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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Energy Innovations Small Grant Program: 2011 Independent Assessment Reports is the interim report for the Energy Innovations Small Grant Program (contract number 500-98-014) conducted by San Diego State University Research Foundation. The information from this project contributes to all of the Energy Research and Development Division's Programs.

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For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Since 1997, the California Energy Commission's Public Interest Energy Research (PIER) program has been conducting competitive solicitations to advance science or technology in seven program areas to benefit California ratepayers. In addition, the Energy Commission has also funded and managed the Energy Innovations Small Grant (EISG) Program since 1998. The EISG program advances research into new and innovative energy concepts and technologies not yet sufficiently established to meet traditional research and development (R&D) funding requirements.

The EISG program supports early phase development of promising new energy technology concepts. This category of projects is not covered by PIER general solicitations that focus primarily on development of established concepts. Qualifying EISG projects address one of the defined PIER RD&D areas. If the feasibility of an innovative energy concept is proven through the EISG project work, then traditional R&D funding may become available to further develop the project.

Independent Assessment Reports are completed for every EISG grant project. These reports outline the objectives of the project, discuss the successes and failures, and offer recommendations for potential future work. This report presents a collection of 21 independent assessment reports for EISG grant projects awarded during 2011 except where noted.

Keywords: Ratepayer, California Energy Commission, Energy Innovations Small Grant, EISG, Independent Assessment Report, IAR, Public Interest Energy Research, PIER RD&D, electricity, natural gas, transportation, research, energy technology concepts, project, market, outcomes, conclusions, benefits

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EXECUTIVE SUMMARY

The Energy Innovations Small Grant (EISG) program is a component of the Public Interest Energy Research (PIER) Program managed by the California Energy Commission. The PIER Program benefits California electric and gas ratepayers by funding energy research, development, and demonstration (RD&D) projects that are not adequately provided for by the competitive and regulated energy markets.

The Energy Commission recognizes it is critical to support the early development of promising new energy technology concepts that are not mature enough to be covered by PIER general solicitations. Not all PIER research is carried out by large corporations or by universities – individuals can have a slice of the PIER investment funds through the EISG program. The EISG program awards up to $150,000 for hardware projects and $50,000 for modeling projects to small businesses, non-profits, individuals and academic institutions that show viability of new, innovative energy concepts. Research projects must target one of the PIER R&D areas, address a California energy challenge and provide a potential benefit to California electric and natural gas ratepayers. Many past EISG projects, such as the Wine secrets tartrate removal system and Clipper Wind's distributed generation drive, have been successfully commercialized and leveraged the initial PIER seed funds with additional private or federal funding.

The 2011 EISG program awarded almost $1.8 million to 21 unique and innovative projects ranging from biofuels production to laser sensors for preventing gas pipeline explosions. This report summarizes the Individual Assessment Reports for grant projects that were awarded in 2011 (except where noted) and that have not been previously published (Table 1).

All data sources for tables and figures are from the author unless otherwise noted.

CHAPTER 1: Introduction

2011 EISG Projects with IARs Included in this Section

Project	Researcher	EISG Funding
Solar Electric Power from Heat Pulses to Silicon (2009)	Roshan Energy	$ 95,000
Wireless Sensors for Real Time Monitoring of Induction Motors (2009)	University of California Riverside	$93,538
Flameless Combustion in Air-Cooled, Hybrid Solar Central Receivers (2010)	San Diego State University	$94,940
Catalysts for Oxidizing Water to Oxygen for Hydrogen Generation	San Diego State University	$95,000
