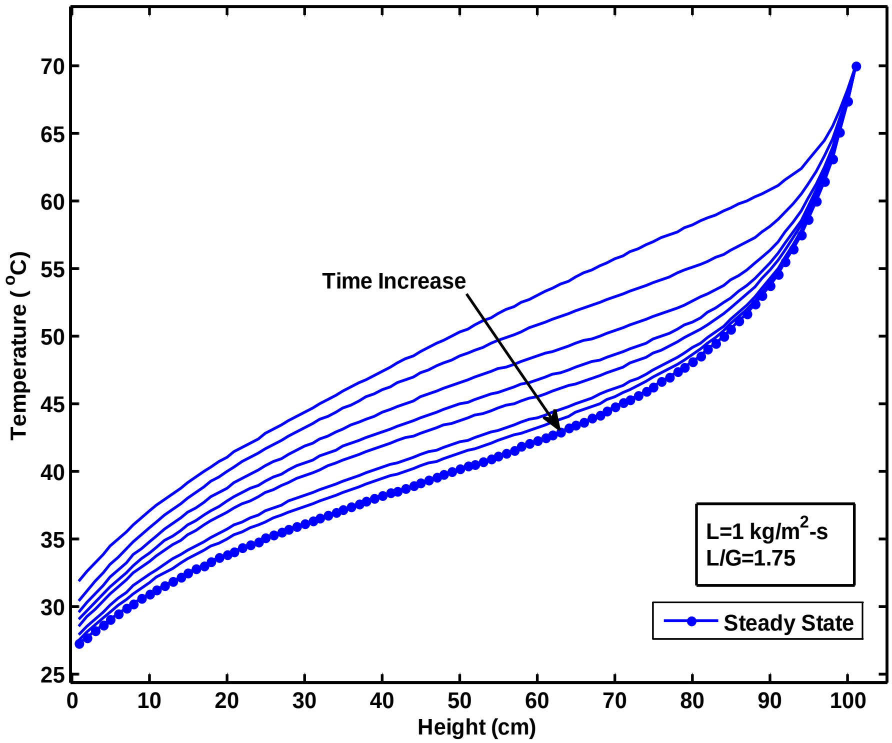

Figure 4. Comparison of Transient and Steady State Temperature Distributions of the Water along the Diffusion Tower

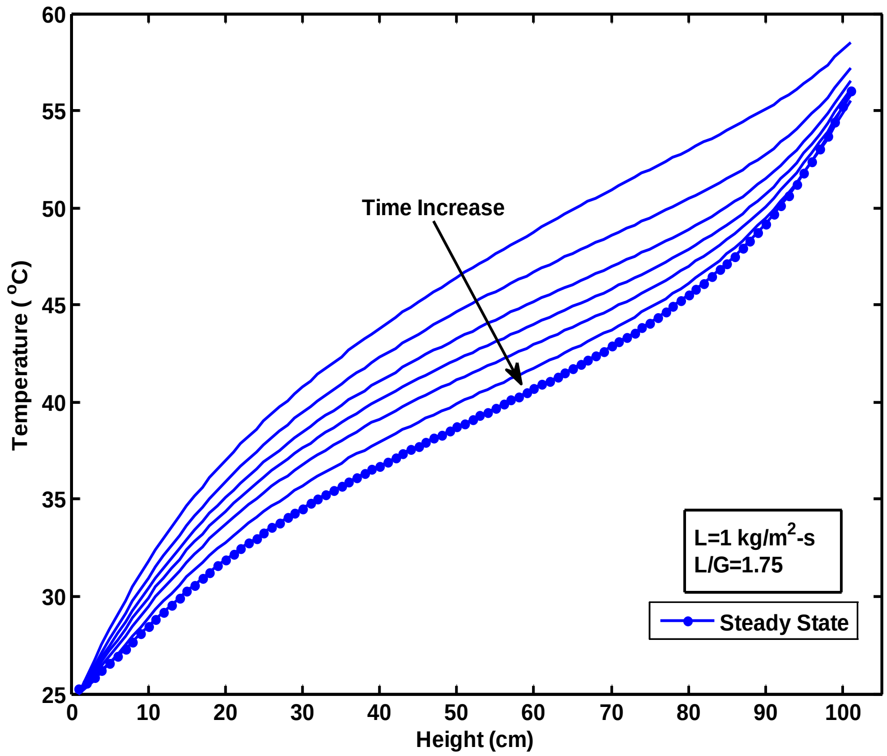

Figure 5. Comparison of Transient and Steady State Temperature Distributions of the Air along the Diffusion Tower

References

[1] Klausner, JF, Li, Y, Mei, R, 2006. Evaporative Heat and Mass Transfer for the Diffusion Driven Desalination Process, J. of Heat and Mass Transfer, 42: 528-536.
[2] Li, Y, Klausner, J, Mei, R, Knight, J, 2006a. Direct Condensation in Packed Beds, Int. J. Heat and Mass Transfer, 49: 4751-4761.

Project (2) - Multiple-effect Solar Still

An extensive Matlab model has been developed to simulate the mass and heat transfer mechanisms through a diffusion-driven, multiple-effect solar still (Fig. 1). The model was developed to simulate operation and then optimize the design parameters.

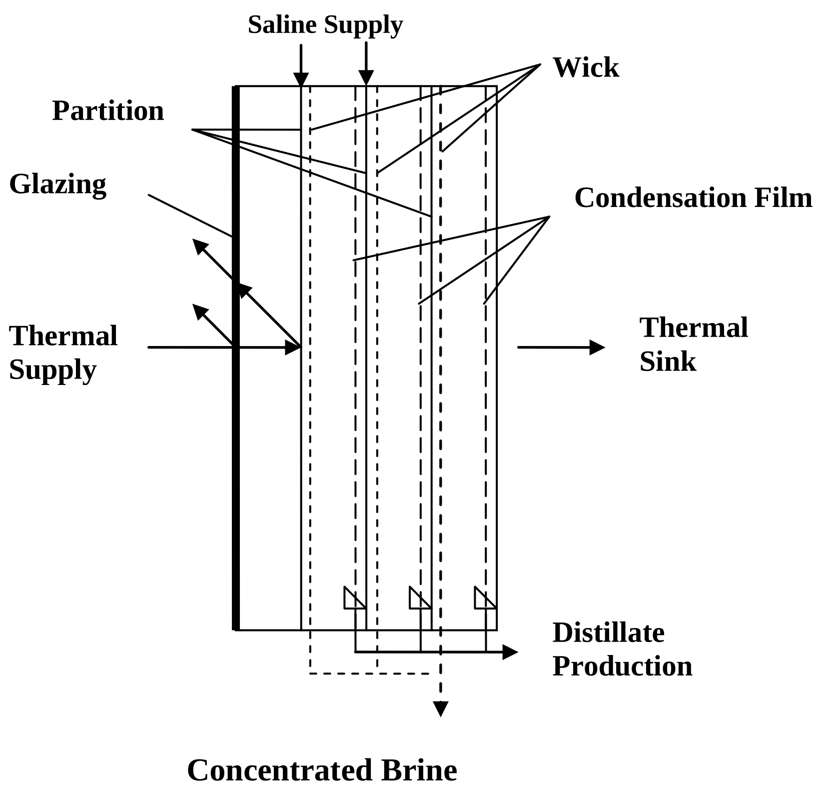

Figure 1 Schematic of multiple effect distillation system for which simulation model was developed.

The 2-D model included vertical resolution in addition to horizontal resolution in order to capture the temperature and concentration gradients along the vertical direction of the distillation cells. It was found that the common 1-D analysis found in the literature, which calculates production rates based on average cell temperatures, may over predict the production rates because the average temperature does not include the non-linearity of radiative and evaporative heat transport along the vertical direction. Temperature dependent properties were also iteratively solved at each vertical element and it was found that particularly the gradient in the Coefficient of Binary Diffusion plays a significant role in the relative contribution of evaporative transport. This means that production rates through the distillation cell are highly dependent on temperature which causes the lower portion of the still to produce at significantly higher rates than the upper portion.

Table 1 Convergence of performance ratio (PR) based on the model's vertical resolution (m) for the base case. The PR values converge at a vertical resolution of approximately m=5.

Vertical Resolution (m)	Performance Ratio (PR)
1	2.73
2	2.59
3	2.54
4	2.52
5	2.51
6	2.50
7	2.49
8	2.49
9	2.49
10	2.48
11	2.48
12	2.48

Pseudocolor plots were used to visually depict the 2-D gradients of temperature, temperature gradients, property values, mass flow rates, and salinity concentration (Fig. 2). The Heat Rate Ratio (HRR) was defined and visually depicted to show the relative contribution of various heat transport mechanisms throughout the system with a particular focus on the evaporative HRR (Fig. 3).

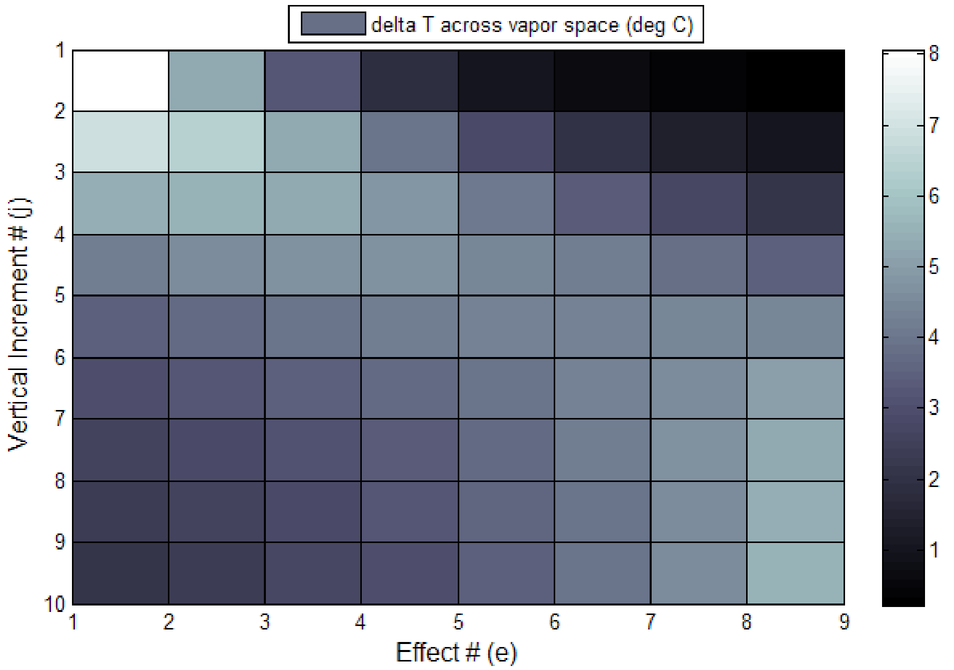

Figure 2 Temperature differential across the vapor space (T_w-T_{cf}) at each effect and vertical element throughout the system.

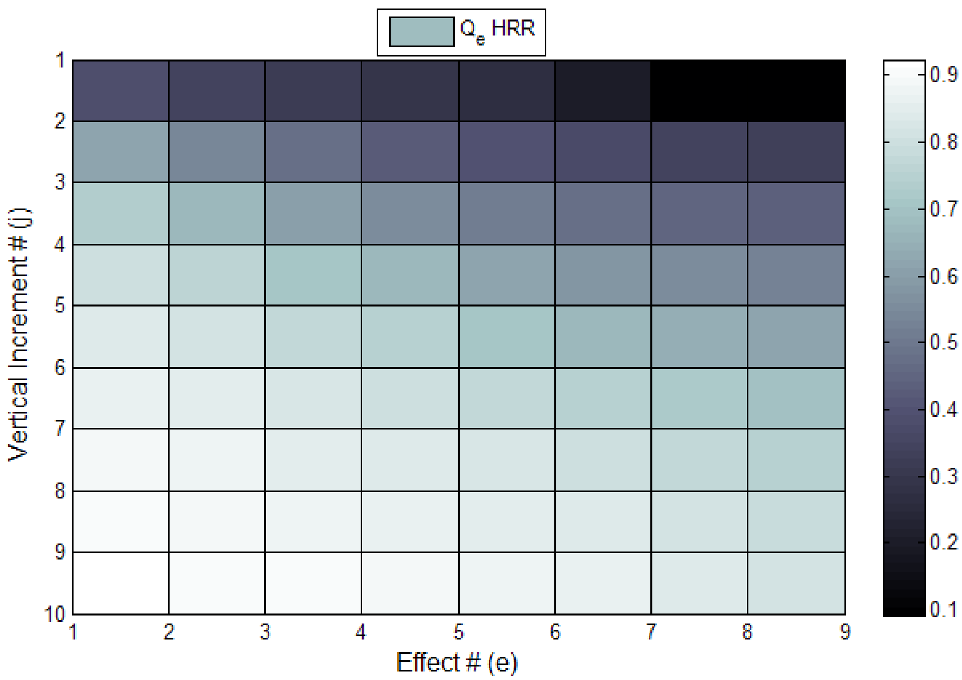

Figure 3 Heat Rate Ratio of evaporative heat rate to the total heat rate for each effect and vertical element (Q_e HRR). Note that evaporative transport contribution is low in the upper portion of the still and dominates in the lower portion.

Independent variables of the system were categorized into the following categories: environmental, material, geometrical, mass flow (or feedrate ratio), and recuperation. Each independent property of interest was parametrically modeled against the number of distillation effects in the system to provide a Performance Ratio (PR). It was found that the gap spacing between each evaporator and condenser along with the feedrate ratio to each effect and the emissivity of the solar absorber were among the strongest contributors to performance.

Various configurations of heat recuperation including sensible heat recuperation (SHR) at the mass stream exits and latent heat recuperation (LHR) at the final condenser were defined and modeled to test the impact on the performance ratio (Fig. 4). It was found that the combination of both systems resulted in the greatest performance with SHR providing the most benefit between the two.

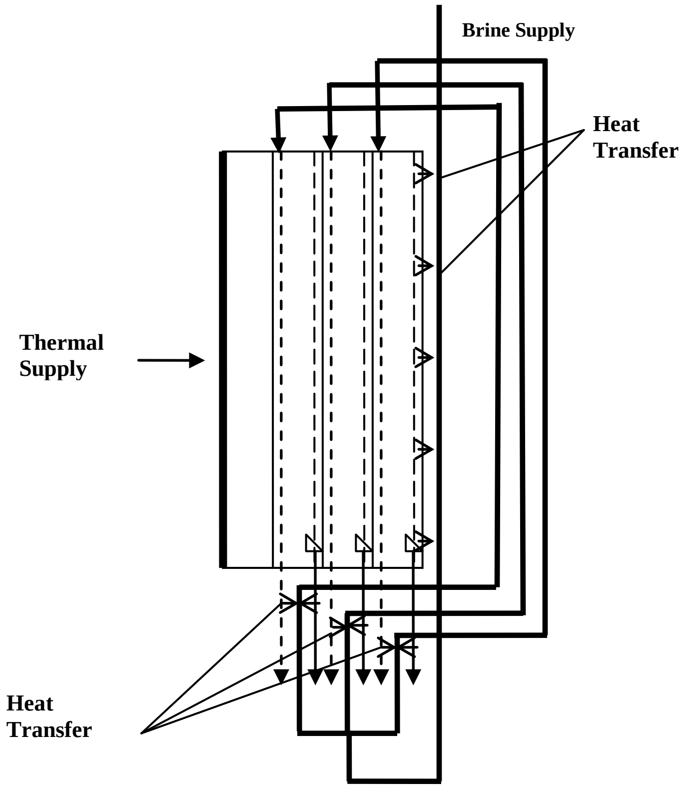

Figure 4 Latent heat recuperation (LHR) coupled with multi-stage sensible heat recuperation (SHR-2) from the concentrated brine and production distillate mass flows**.**

Optimized systems were then modeled including ideal material selections, geometrical configurations, and feedrate ratios along with both heat recuperation systems (Fig. 5, Case VI). It was predicted that such an optimized system with 15 distillate effects can possess a PR of over 8. This is extremely high for a low temperature solar still according to the literature.

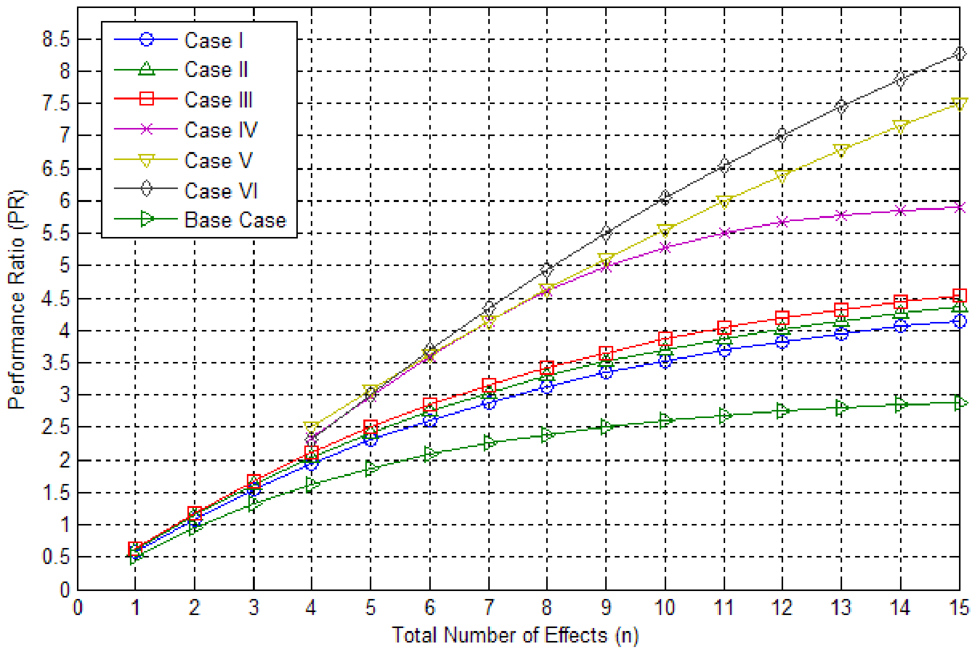

Figure 5 Performance Ratio (PR) of various systems with different levels of parameter optimization. Case VI represents all parameters optimized with both LHR and SHR.

An experiment designed to quantify the accuracy of the numerical simulation of a diffusion driven solar still has been designed. The following drawing (Fig. 6 and 7) is an exploded view of the experimental design showing the various components. The cell consists of a heater, evaporator plate, wick, condenser plate, and the surrounding insulation. The distillation cell has been designed for measurement of the temperatures of the evaporator and condenser plates at various points along their respective surfaces. The materials required for the experimental setup have been acquired. Fabrication of the experimental setup, consisting of minor machining and assembly, is set to begin.

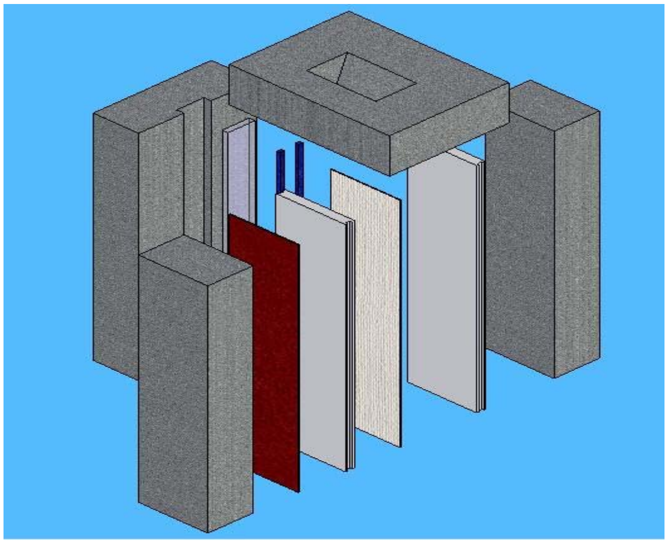

Figure 6 Experimental design of the distillate effect- (1)

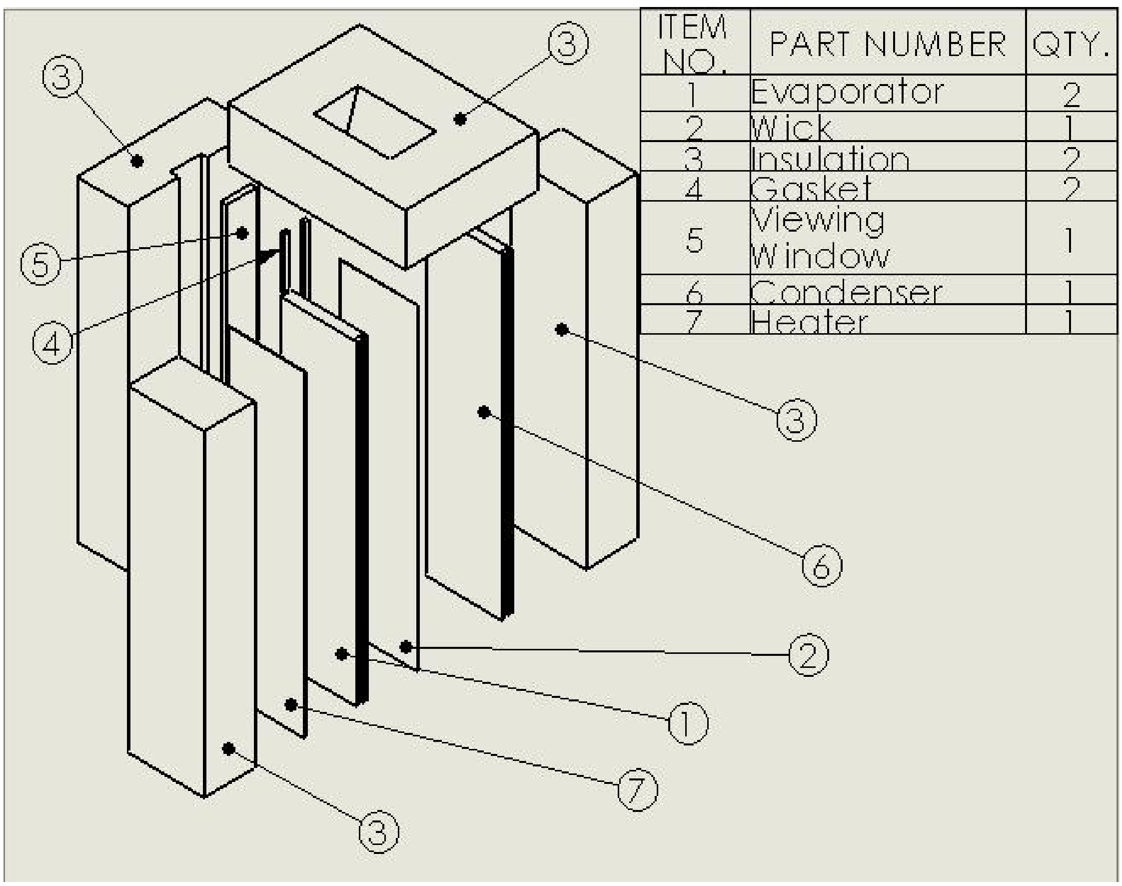

Figure 7 Experimental design of the distillate effect- (2)

FESC
Florida Energy Systems Consortium

UNIVERSITY OF FLORIDA

Combined Cooling, Heat, Power, and Biofuel from Biomass and Solid Waste

PI: William Lear
Students: Minki Kim (PhD); Elango Balu (PhD); Harsh Khandelwal(MS)

Description: The goal of this project is to provide the underlying research and demonstration of a novel technology which would enable the economic utilization of dispersed biomass and solid waste resources to produce electric power, cooling, heat, and transportation fuels. This integrated gasification and power generation system combines University of Florida advances in high-temperature gasification, hydrogen generation and separation, and advanced gas turbine systems. Their integration is expected to result in significant improvements in the cost, emissions, feedstock flexibility, and water requirements, all in a relatively compact, modular plant system. This in turn will enable much greater utilization of renewable energy supplies, helping the development of a sustainable energy supply infrastructure.

Budget: $576,000

Universities: UF

External Collaborators: Siemens Power Generation, Florida Turbine Technologies, Energy Concepts Co.

Progress Summary

Progress has been made in three broad areas: development of a system architecture and thermodynamic model, development of models and system-level experiments for the PoWER gas turbine unit, and exploration of the underlying science and demonstration of the high temperature steam gasification subsystem. These activities are structured in such a way as to allow stepwise research and development of the overall plant in outlying years.

The system architecture includes the full integration of waste heat and water produced in the gas turbine module with the gasification subsystem. This in turn allows efficiency gains, reducing the proportion of hydrogen utilized internally, and allows zero net usage of external water resources. A thermodynamic system model is operable, though more sophisitcation is needed for full optimization of the system and accurate prediction of performance.

The PoWER system has been implemented as an experimental system in previous programs. Experimental results from the combustion process have been obtained, allowing the quantification of soot and other emissions in flameless combustion, including the effect of biofuels. Combustion modeling supports the experimental findings. System thermodynamic models have shown the potential of the PoWER system to improve efficiency and produce fresh water. These models will later be integrated into the overall system model for improved fidelity.

On the gasification side, first we have developed a physics-based thermal-chemical high-temperature steam gasification model that is based on a completely self-sustained gasification process with no external heat source require nor water supply needed. The only input materials are the biomass feedstock and pure oxygen for the hydrogen combustor. Through the combustion of the hydrogen taken from the produced syngas with the externally supplied oxygen, the hydrogen combustor produces the high-temperature steam that is used as the gasifying agent. The water vapor in the syngas is retrieved through a condenser and re-heated by the syngas in a heat exchanger to supplement the gasifying stean stream and to conserve water. After performing a heat and mass balance analysis using the model, the results suggest that with a steam temperature of 2000C, the fraction of hydrogen taken from the syngas for the hydrogen combustor is around 60% for a steam to biomass ratio of 3. For the syngas composition, 40% in mole fraction is hydrogen and 20% is carbon monoxide at a steam to biomass ratio of 3. The rest are methane, carbon dioxide and water vapor.

We have also designed and built a trailer-scale biomass to energy system. This system will be used as an experimental apparatus and also for demonstration to the public. the system is composed of a gasifier, heat exchanger, cyclone separator, wet scrubber, radiator, engine-generator set and battery pack. The gasifier is the main part of the system and is a basic down-draft system with the capacity of handling about 40 lb of biomass per two-hour batch process.

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I. Chemical equilibrium modeling of the allothermal steam gasification of woody biomass

The allothermal steam gasification process that converts the woody biomass to synthesis gas is composed of two steps (1) pyrolysis and/or thermal decomposition and (2) gasification by high-temperature steam, no partial oxidation). Only steam will be introduced into the gasifying chamber as the gasifying agent. Oxygen is completely blocked so no partial oxidation or combustion will take place in an oxygen-starved environment. The high temperature steam, gasifying agent, from a hydrogen burner will serve also as a heat carrier. The biomass is first thermally decomposed toward volatile species and solid residual (basically char). The volatile species consist primarily of higher hydrocarbons including tars as well as light gases, but is immediately decomposed further to permanent gases such as carbon monoxide, hydrogen (pyrolysis and subsequent thermal cracking). This step advances quickly in the high temperature and intense heat transfer environment. In the second step (post-pyrolysis or gasification), the gasifying agent reacts with the residual char to produce gases (heterogeneous reactions). Also, there will be gaseous phase reactions such as water-gas-shift and methane reforming reactions (homogeneous reactions). Char and volatile are difficult to be modeled thermodynamically because of their complexity as a material. Char is assumed as graphite, solid carbon, in this work. Three Independent equilibrium reactions are assumed as the core of the chemical processes as given below,

$CH_4 + H_2O \longleftrightarrow CO + 3H_2$ *Methane reforming*

$CO + H_2O \longleftrightarrow CO_2 + H_2$ *Water gas shift*

$Cs + H_2O \longleftrightarrow CO + H_2$ *Heterogeneous water gas shift*

First we developed a model to investigate the heat and mass balance of a totally self-sustained gasification system and its schematic is shown in the Figure 1 below.

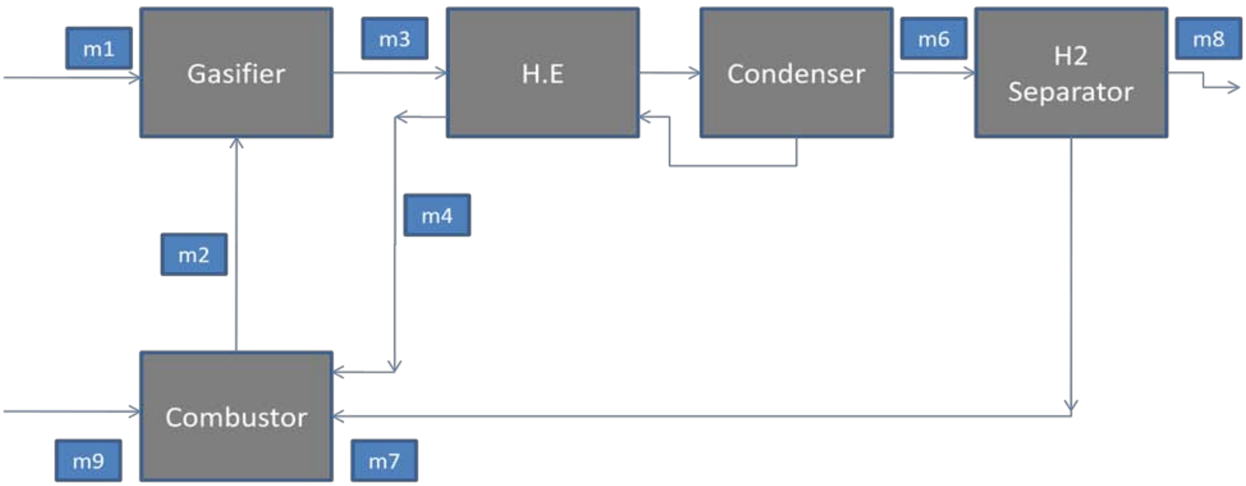


Figure 1. Gasification system process flow diagram

As shown in the system diagram above, the only input materials to the system are m1 (biomass feed) and m9 (oxygen) for the hydrogen combustor. M3 is the syngas produced from the gasifier. The condenser is used to retrieve the water and the heat exchanger is intended to capture the syngas heat to heat the condensed liquid water, m4, back to as high a temperature as possible for re-cycling back to the gasifier. M7 is the hydrogen taken from the syngas, m6, to the hydrogen combustor as fuel. Therefore, the system does not require any external heat source or water supply. The energy and mass balance calculations have been performed for the gasifier using 3 different inlet steam (H_2O) temperatures of 1500C (Case 1), 2000C (Case 2) and 2500C (Case 3) for a range of STBM (steam to biomass ratio). Typical results are given for steam temperature at 2000C (Case 2). In Figure 2, we found that the fraction of hydrogen taken back from the syngas for recycling in the gasifier ranges from 98% to 57% for steam to biomass ratio (STBM) from 1.4 to 4. In Figure 3, we conclude that the higher the STBM the higher the production of H_2 and CO.

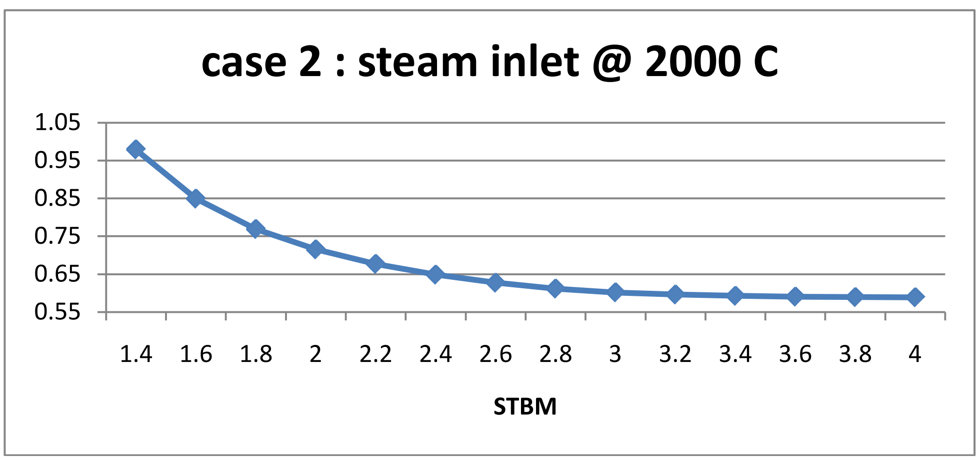


Figure 2. Fraction of hydrogen taken from syngas for recycling back to the gasifier vs. STBM.

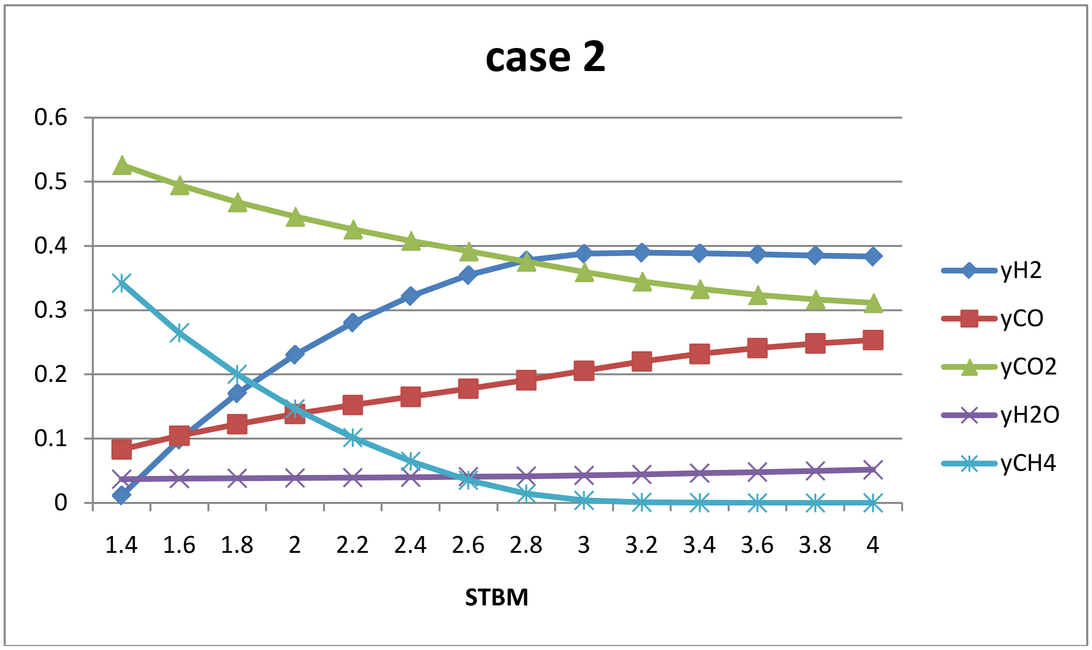


Figure 3. The mole fraction distributions of the produced syngas vs. STBM.

II. Experimental Facility Development – A Trailer Scale Biomass to Energy System

As shown in Figure 4, the system is composed of a gasifier, heat exchanger, cyclone separator, wet scrubber, radiator, engine-generator set and battery pack. The gasifier is the main part of the system and is a basic down-draft system with the capacity of handling about 40 lb of biomass per batch. Next crucial part of the system consists of the cyclone separator and the wet scrubber which together form the gas-clean up unit. This is to ensure the quality of syngas that is fed to the engine.

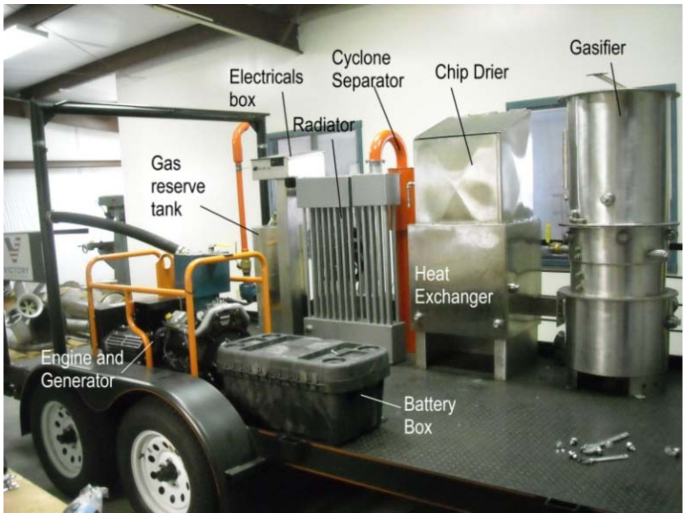


Figure 4. Trailer scale biomass to energy system

The final component will be that of the conversion unit that turns the enthalpy available in the syngas (heat energy) to electrical energy. The power produced could be used directly to run any loads or could be stored in battery packs. The rpm of the engine has to be tuned down to ensure complete combustion of the gas that is being fed in to the combustion chambers and to prevent deposition of soot particles on the engine compartments.

II. Flameless Combustion Experiments and Modeling

The Power, Water Extraction, and Refrigeration (PoWER) system is the energy conversion subsystem to be eventually integrated with the steam gasification plant described above. One important feature of the PoWER system is that the combustion environment features high diluent concentrations, resulting in significantly reduced flame temperature. This in turn produces a flame characterized by very low soot production, highly-uniform temperature field, and low flame luminosity, so that the regime is termed flameless combustion. The low flame temperature reduces NOx without complex dry low-NOx technology; the low soot formation helps to reduce CO emissions. Overall, the primary regulated pollutants – NOx, particulates, unburned hydrocarbons, and CO – are simultaneously reduced to levels well below the current state of the art. At the same time, fuel flexibility is enhanced, making this system ideal for coupling to a biomass/MSW gasifier with a wide range of syngas compositions. This in turn makes the economics more attractive, as a single system is expected to be applicable in multiple applications with minimal or no modification.

Preliminary experiments have been conducted to compare operation with bio-derived fuels to conventional fuels. These experiments were performed in our experimental PoWER engine, shown in Figure 5. Typical experimental results are shown in Figures 6 and 7, where fuel flow rates and soot formation data are presented. Figure 6 compares the fuel flow requirements of various types of biofuel, compared to conventional fuel; the results follow the variation in fuel heating value, indicating negligible effect on combustion efficiency. Figure 7 shows sooting tendency, obtained by an optical specroscopic technique, where the sooting tendency of the biodiesels tested are superior to that of conventional diesel fuel.

Figure 5. Experimental PoWER engine

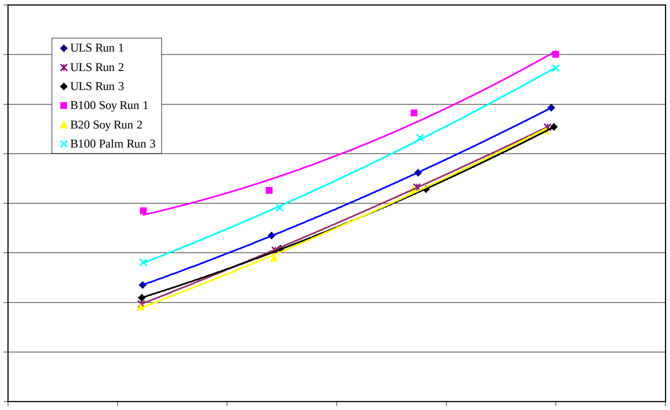


Figure 6. Biofuel flow rate comparison

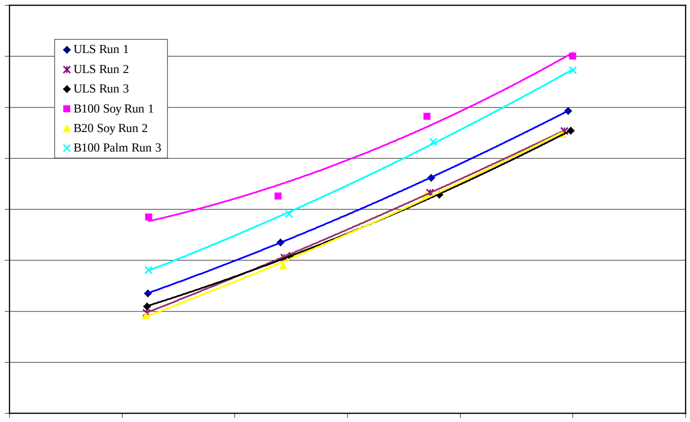


Figure 7. Sooting comparison amongst biofuels for varying engine load

Combustion modeling has accompanied the experiments, using the Cantera chemical kinetics code. A parametric study of various biofuel surrogates has been performed, including not only the effects of stoichiometry and reactor residence time, but also the dilution level, simulating the PoWER combustor. The results agree with the experimental trends qualitatively, though significantly lower soot levels are predicted. The most likely explanation for the quantitative disagreement is that the model is a perfectly stirred reactor, whereas the experiment includes heterogeneous effect due to spray evaporation and mixing. These heterogeneous effects are well known to enhance soot significantly, though the overall soot levels of model and experiment are considered quite low.

UNIVERSITY OF FLORIDA

Non-Contact Energy Delivery with Integrated DC-AC Inverter for PV System

PI: Jenshan Lin
Students: Zhen Ning Low (PhD), Joaquin Casanova (PhD), Raul Chinga (PhD), Jason Taylor (MS), Yan Yan (PhD), Xiaogang Yu (PhD)

Description: Innovative non-contact energy delivery method will be used in photovoltaic energy generation system to accelerate the system deployment. Instead of delivering electric power using cables penetrating through building structures, magnetic field coupling allows power to be transferred wirelessly through building walls and roofs. In the meantime, the DC electric energy from photovoltaic cells is converted to AC energy. This enables the photovoltaic system to be quickly set up or relocated, and the collected solar energy from outdoor system can be conveniently delivered to indoor appliances. Techniques to achieve high efficiency at high power delivery through different building structures will be studied for this plug-and-play architecture.

Budget: $252,000

Universities: UF

External Collaborators: NA

Progress Summary

We have introduced a new concept of using magnetic coupling for wireless delivery of energy from outdoor photovoltaic system to indoor electrical system. Replacing traditional electrical cables penetrating through building structures, magnetic coupling using two coils separated by a distance allows power to be transferred wirelessly through building walls and roofs. While generating magnetic field, the DC electric energy from photovoltaic cells is converted to AC energy, which can potentially be merged with DC-AC inverter function required in the system. This enables the photovoltaic system to be quickly set up or relocated, and the collected solar energy from outdoor system can be conveniently delivered to indoor appliances. High efficiency DC-AC generation and high efficiency magnetic coupling are the key challenges. We have studied different design approaches and conducted experiments to address these two challenges.

The DC-AC generation requires high efficiency inverter. Previously we have demonstrated using Class-E power amplifier architecture to achieve 295W at 75% efficiency for near-field wireless power transfer. Although Class-D architecture has been commonly used in power electronics, the Class-E architecture has two advantages: only one transistor is needed rather than two in Class-D architecture and Class-E can deliver more AC power under the same DC supply voltage. Therefore Class-E architecture is used in our approach. The inverter design also requires a choice of impedance transformation network. Because of the increase in separation between inductive coils, the previously used impedance transformation network topology may not be suitable for this new application since the operating frequency may need to be changed. After the experiment, it was found out that the Series-Series topology works best.

The increase in distance between coils presents the greatest challenge to the magnetic coupling because the coupling coefficient decreases as the distance increases. To overcome this challenge, it is found that the operating frequency of magnetic coupling needs to be increased and the size of coil also needs to be increased to achieve high efficiency energy transfer. It is found that the dimension of coil has to be about the distance between coils. Our first goal is to achieve energy transfer through a 50 cm gap. The coil is therefore designed as a 50 cm x 50 cm, 8-turn rectangular coil. The same coil is used in both transmitter and receiver sides. Based on these conditions, the optimum operating frequency is determined to be about 760 kHz.

Several experiments were performed to test the system. The system achieves better than 60% efficiency in a wide power delivery range when the distance between coils is 30 cm. The system can still achieve 50% efficiency when the distance between two coils is increased to 50 cm. The efficiency is end-to-end efficiency including all the losses in the inverter and the magnetic coupling. The system also shows robust performance against misalignment between coils.

2009 Annual Progress Report

Our project consists of implementing a design that will allow us to deliver the power gathered by the solar panels without using wires penetrating building structures. This will be achieved by sending the power wirelessly via magnetic coupling.

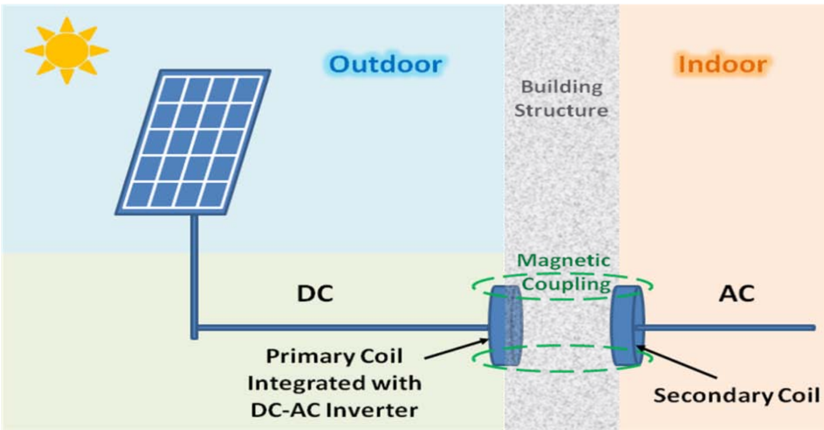


Figure 1: Concept diagram of noncontact energy delivery for PV system

Figure 1 shows the concept diagram. This architecture will bring many advantages. Since no wires need to go through the building structures, the installation cost and time will be reduced. The system will be easily installed and uninstalled if necessary. No wires will be exposed, making it suitable for conditions where full insulation is required. This system has the potential to have a great impact. Decreasing the cost of the PV systems will promote broader use of them. As demand increases, the price of PV systems will drop. As market capitals increase, companies will invest more towards research and development. This will further lower the price and improve PV system performance.

The distance between coils is the major challenge in this system. Our research group has previously developed a planar wireless power transfer system. However, that system was for the near field power transfer with coil separation on the order of 1cm. The proposed system will require the coils to be separated by a distance up to 1 meter. As the magnetic field decreases quickly when moving away from the coil carrying the current, the magnetic coupling coefficient between coils will decrease as the separation between them is increased. If not properly compensated in the design, the energy transfer efficiency will decrease and the power delivery will drop. Possible solutions include: increasing the size of the coils, decreasing the size ratio between the coils (1:1 is the best), and using magnetic materials (e.g., ferrite materials).

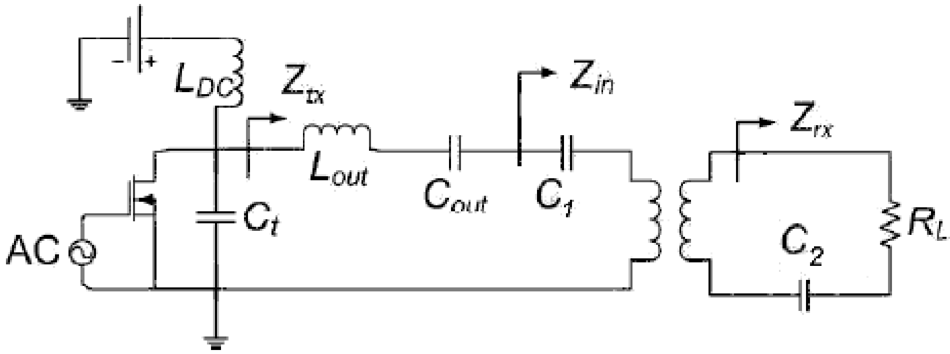
Since AC power is needed for magnetic coupling, potentially the DC-AC inverter for generating 110V 60Hz AC power can be integrated in the proposed PV system. However, currently the optimum operating frequency for achieving high efficiency magnetic coupling is at a much high frequency. Therefore magnetic coupling at 60 Hz will be studied later and the benefit to system performance will be evaluated.

	Constant variable	**Class E normalized to Class D**
Drain voltage stress	Supply voltage	3.562
Drain voltage stress	Power delivery	2.112
Power delivery	Supply voltage	2.847
Supply voltage	Power delivery	0.593

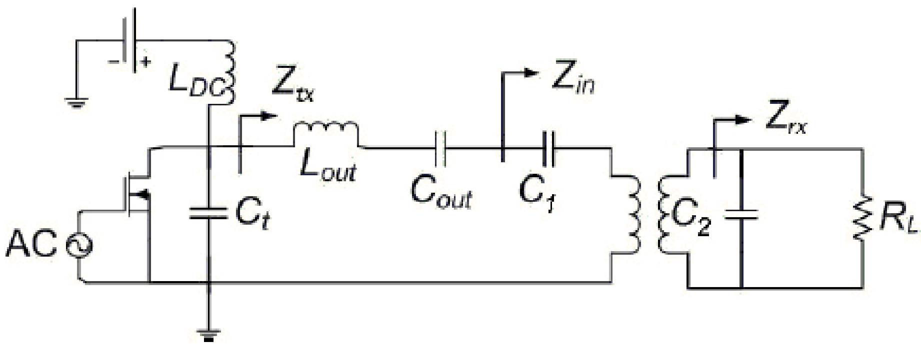
Table 1: Comparison between Class-E and Class-D

The DC-AC generation requires high efficiency inverter. Previously we have demonstrated using Class-E power amplifier architecture to achieve 295W at 75% efficiency for near-field wireless power transfer. Although Class-D architecture has been commonly used in power electronics, the Class-E architecture has two advantages. Only one transistor is needed in Class-E but two transistors are needed in Class-D. Also, Class-E can deliver more AC power than Class-D under the same DC supply voltage. The disadvantage of using Class-E architecture is that the voltage stress on transistor is higher in Class-E than in Class-D. Table 1 shows the comparison between these two architectures. It can be seen that to deliver same amount of power, the transistor drain voltage stress in Class-E is 2.112 times than in Class-D. However, for the same DC supply voltage, Class-E can achieve 2.847 times power delivery than Class-D. Considering the tradeoffs, Class-E architecture is used in our approach.

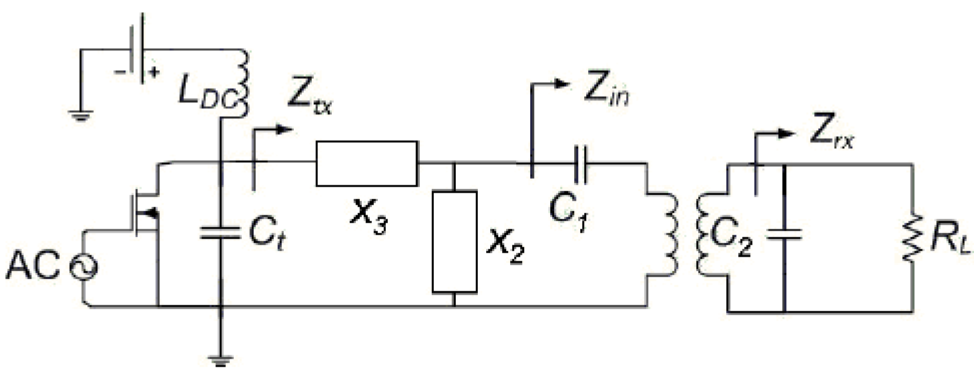
The inverter design also requires a choice of impedance transformation network. The impedance transformation network is needed to work with inductively coupled coils to match the load impedance to the output impedance of Class-E inverter. Because of the increase in separation between inductive coils, the previously used impedance transformation network topology for near-field energy transfer may not be suitable for this new application requiring mid-range energy transfer since the operating frequency may need to be changed. Three topologies were evaluated: series-series, series-parallel, and T-network. Figure 2 shows the circuit schematics of these three topologies. In each topology, Class-E inverter using one MOSFET transistor is shown at left. A low-power clock signal is used to switch the transistor on and off and convert the DC supply power to AC power at transistor output. The AC operating frequency can be set by the clock. Ideally, this type of switching amplifier can achieve efficiency nearly 100%.



(a) Series-Series impedance transformation



(b) Series-Parallel impedance transformation



(c) T-network impedance transformation

Figure 2: Impedance transformation network topologies. (a) Series-Series. (b) Series-Parallel. (c) T-network.

Three prototypes using the above three topologies were built using the same type of transistors. Two 8-turn coils of 30 cm x 30cm were built. The 1:1 size ratio of transmitter and receiver coils optimizes the coupling efficiency. Experiments were conducted to test the performance when same DC supply voltage was provided and the coils were separated by 30 cm. The optimum operating frequency was determined to be 761.79 kHz. Load resistance was swept to measure the power delivered to the load and the overall end-to-end system efficiency.

Figure 3 shows the performance comparison for the three topologies. It can be seen that the series-series topology has the highest power delivery and efficiency among all three (green curves). In addition, a desirable trend of decreasing power delivery with increasing load resistance is obtained. This power delivery trend is needed to ensure that for smaller load (higher load resistance), less power is delivered. It can be seen that more than 60% efficiency is achieved in a wide power delivery range. The lower efficiency at low power delivery is not an issue since the overall power is low. From the experimental result, it can be concluded that series-series topology is the one should be used.

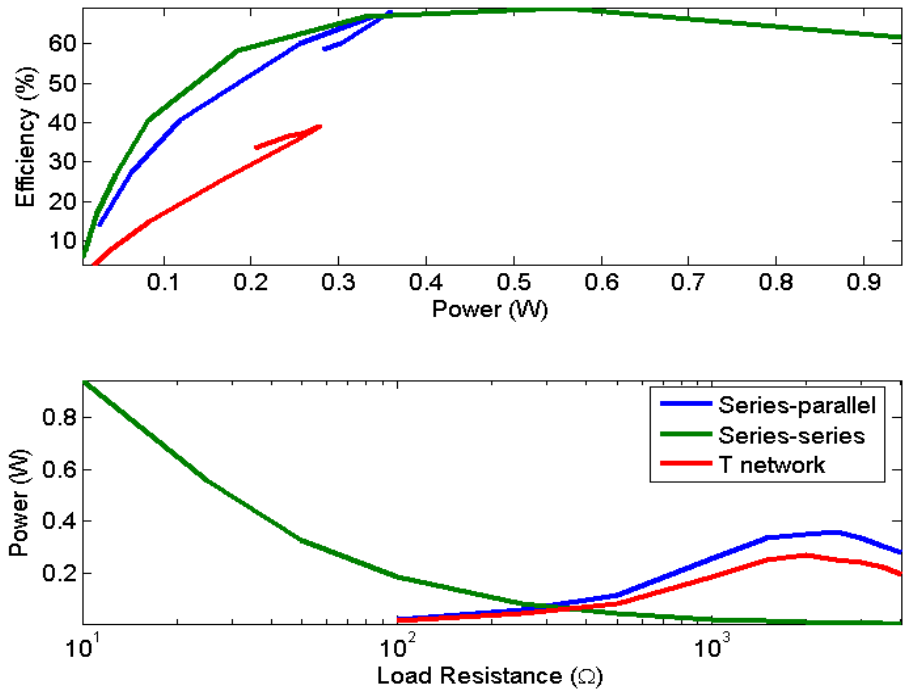


Figure 3: Comparison of efficiency and power delivery of three different topologies of impedance transformation network

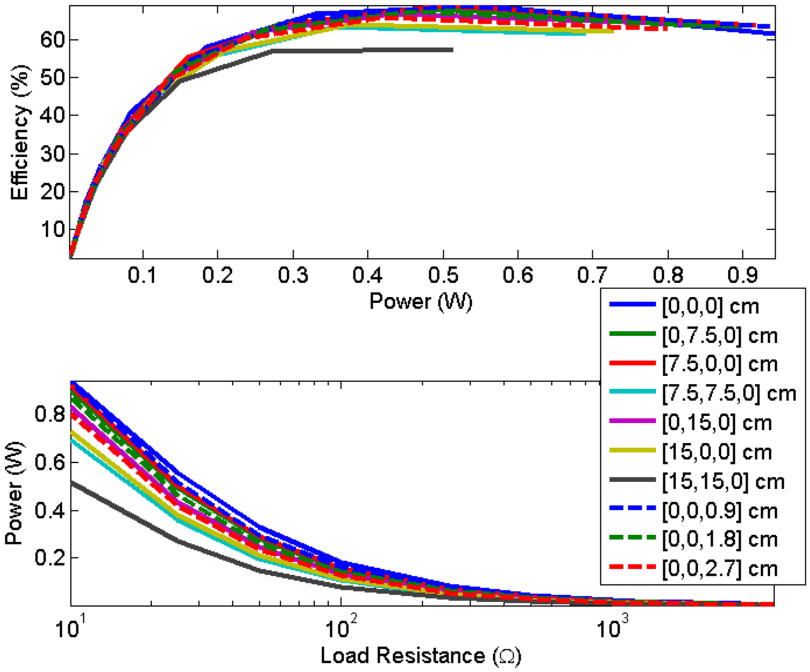


Figure 4: Sensitivity analysis of coils alignment

The system's sensitivity to the alignment of two coils was tested by measuring the efficiency and power delivery at different vertical position (z) and lateral position (x, y) offsets. The performance curves are shown in Figure 4. The offset vector for each curve is indicated in the legend. For example, [0, 7.5, 0] indicates the receiver coil position is displaced by 7.5 cm in the y direction, as compared to the previous experiment with perfect lateral alignment of coils separated by 30 cm. In general, the efficiency and power delivery decrease with increasing lateral offset. The worst performance is when the receiver is offset by [15, 15, 0] (a very large offset causing zero projection overlap between coils): the received power is decreased by 0.5 W and the efficiency is decreased by 15%. However, these decreases are small enough for all other offsets (less than 0.2 W and 9%). It can be concluded that the system is robust with regards to alignment of coils.

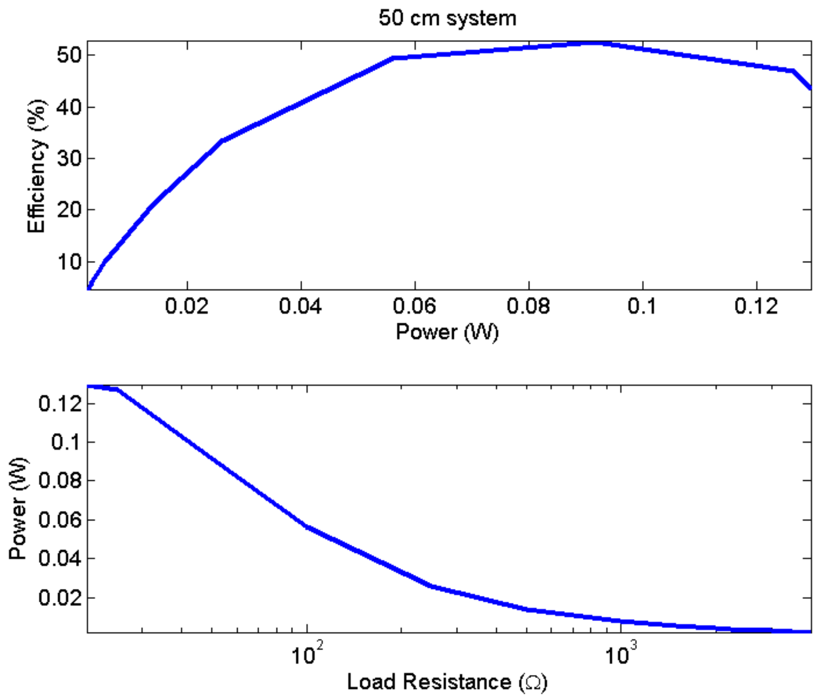


Figure 5: Efficiency and power delivery of the system with 50 cm separation between coils

An experiment was conducted to test the system's performance at 50 cm separation between coils. Two 8-turn coils of 50 cm x 50 cm were built. The operating frequency was tuned slightly to 758.1 kHz to optimize the performance. Figure 5 shows the test result. 50% efficiency can still be achieved. Increasing power delivery has not been the focus of the design yet. After determining the optimum circuit, the power level will be increased.

Conclusion: Designs to achieve mid-range noncontact wireless energy delivery have been studied. Class-E DC-AC inverter architecture and series-series impedance transformation network topology were chosen. In order to achieve high efficiency magnetic coupling, inductive coils need to have the same dimension as the separation between coils. 50% energy delivery efficiency can be achieved when the separation is 50 cm.

UNIVERSITY OF FLORIDA
Carbon Capture and Sequestration

PI: Sabine Grunwald, Tim Martin

Description: Cost-effective CO_2 removal is required to accommodate growth and bridge our transition to greater energy diversity and efficiency. Several carbon sequestration approaches are under development by our team utilizing abundant Florida resources. Geological sequestration by CO_2 injection into saline carbonate aquifers is being developed and tested by USF, representing a new sequestration technology. Biomass-based sequestration is being developed at UF using Florida forests and crops and has widespread support of its agricultural industry. Efforts in this area include the development of a terrestrial carbon information system which will provide a spatially- and temporally-explicit platform for sharing and analyzing terrestrial carbon data, and development of processes for converting by-products of renewable fuel production to a carbon sink. Chemical sequestration to useful products is being developed by UCF via a novel catalytic process that includes solar-derived H_2. The resulting elemental carbon and lignin-based polymers can be stored and transported at ambient temperatures and pressures, and stored in geologic formations or used as possible commercial products. Each approach offers unique advantages to offset our transition to more carbon neutral power and transportation. Cost-effective carbon capture and sequestration is of primary interest to the major Florida power companies. They have proposed formation of a state-wide consortium to address this issue and the proposed Consortium can serve this role. Florida agricultural industries are also very interested in developing carbon sequestration as a supplemental land use.

Budget: $398,880

Universities: UF

Progress Summary

Summary project: Database infrastructure for integrative carbon science research (Grunwald, Martin and Beck):

Rising CO_2 concentrations in the atmosphere and effects on global climate change have been well documented, and future impacts are uncertain but potentially devastating. Florida's natural and agro-forest ecosystems have much potential to sequester carbon in biomass and soils due to unique climatic and landscape conditions. However, research gaps exist to accurately assess carbon pools and fluxes at coarse scales, ranging from county to the region and larger. The overarching objective of this project is to address these obstacles by creating a terrestrial carbon information system (called "TerraC") for the carbon science community, focused on ecosystems in Florida. The information system will be administered through the UF Carbon Resources Science Center (http://carboncenter.ifas.ufl.edu), a multi-disciplinary Center dedicated to research in support of enhanced agricultural and natural resource carbon management.

The development of the information system will proceed in two phases (Figure1). The first phase (now in progress) involves defining and building the core database structure, and design and implementation of custom query and upload tools. Stage 2 will involve linking the TerraC system to a user-friendly Google Earth interface, which will allow interactive queries and the creation of maps and other products.

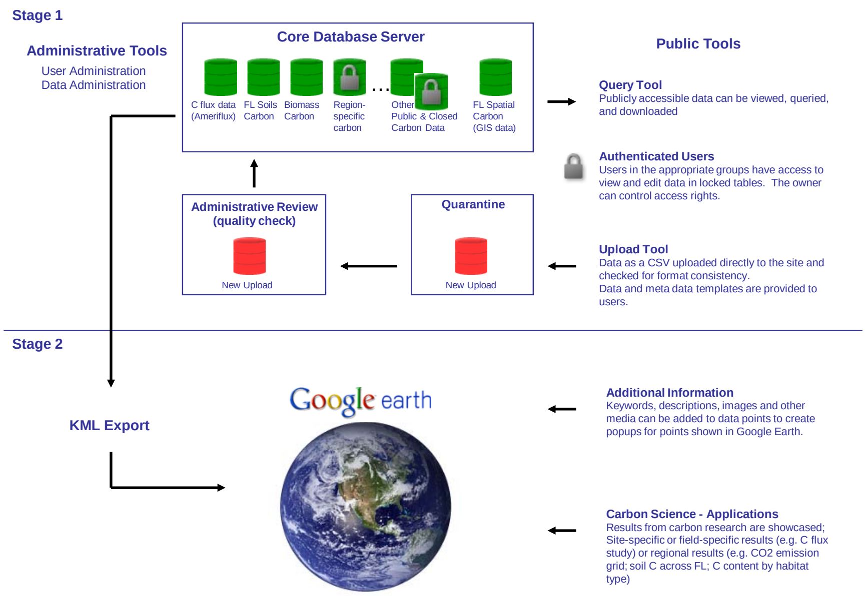


Figure 1. Schematic outlining the structure of the TerraC terrestrial carbon information system.

A project web URL has been obtained (http://terrac.ifas.ufl.edu) to house project updates and, eventually, to serve as a portal to the information system.

FESC
Florida Energy Systems Consortium

UNIVERSITY OF FLORIDA

Development of Biofuel Production Processes from Synthetic and Biomass Wastes

PI: Pratap Pullammanappallil
Students Diane Chaulic, PhD, Microbiology and Cell Science; Zhuoli Tian, PhD, Agricultural and Biological Engineering; Gayathri Ram Mohan, MS, Agricultural and Biological Engineering

Description: With the ever-increasing price of petroleum and its finite supply, it is of high priority to develop domestic sources of transportation fuel, as well as other chemicals. Ethanol is an attractive alternate fuel that is being produced from corn starch. It is necessary to target other feedstocks for biofuel production and develop processes that have a minimal environmental impact. There is considerable ongoing research on developing processes and catalysts for conversion of biomass to biofuels like ethanol (called cellulosic ethanol process). But this project addresses other feedstocks with the following objectives: 1) development of biocatalysts for the conversion of waste biodegradable poly lactic acid based plastics to ethanol and 2) development of processes that processes for the production of additional fuels like biogas, bio-oil and biochar from the waste and byproducts of a cellulosic ethanol plant for the clean up and reuse of these waste streams

Budget: $192,000

Universities: UF

Progress Summary

<u>Process development for biogasification and clean up of cellulosic ethanol stillage</u>

Batches of cellulosic ethanol stillage produced from conversion of hardwoods and sugar cane bagasse were obtained from biofuel pilot plant. These were characterized (chemical oxygen demand, ammonia and phosphate).
Biochemical methane potential assays were conducted on aliquots of these samples.
Hardwood derived stillage yielded more methane per volume of sample than bagasse derived stillage.
The stillages contained 160 ppm of phosphate and 17 ppm of ammonia.

<u>Biocatalyst development for conversion of waste PLA based plastics to ethanol</u>

Extensive literature review was conducted to identify strains possessing the adequate L(+)-LDH gene.
Some strains were then obtained. All strains except *Lactobacillus helveticus 53/7* has been received, rehydrated, and grown in appropriate medium in order to extract the genomic DNA used in the first set of PCR reactions. All *Lactobacilli* were grown into MRS medium except for *Bacillus caldolyticus* which has been grown into Nutrient broth at 60ºC.
Construction of the triple *E.coli* mutant has started.

FESC
Florida Energy Systems Consortium

UNIVERSITY OF FLORIDA

Engineering Biocatalysts for Hemicelluloses Hydrolysis and Fermentation

PI: James F. Preston
Students: Changhao Bi (Ph.D.) awarded April 2009

Project Description:

Goals and Objectives:
Our goal is to develop biocatalysts for the cost-effective production of fuel alcohols and chemical feedstocks from underutilized sources of renewable biomass and evolving energy crops. To reach this goal protocols for efficient saccharification of hemicellulose fractions from these resources will be developed.
Objectives are to:
Develop improved enzyme-mediated saccharification protocols of hemicelluloses with existing bacterial biocatalysts for production of biofuels and chemical feedstocks.
2. Develop Gram positive biocatalysts for direct conversion of hemicelluloses to biobased products.
3. Develop systems with bacterial biocatalysts for efficient bioconversion of the hemicellulose fractions of perennial energy crops (poplar, eucalyptus, switchgrass, energy cane) to targeted products.

Budget: $192,000

Universities: UF

External Collaborators: Collaborations are in various units within the University of Florida:
L.O. Ingram and K.T. Shanmugam, Microbiology and Cell Science; F. Altpeter, Agronomy; G. Peter, Forest Resources and Conservation

Progress Summary

Development of a bacterial biocatalyst for the complete conversion of hemicellulose hydrolysates to biobased ptoducts.

This support allowed Changhao Bi to complete his Ph.D. and contributed to the development of a new strains of *Enterobacter asburiae* JDR-1 that efficiently converted hemicelluloses hydrolysates to either D-lactate or to ethanol. Relevant publications from this effort include:

Bi, C., X. Zhang, J.D. Rice, L.O. Ingram, J.F. Preston. 2009. Genetic engineering of *Enterobacter asburiae* strain JDR-1 for efficient D(-) lactic acid production from hemicellulose hydrolysate. Biotechnol. Lett. 31:1551-1557.
Bi, C., X. Zhang, L.O. Ingram, J.F. Preston. 2009. Genetic engineering of *Enterobacter asburiae* strain JDR-1 for efficient ethanol production from hemicellulose hydrolysates. Appl. Environ. Microbiol. 75:5743-5749.

A relevant patent application from this effort is:

U.S. Provisional Application SN 61/115, 722 UF #12617 “Biocatalyst for complete conversion of hemicellulose to biobased products”. Preston, J.F., C. Bi, and J.D. Rice. Filed 11/18/2008.

Develop improved enzyme-mediated saccharification protocols of hemicelluloses with existing bacterial biocatalysts for production of biofuels and chemical feedstocks

Endoxylanases and alpha-glucuronidases encoded by genes from mesophilic *Paenibacillus* sp. JDR-2 and the extreme thermophile *Thermotoga maritima* have been produced as recombinant enzymes in *E. coli* the provide catalysts for the efficient conversion of the xylans of hemicelluloses to ethanol using the biocatalysts *Klebsiella oxytoca* P2 and *Enterobacter asburiae* E1. Additional studies are in progress to refine the conditions to maximize the conversion of hemicelluloses from forest resources and agricultural residues to ethanol as a biofuel and D-lactate as a chemical feedstock for bioplastics.

Develop Gram positive biocatalysts for direct conversion of hemicelluloses to biobased products

The definition of the xylan-utilization regulon in *Paenibacillus* sp. JDR-2 has been further refined with the recently completed sequence of the genome of this bacterium. This has identified the combination of the transcriptional regulators, transporters and intracellular enzymes that collectively assimilate the products of extracellular depolymerization of xylans and convert these to fermentable xylose. This has provided evidence for a process in which assimilation and of metabolism of the products of depolymerization is coupled to the depolymerization process that is catalyzed by a cell-associated endoxylanase, allowing efficient and rapid conversion of xylans to fermentable xylose by single bacterial biocatalysts. The results of this discovery are the subject of a publication:

Nong. G., J.D. Rice, V. Chow, and J.F. Preston. 2009. Aldouronate utilization in *Paenibacillus* sp. JDR-2: Physiological and enzymatic evidence for coupling of extracellular depolymerization with intracellular metabolism. Appl. Environ. Microbiol. 75:4410-4418.

and also provided supporting information for a provisional patent application:

U.S. Provisional Application SN 60/982,623. UF# 12619. Xylan-Utilization Regulon for Efficient Bioprocessing of Hemicellulose and Uses Thereof. Preston, J.F., V. Chow, G. Nong, J.D. Rice, and F.J. St. John. Filed 10/22/2008.

FESC
Florida Energy Systems Consortium

UNIVERSITY OF FLORIDA

Thermophilic Biocatalysts for the Conversion of Cellulosic Substrates to Fuels and Chemicals

PI: K.T. Shanmugam
Students: Yue Su (Ph. D.) and Brelan Moritz (Ph. D.)

Description: Biomass is an attractive source of sugars for a state like Florida that produces very limited amount of corn for fermentation to produce ethanol as transportation fuel or other products such as lactic acid that can be converted to bioplastics. Florida currently generates about 8.7 million tons of dry cellulosic biomass per year (US-DOE) that can be converted to about 0.7 billion gallons of ethanol. With specific energy crops and short rotation trees cultivated for energy production using the abundant sunshine and water resources, the ethanol produced from biomass can be significantly increased to meet the demand for transportation fuel in the State of Florida. Before biomass-based fuels and chemicals become an economic reality, several key steps in the depolymerization of biomass to constituent sugars need to be addressed. One is depolymerization of cellulose to glucose by fungal cellulases before fermentation to ethanol by microbes. The current estimated cost of fungal cellulases is $0.32 per gallon ethanol produced and this cost is targeted for reduction to $0.10 or less by year 2012 (DOE). We have demonstrated that by increasing the temperature of Simultaneous Saccharification and Fermentation (SSF) of cellulose from 30-35 ºC to 50-55 ºC, the amount (and associated cost) of cellulases can be reduced by the required 3-fold with the current commercial enzyme preparations. A microbial biocatalyst that produces ethanol or other chemicals as the main fermentation product and can also function at this higher temperature and pH 5.0 in conjunction with the fungal cellulases in the SSF process is a critical component of this process. We have identified a thermophilic facultative anaerobe, *Bacillus coagulans*, with versatile metabolic capability as the microbial platform for the SSF of biomass to products and engineering this L(+)-lactic acid producing bacterium to produce ethanol. *The primary objective of this proposed study is to construct a B. coagulans derivative that produces ethanol as primary product of fermentation and to enhance the ethanol productivity of the engineered derivative.*

Budget: $192,000

Universities: UF

Progress Summary

We have constructed *B. coagulans* derivatives that lack two of the three metabolic pathways that compete with ethanol production during fermentation. These deletion derivatives have lower growth rate and productivity and produced in addition to ethanol, 2,3-butanediol. These mutant strains are biochemically characterized to identify the rate-limiting steps in ethanol production for further genetic modification. Mutagenesis of these derivatives to eliminate the 2,3-butanediol pathway is in progress. Upon eliminating all the competing pathways, the specific rate of ethanol production will be enhanced by metabolic evolution to obtain a thermophilic microbial biocatalyst that can ferment biomass-derived sugars to ethanol in a cost-effective manner to support a biomass-based ethanol industry.

FESC
Florida Energy Systems Consortium

UNIVERSITY OF FLORIDA

Integrated PV/Storage and PV/Storage/Lighting Systems

PI: Franky So
Students: Ming-Che (Tim) Yang, William Hammond, Edward Wrzesniewski, Cephas Small, Fred Steffy (Ph.D.); Thomas McGilvray (undergrad)

Description: The goal is to increase the efficiency and reduce the cost of solar power through the integration of PV, Li-battery, and LED lighting technologies. Since all components are in the form of thin films, the PV/battery/LED system can be integrated as a single module. Since half of the materials cost of each device is the substrate, integrated module will also reduce materials costs and processing steps. Importantly, their integration further eliminates the need for inverters since they are all low-voltage devices. Such an integrated device can be used to store energy during the day and power the LED panel for lighting in the evening. In addition, we will explore the possibility of fabricating a semi-transparent module. The success of this Task will lead to a novel solar-power lighting panel that can be used as a sky light during the day and a lighting panel during the night without using grid-power. We not only will develop the technologies, but also integrate devices and perform technology-economic evaluation, including life-cycle costs.

Budget: $576,000

Universities: UF

Progress Summary

There is great interest in developing renewable resources and improving the technologies for energy interconversions. The transformations of light into electricity (electrical energy generation in photovoltaic cells), electrical energy storage (rechargeable batteries) and electricity into light (light generation in light-emitting diodes) are three important interrelated areas that have attracted considerable research and commercial interest. Organic/polymer materials have been investigated for these transformations and undoubtedly play key roles in efficient production, transformation and utilization of solar energyThe main objective of the current work is to develop high efficiency solar energy at cheap cost for integrated PV/battery/lighting system. The development of self-contained power supplies that are suitable for electrical/lighting application depends upon the development of thin-film batteries and photovoltaic cells. In this project, we independently explore and develop the efficient and cost effective device component such as photovoltaic, batteries and organic light emitting devices.

In the PV area, our focus is to develop high efficiency transparent polymer PV cells. Our initial focus is to study the effect of anode interlayer on cell performance. Using molybdenum trioxide, we were able to demonstrate 15-20% enhancement in cell performance. In the lithium ion battery area, we have developed a new class of electrodes based on Co-free, Ni and Mn containing Li transition metal oxides. This class of electrode materials has a composite ‘layered-spinel’ structure in nano-scale and batteries made with these electrode materials offer nearly 50% more energy density than the batteries made with the current state-of-the art cathode materials. In the OLED area, using a p-i-n structure, we have demonstrated white emitting OLEDs with luminous efficiency exceeding 70 lm/W. Our next step is to demonstrate transparent PV cells and OLED devices and integrate them with the lithium ion batteries developed in this program.

Efficient Polymer solar cells

Franky So

Polymer solar cell (PSC) has attracted increasing attention due to their inexpensive, flexible, light weight and large area device fabrication. However, the efficiency of the PSC achieved so far, not yet sufficient for large scale implementation. One of the fundamental requirements for efficient operation of polymer solar cell is effective carrier extraction from the active layer to the electrode. But, poor understanding of interfacial phenomena of electrode and active layer limits the efficient charge collection and hence affects the cell performance. Here, we demonstrate that the power conversion efficiency (PCE) of polymer solar cells can be enhanced by using molybdenum oxide (MoO_3) as an anode interface layer. In this work, we have studied the effect of MoO_3 interface layer on polymer photovoltaic cells. The devices we studied includes poly(3-hexylthiophene (P3HT) : {6,6}-phenyl-C61 butyric acid methyl ester (PCBM), poly(2-methoxy-5-(3,7-dimethyloctyloxy)-*1,4*-phenylene vinylene (MDMO-PPV):PCBM bulk heterojunction cells and it shown in Figure 1(a). The energy level diagram of all components used in PV cells and molecular structure of polymers are shown in Figure 1(b).

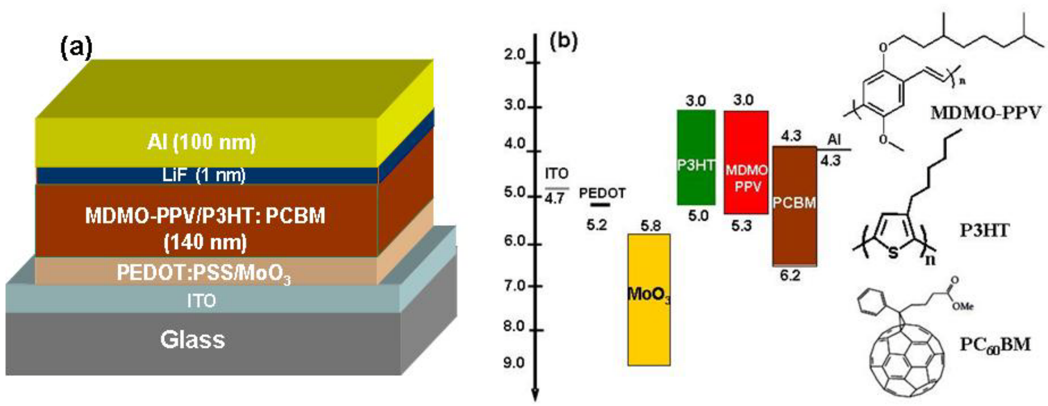


Figure 1. (a) A schematic device structure of polymer solar cell (b) energy levels of the donor polymers, acceptor, buffer layer materials, electrodes and molecular structure of MDMO-PPV, P3HT and PCBM.

Figure 2(a) shows the photo J-V characteristics of the P3HT:PCBM cells with the PEDOT:PSS and the MoO_3 interlayers. The device performance of the P3HT:PCBM cells with the PEDOT:PSS interlayer and the MoO_3 interlayer is summarized in Table I. From Figure 2, we found that there is an 8% increase in fill factor due to the MoO_3 interlayer indicating that replacing the PEDOT:PSS layer with a MoO_3 interlayer reduces the series resistance of the P3HT:PCBM cells. The series resistance of the P3HT:PCBM cell with the MoO_3 interlayer is about 42% lower than that of the PEDOT:PSS cell as shown in Table I. Overall, the P3HT:PCBM cell with the MoO_3 interlayer has a power conversion efficiency 16% higher than that with the PEDOT: PSS cell. The effect of MoO_3 interlayer on MDMO-PPV PV cells (Figure 2(b)) are qualitatively similar and enhancements in both short-circuit current and fill factor were observed, resulting in about 20% enhancement in power efficiency as shown in Table I.

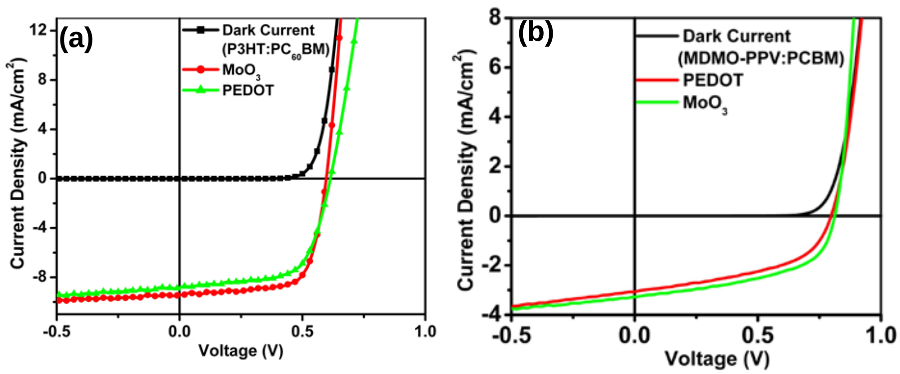


Figure. 2. The J-V curve of (a) the P3HT:PCBM cells and (b) the MDMO-PPV:PCBM cells with the PEDOT:PSS and MoO_3 interlayer .

The enhanced device performance can be attributed to the reduction in contact resistance between the active layer and the anode due to the change in interface energetic by the MoO_3 interface layer.

Polymer cell	Interlayer	J_{SC} (mA/cm^2)	V_{OC} (V)	FF (%)	ηP (%)	R_s (Ωcm^2)
P3HT:PCPM	PEDOT	7.95	0.58	62.0	2.85	12.9
	MoO_3	8.20	0.60	67.0	3.31	7.5
MDMO PPV:PCBM	PEDOT	3.00	0.79	49.0	1.19	35.0
	MoO_3	3.30	0.80	52.0	1.36	20.5

Table 1.Performance summary of polymer PV cells with and without the MoO_3 interlayer

High Volumetric Energy Density and Long Life Lithium Batteries

Shirley Meng

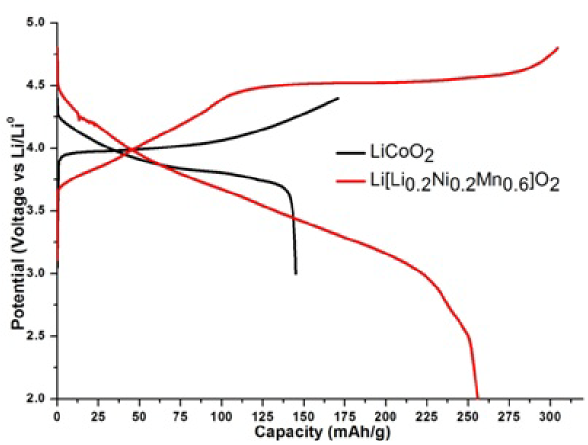


Fig. 3. Charge-discharge curve (red) of a new lithium ion cathode material developed in Meng's group. The black curve is obtained from commercial LiCoO2 cathode used in conventional lithium ion batteries.

Over the past decades, while rechargeable batteries have made remarkable progress in terms of energy density, the improvement in energy density still falls short of the performance requirements for energy storage for renewable energy sources, such as solar, wind etc. for the Integrated PV/Battery Storage/Lighting system proposed in this FESC project, high volumetric energy density lithium ion batteries with long cycle life will be developed as a storage component in the solar-powered lighting module. To meet the grid-free operation requirements, conventional lithium ion batteries (LIBs) used in consumer electronics do not have the energy density and cycle life that will enable the lighting module to be completely grid-free. New ultra high energy density and longer cycle life materials must be developed to fulfill the demands.

Meng's group has developed a new class of electrodes based on Co-free, Ni and Mn containing Li transition metal oxides. This class of electrode materials has a composite 'layered-spinel' structure in nano-scale and batteries made with these electrode materials offer nearly **50%** more energy density than the batteries made with the current state-of-the art cathode materials as shown in Fig. 3. Due to the composite nature of the electrode materials, their structural and electrochemical stability are much better than the conventional layered oxides used in the current lithium ion batteries. Meng's group has successfully optimized the synthesis process, the particle size of the samples we produce are within 100-300nm with uniform morphology, as seen in Fig. 4. Furthermore, our results indicate that the stoichiometries of the precursors play a critical role on the electrochemical properties of these lithium excess manganese nickel oxide materials. Based on the comparison of the synthesis techniques, it can be seen that the surface, the amount of Li/Ni interslab mixing, the superlattice intensities and the layered characteristics of the materials are all critical for the reversible capacity. The detailed results will be reported in our manuscript, titled "The effect of synthesis temperature and stoichiometry on the electrochemical properties of $Li[Li_{1/3-2x/3}Ni_xMn_{2/3-x/3}]O_2$", which will be submitted for journal publication by the end of this year. This manuscript will also be presented in the upcoming electrochemical society (ECS) annual meeting in Vienna, Austria.

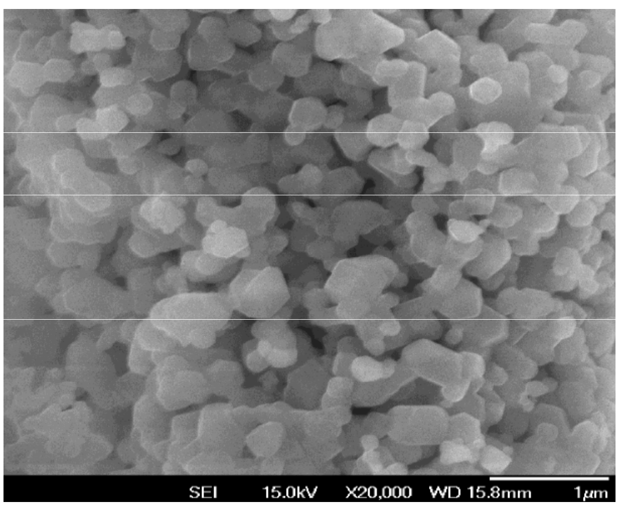


Fig. 4. Scanning Electron Micrograph of the lithium excess manganese nickel oxides synthesized through optimized synthesis route. The samples show uniform morphology and particle size range from 100-300nm.

Nevertheless, these materials still suffer from the lack of lithium mobility. Our main objective in the next stage of the project is to fabricate LIBs for the integrated module with these electrode materials and to improve the lithium mobility in these new high energy density materials. Based on our research finding the surface may be the most critical factor limiting lithium diffusion. We plan to combine ex-situ and in-situ X-ray characterization tools, as well as electrochemical impedance measurement to provide a detailed explanation of the lithium diffusion mechanism in these materials. If the surface is identified as the major limiting factor, special coatings may be applied to increase the conductivity.

High Efficiency White Organic Light-Emitting Devices

One of the key device components in the demonstration of the PV/OLED/LiB integrated system is the white OLEDs. In the past year, we have successfully demonstrated small area (4 mm^2) white OLEDs with maximum efficacy approaching 70 lm/W. These devices were based on three organic electrophosphorescent emitters, FIr6, $Ir(ppy)_3$, and PQIr, emitting blue, green, and red light, respectively. The molecular structure of these molecules and their electroluminescence (EL) spectra are shown in Fig. 5. These devices also employed the *p*-*i*-*n* device architecture with dual emissive layers, each of which contains all three emitters (also see Fig. 5).

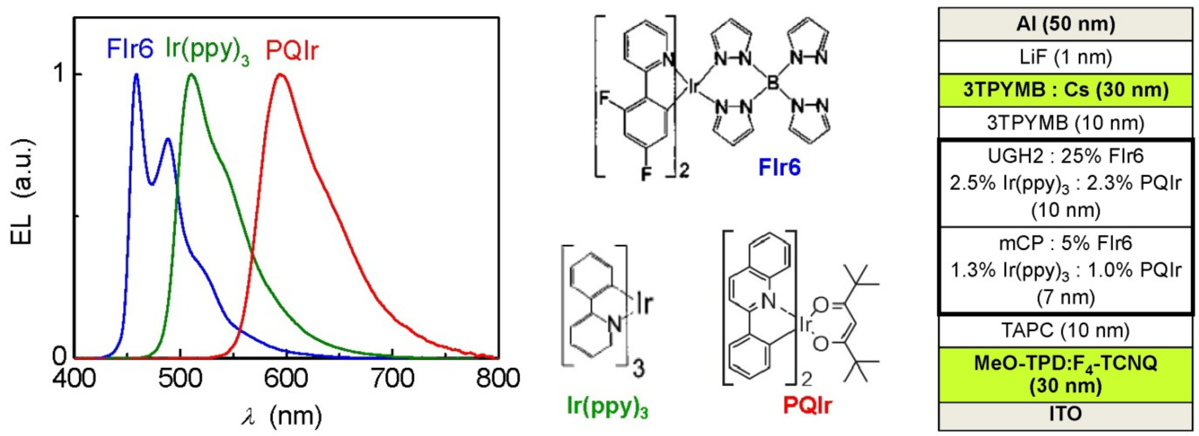


Fig. 5. Electroluminescent spectra and molecular structures of the three phosphorescent emitters as well as the schematic device structure of the white OLEDs.

The current density-luminance-voltage (J-L-V) characteristics of the white OLEDs are shown in Fig. 6(a). These devices have a very low turn-on voltage of 2.9 V, and the operating voltages at L = 100 cd/m^2 and 1000 cd/m^2 are 3.5 V and 4.0 V, respectively. Such low operating voltages certainly match with the voltage output of the lithium-ion batteries to be used in the integrated system. This device has a maximum efficacy (or power efficiency) of η_P = 40 lm/W at a luminance of L $\approx$ 10 cd/m^2 as shown in Fig. 6(b) The efficacy is slightly reduced to 36 and 26 lm/W at L = 100 and 1000 cd/m^2, respectively. These luminance values correspond to typical display and lighting brightnesses. When a hemispherical lens was attached to the glass substrate, an approximately 70% higher efficacy is achieved due to the enhanced extraction of waveguiding modes in the glass substrate, leading to a maximum efficacy of nearly 70 lm/W. As shown in Fig. 6(c), the EL spectrum of these device do not change significantly as the brightness is varied from 10 to 1000 cd/m^2. The Commission Internationale de L'Eclairage coordinates of the white OLED is (0.37, 0.40), and the color rendering index (CRI) is about 80.

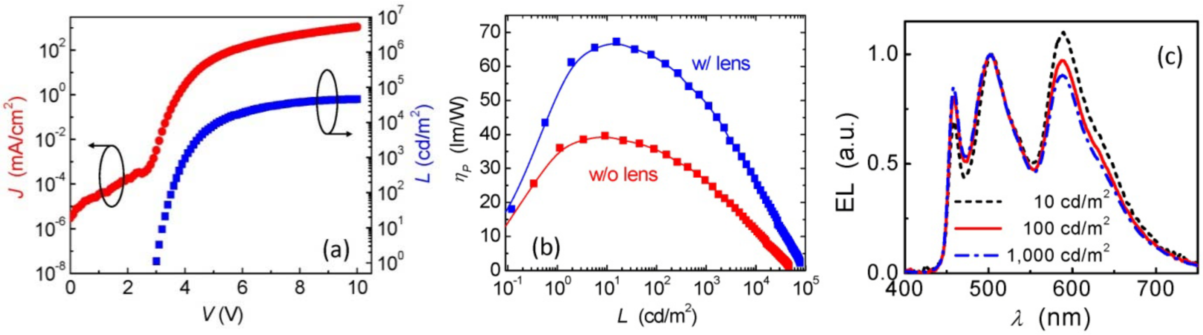


Fig. 6. (a) Current density-luminance-voltage (J-L-V) characteristics of the white OLEDs. (b) Efficacy (or power efficiency) as a function of the luminance for devices with or without a hemispherical lens attached to the substrate. (c) EL spectra of the devices at different luminance levels.

UNIVERSITY OF FLORIDA

Water-Use Efficiency and Feedstock Composition of Candidate Bioenergy Grasses in Florida

PI: Lynn E. Sollenberger
Co-PI's: John Erickson, Joao Vendramini, Robert Gilbert
Students: Arkorn Soikiew (M.S.), Chae-In Na (Ph.D.), Jeff Fedenko (M.S.)

Description:
Florida ranks first in the USA in annual growth of plant biomass because of a large cultivatable land area, high rainfall, and long growing seasons. The development of high yielding production systems for energy crops that can be grown in Florida is considered essential for establishment of a sustainable biomass to energy industry. This is the case because long-term availability of sufficient amounts of reasonably priced biomass will be an important determinant of <u>if</u> and <u>where</u> new biofuel and bioenergy facilities will be built. Because of its size and large number of climatic zones, there will be large regional differences in what energy crops can be used at various locations in Florida and how they will perform. In this project, we are conducting applied research at locations throughout Florida with sweet sorghum, sugarcane, energycane, giant reed, miscanthus, erianthus, and elephantgrass to provide important agronomic practice, yield, water use, and chemical composition information for Florida growers, bioenergy producers, and policy makers. This information will support decision making regarding which crops are adapted to specific environments, which are best suited to particular management practices (e.g., irrigation or none), and which have the desired chemical composition for the intended bioenergy use.

Investigators in the project include Dr. Lynn Sollenberger and Dr. John Erickson (agronomists at University of Florida), Dr. Joao Vendramini (agronomist at the Range Cattle Research and Education Center at Ona, FL), and Dr. Robert Gilbert (agronomist at the Everglades Research and Education Center at Belle Glade, FL). Graduate students involved in carrying out project research include Jeff Fedenko, Arkorn Soikiew, and Chae-In Na, all of whom started their grazduate programs in August 2009. External collaborators include Speedling, Inc., which has provided planting material of miscanthus.

Budget: $191,981

Universities: UF

External Collaborators: Speedling, Inc.

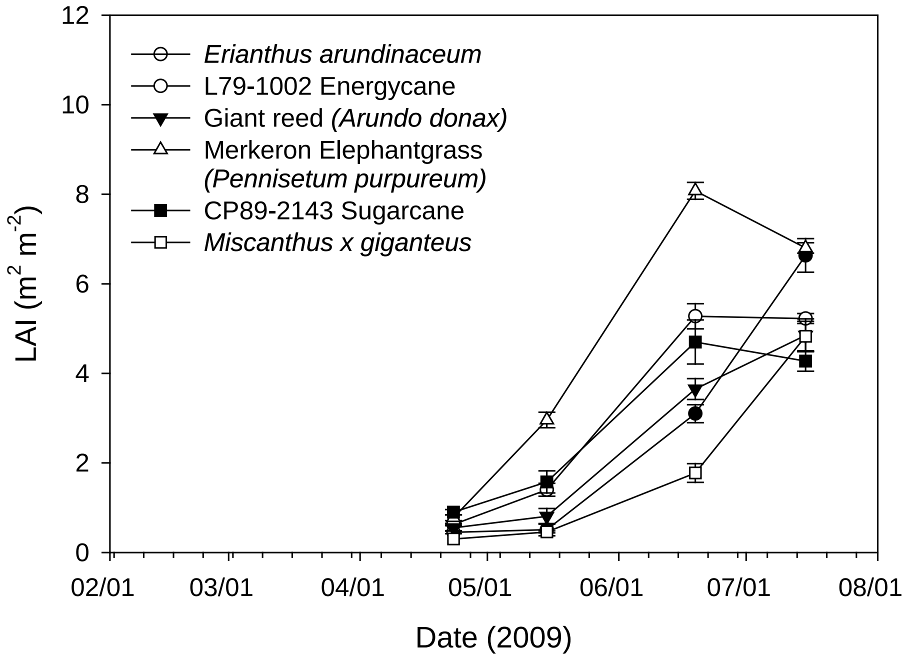
Progress Summary

Replicated experiments studying sweet sorghum (annual grass) and six perennial grasses have been established in North Florida (Citra), Southcentral Florida (Ona), and South Florida (Belle Glade). Data collection was initiated by assessing leaf area development of the six perennial grasses, sweet sorghum biomass and sugar yields, and water-use for several of the perennial grasses. Because of the relatively short period since initiation of the research (July 1, 2009), there are limited data available at present and samples for analysis of feedstock composition of most grasses are not yet available.

Leaf area accumulation data for the six perennial grasses has been summarized and is presented in Table 1. These data illustrate the initial superiority of Merkeron elephantgrass compared to other perennial grasses in establishing a full canopy and maximizing light interception. This trait is expected to be closely associated with biomass yield, a response that will be quantified directly at the end of the growing season in December 2009. In the most recent data from Belle Glade (collected on 22 September), elephantgrass retained the highest ranking among perennial grasses with a leaf area index of 9.7 which was greater than energycane and sugarcane (6.9 and 6.5, respectively). Giant reed and erianthus were next at 5.2 and 4.2, with miscanthus having the lowest leaf area index of 2.6. These early results support a preliminary conclusion that elephantgrass, energycane, and sugarcane are the most likely to be successful biomass-producing perennial grasses in Florida.

Harvesting sorghum has occurred throughout the summer and fall, and the effects of location, planting date, and variety on biomass and sugar yield will be known by the end of 2009. Yields of the perennial grasses will be determined in December 2009, and samples will be analyzed subsequently to determine their chemical composition. Water-use data are now available for the 2009 growing season and will be summarized and analyzed during the remainder of 2009

Citra



Belle Glade

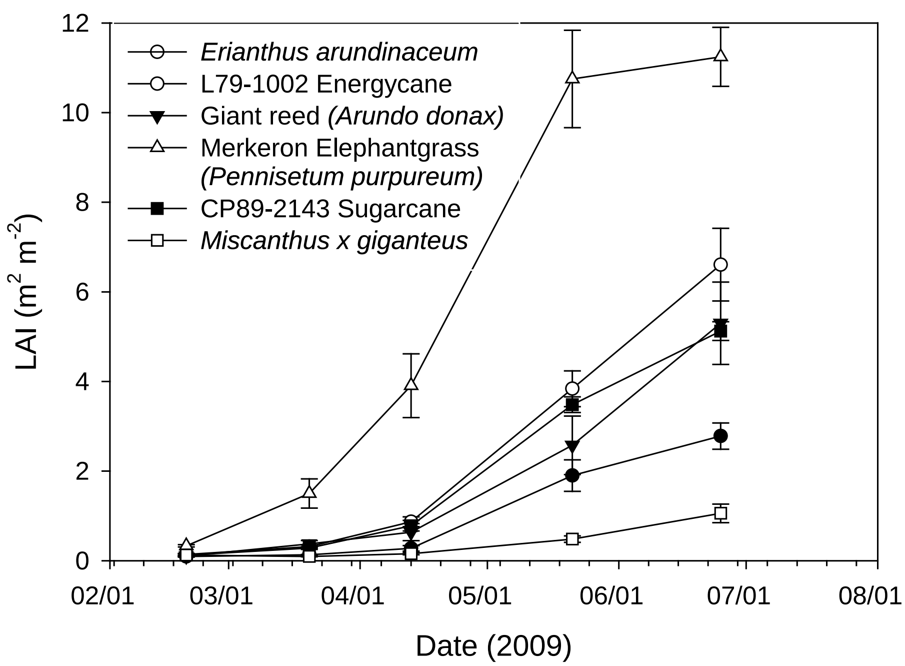


Figure 1. Leaf area index of perennial bioenergy grasses during the establishment period at Citra and Belle Glade.

UNIVERSITY OF FLORIDA

Biocatalytic Lignin Modification for Carbon Sequestration

PI: Jon Stewart

Description: After cellulose, lignin is the second most abundant forma of carbon in plants. Lignin's complex structure makes it difficult to use this material in value-added products, and ahte vast majority of lignin is currently burned to provide energy for factory operations. While burning plant derived lignin does not add to global greenhouse gas levels, having options to remove lignin from the global carbon cycle would lead to diminished atmospheric CO2 levels. This could be accomplished by chemically altering lignin's structure to facilitate long-term terrestrial sequestration or using it in value-added products that would not be discarded immediately. We will use Nature's catalysts (enzymes) to tailor the chemical structure of lignin for both deep-well injection (by using lignin derivatives as drilling "muds") and for materials that can be used in building, packaging, and other manufactured products.)

Budget: $200,000

Universities: UF

Progress Summary

New project – no progress reported.

FESC
Florida Energy Systems Consortium

UNIVERSITY OF FLORIDA

An Integrated Sustainable Transportation System

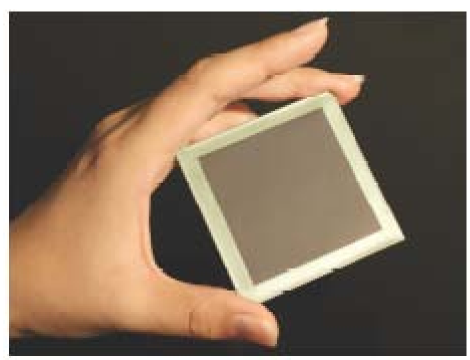
PI: Eric Wachsman **Co-PI:** Shirley Meng
Students: Dan Gostovic, Dong Jo Oh, Eric Armstrong, Byung Wook Lee, Kang Taek Lee, Nick Vito and Christopher, R. Fell (Ph.D.); Patrick Wanninkopf, Eric Klump, Nicholas Sexson, Kevin Seymor, and Thomas McGilvray (Undergrad)

Description: The proposed vehicle, operating on biofuel while in transit and charged by the sun while parked, is the ultimate sustainable transportation system operating completely on renewable American energy resources. Moreover, the use of solid oxide fuel cells (SOFCs) rather than an IC engine in this hybrid vehicle results in a dramatic improvement in efficiency and reduction in emissions. SOFCs are the most efficient technology for converting energy from hydrocarbon fuels to electricity on a "well to wheels" basis. In contrast, the more conventional fuel cells require hydrocarbon fuels to first be converted to H_2, with resultant efficiency losses, followed by losses due to H_2 transport and storage. Therefore, on a system-basis SOFCs hold the potential for producing the least CO_2/kWh from conventional fuels, and if designed to operate on biofuel would in effect be carbon neutral and operating on a renewable resource. *If developed this vehicle would be a transformational change in transportation technology.*
Budget: $594,000
Universities: UF
External Collaborators: Solid-State Energy Technology, Inc., Lynntech, Inc., Planar Energy Devices, Inc., CFX Battery, Inc.

Progress Summary

We have been developing high performance fuel cells and batteries as the critical components of a transformational transportation system. By integrating advanced materials and engineered structures we have achieved *world record performance* solid oxide fuel cells (SOFCs). These SOFCs have acheived ~2 W/cm^2 at 650°C. Since the cells are only ~0.5 mm thick, this corresponds to a power density of ~40 W/cm^3.

With these exceptional power densities we can readily reduce the operating temperatures to 300-500°C. This will allow us to use conventional stainless steel interconnects and BOP, as well as simple elastomeric seals, thus reducing cost and increasing reliability. In addition, operation on reformed JP5 diesel resulted in only a 20% decrease in power density compared to H_2. Thus, our SOFCs can operate directly on hydrocarbon fuels.
A patent application has been filed and we are working with two companies to commercialize the technology. In addition, as part of the commercialization strategy we are scaling up the cell size (see figure) and have submitted an ARPA-E proposal.



6 cm x 6 cm SOFC fabricated in FISE Energy Technology Incubator.

Battery development has resulted in advanced $Li_2M_xNi_{0.5-x-y}Mn_{1.5+y}O_4$ cathodes for Li-batteries. These cathodes result in a dramatic improvement in energy and power density as well as lifetime (charge-discharge cycles). A patent application has been filed and we are working with two companies to commercialize the technology.

2009 Annual Progress Report

Fuel Cell development for the integrated sustainable transportation system

Eric Wachsman

There has been a tremendous effort to lower the operating temperature of solid oxide fuel cells (SOFC) to ~800°C, for cost and reliability considerations. Simultaneously there has been an even larger effort to increase the operating temperature of proton exchange membrane fuel cells (PEMFC) above 100°C, for performance and fuel poisoning considerations. Somewhere in between is the optimum operating temperature for a fuel cell, depending on fuel choice and degree of external fuel processing (vs. relying exclusively on internal reforming).

While there has been some success at developing high-temperature PEM fuel cells operating at temperatures around 140ºC, the power densities and fuel flexibility of these systems are limited. Moreover, there is significant concern that the hydrogen infrastructure necessary for PEMFCs will always make this a future technology with limited market penetration.

In contrast, SOFCs can operate on both current conventional fuels (e.g., natural gas, gasoline, and diesel) and biofuels (biogas, ethanol, and biodiesel). As such, SOFCs offer great promise as a clean and efficient process for directly converting chemical energy to electricity while providing significant environmental benefits (they produce negligible CO, HC, or NO_X and, as a result of their high efficiency, produce about one-third less CO_2 per kWh than internal combustion engines). Moreover, SOFC operation on biofuels is the most energy efficient means to utilize home grown carbon neutral fuels.

Unfortunately, current SOFC technology must operate in the region of ~800°C to avoid unacceptably high ohmic losses. These high temperatures demand specialized (expensive) materials for the fuel cell interconnects and insulation; and significant time and energy to heat up to the operating temperature. Therefore, development of SOFCs to provide reasonable power output at lower temperatures (≤600°C) would make SOFCs both more cost competitive with conventional technology, and significantly reduce start-up times which is critical to transportation and portable power applications.

The problem is, the conductivity of the conventional stabilized zirconia electrolyte (YSZ) is insufficient, resulting in prohibitively high resistance at lower temperatures, even for a thin (~10 μm) electrolyte. To address this we have used the fundamental knowledge of the impact of local crystal structure on conductivity to develop both the most conductive ceria based electrolyte, samarium-neodymium doped ceria (SNDC),[1,2] and the highest conductivity and hence lowest temperature, bismuth oxide based electrolyte, dysprosium-tungsten stabilized bismuth oxide (DWSB)[3,4]. At 500°C, the conductivity of SNDC is 20X that of YSZ, and the conductivity of DWSB is 100X that of YSZ. Thus, creating the opportunity for high power density low temperature SOFCs.

To overcome stability issues in reducing environments we developed a bilayer bismuth-oxide/ceria electrolyte that simultaneously blocks the electronic conduction in the ceria layer and prevents the decomposition of the bismuth oxide layer.[5-8] Using this bilayer approach we have demonstrated that we can combine two highly conductive materials that were otherwise unstable, to produce a highly conductive and stable electrolyte (over 1400 hrs of testing).[5] Further, to develop compatible higher performance cathodes we investigated the role of catalytic activity and microstructure on cathode performance[9-11] and developed a bismuth-ruthenate/bismuth-oxide composite cathode with one of the lowest reported area specific resistances (ASR) ever reported.[12,13]

Anode Supported Cell Development

State of the art, high power density, SOFCs are fabricated based on an anode supported thin (~10 μm) electrolyte. In order to accomplish this it is necessary to both develop the appropriate anode support and thin/thick film electrolyte deposition process. For an ESB/GDC bilayered electrolyte the anode selected was GDC. This was fabricated from tape cast NiO-GDC, followed by an anode functional layer (AFL).[14] For the electrolyte layers we investigated colloidal deposition of GDC and ESB. Unfortunately, due to the insolubility of bismuth oxide it was difficult to obtain the fine powders necessary for colloidal deposition. Results of these investigations and the resultant improvement in cell performance are available in references 15 & 16. Ultimately, the desired structure was obtained by PLD of ESB on top of pre-sintered GDC, that had been colloidally deposited on an NiO-GDC anode support tape, Fig. 1.

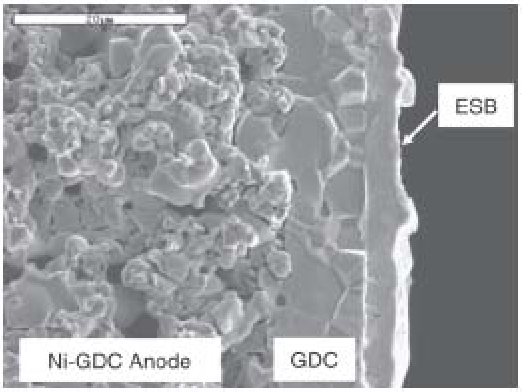


Fig. 1. Cross sectional SEM of anode supported bilayer electrolyte.

Figure 2 shows the current-voltage & current-power performance of the ESB/GDC bilayered electrolyte cell utilizing the BRO7/ESB cathode compared to a single layer GDC electrolyte cell. In both cells the OCP is significantly lower than theoretical. This is due to the mixed ionic-electronic conducting behavior of ceria electrolytes, the OCP decreases as thickness decreases.[14,17,18] Therefore, the OCP values of the samples utilizing thin GDC electrolytes were lower than that of pressed thick GDC electrolytes in all cells tested. However, what can also be observed is that the ESB layer increased the OCP consistent with the bilayer concept. Moreover, we believe that a relatively thicker bismuth oxide layer will result in obtaining near theoretical OCPs and this work is ongoing.

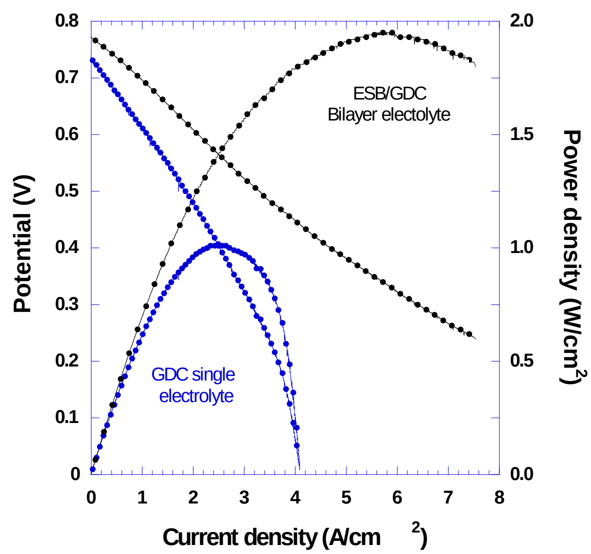


Fig. 2. Performance comparison of bilayer and single layer electrolyte cells at 650°C; air-cathode and H_2/H_2O anode.

What can also be seen is a doubling of the power density due to both the increase in OCP and the reduction in ASR. The 2X increase in power density for the bilayer cell resulted in power densities of ~2 W/cm^2 at 650°C.[14,15] This is *world record performance* and since the cells are only ~0.5 mm thick, this corresponds to a power density of ~40 W/cm^3.

With these exceptional power densities we can readily accommodate a decrease in power associated with operating the SOFCs at temperatures of 300-500°C. This will allow us to use conventional stainless steel interconnects and BOP, as well as simple elastomeric seals, thus reducing cost and increasing reliability. In addition, operation on reformed JP5 diesel resulted in only a 20% decrease in power density compared to H_2. Thus, our SOFCs can operate directly on hydrocarbon fuels.

Our low temperature SOFC provides a major opportunity to employ nano-catalysts in the electrodes. By reducing operating temperature to≤600°C we will overcome electrode sintering/coarsening issues, thus allowing the use of nano-structures to increase electrocatalytic activity and specific surface area. We can then enhance electrode performance by impregnating catalytically active transition metal nano-clusters into the cathode and anode to decrease activation polarization losses.

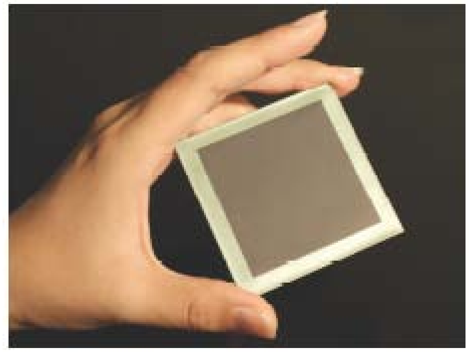


Fig. 3. 6 cm x 6 cm SOFC fabricated in FISE Energy Technology Incubator.

A patent has been filed "Advanced Materials and Designs for Low Temperature SOFCs," E. D. Wachsman, Filed October 14, 2008, U.S. Patent Application Serial No. 61/105,294 and we are working with two companies to commercialize the technology, Solid-State Energy Technology, Inc., and Lynntech, Inc. In addition, we are scaling up the cell size as part of the commercialization strategy (Fig 3.). Finally, our ARPA-E concept paper "Low Temperature Solid Oxide Fuel Cells; A Transformational Energy Conversion Technology" was one of only very few selected by DOE for a full proposal, which we have subsequently submitted.

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Energy storage in the integrated sustainable transportation system

Shirley Meng

Currently available energy storage technologies fall short of performance requirements for using electrical energy efficiently in transportation applications. For vehicle applications, Lithium Ion Battery (LIB) technology is attractive for its high energy density compared to previous battery technologies, such as Ni-MH batteries. However, for Plug-in HEVs (PHEV) and other systems of larger size (2-100 kWh), further improvements in power density (kWh/kg), energy density (kWh/kg), and lifetime are necessary. HEV life targets are ~300,000 cycles under typical pulse power profiles, while PHEV targets are ~6000 charge-discharge cycles; desired calendar life in both instances is ~10 years. For the proposed new system, we have taken two approaches to achieving these goals. One is to develop higher voltage positive electrode, focusing on specific compounds that have the potential for increased energy density concurrent with high power and improved safety. A second is to understand the mechanisms of life degradation, and to design materials and cells with improved cycle life.

Electrochemical energy storage systems are inherently complex, and the successful technology for the proposed application must combine essential features including intrinsically high (thermodynamic) energy density; adequate power achieved through materials and systems design; electrochemical and materials stability for long life; economical materials synthesis and device fabrication; reasonable cost; and adequate safety and manageable toxicity. In Li-ion systems the **electrodes** are the most expensive active components, comprising the highest mass fraction of the battery, plays a critical role in determining energy density by setting the positive electrode potential, and often limits the charge/discharge rate of the system. Combining first principles virtue materials design and innovative synthesis routes, cathode materials with more than 1000Wh/kg (see Fig.4 comparison with current materials) have been demonstrated in our laboratory. We have developed a new class of cathodes likely to combine high power and energy density at low cost – $Li_2M_xNi_{0.5-x-y}Mn_{1.5+y}O_4$ (M=transition metals). Because the Mn oxidation state is mainly 4+ the material is very stable at all state of charge and no Mn dissolution occurs. The use of the Ni redox couple increases the lithium intercalation potential to ~4.7V. Theoretical energy density of this spinel-type cathode is higher than that of any existing cathode material. (Fig.4) Although it is commonly believed that the charge/discharge cycle proceeds as two topotatic 2-phase reactions (shown in Fig.5a), good rate capability of this material has been demonstrated in our lab (Fig.5b).

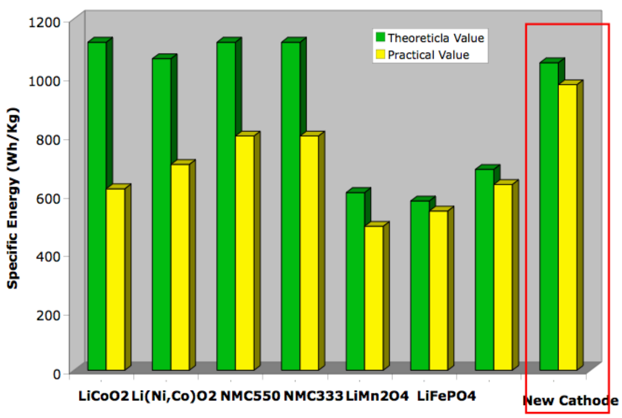
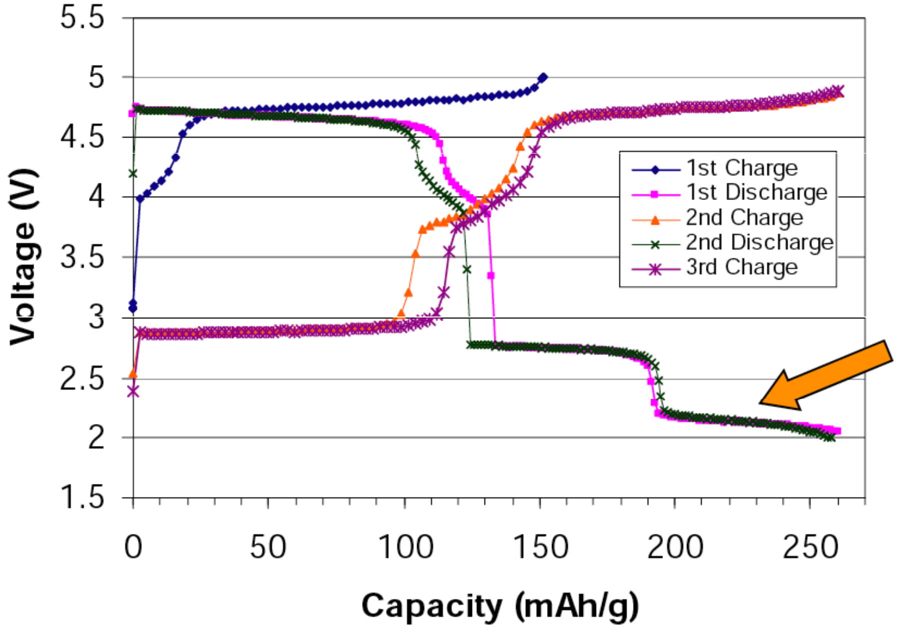
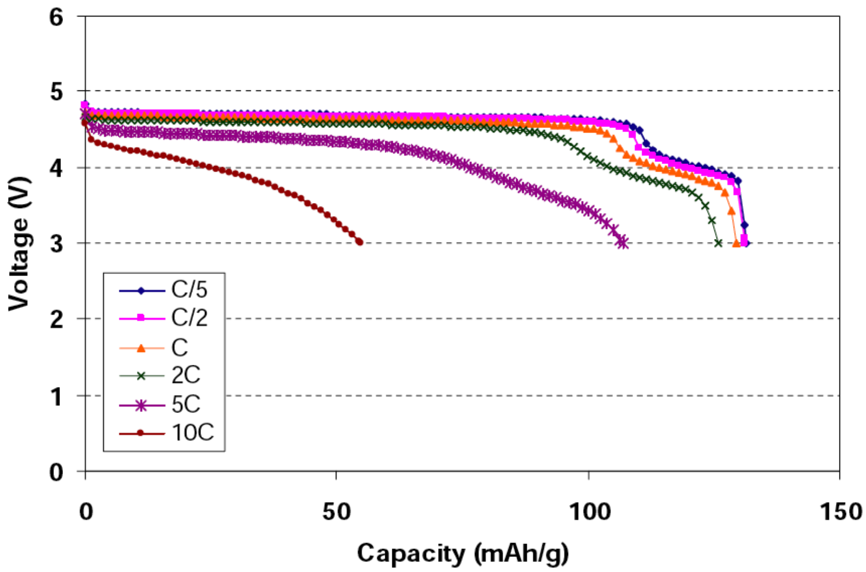


Fig. 4 Comparison of energy density of various cathode materials in lithium ion batteries



(a)



(b)

Figure 5. Electrochemical Properties of optimized $Li_2M_xNi_{0.5-x-y}Mn_{1.5+y}O_4$ (a) charge-discharge capacity and (b) rate capability testing

As a result of our current development, we have filed a patent application [Y. S. Meng, "High Energy Density Cathode Materials for Lithium Ion Batteries," US 61/162766, pending, 2009]. Currently a Florida based company (Planar Energy Devices Inc.) and a California based company (CFX Battery Inc.) are evaluating the option to license.

Our first principles calculations have identified several transition metal elements M that will significantly enhance the lithium mobility and cycle life in this system. They include Cr, Cu and Ti. We will focus on improving safety characteristics and cycle life of these high energy electrodes in the near future, the objectives are to improve the safety by transition metal doping of surface coating and improve cycle life (90% retention up to 300 cycles).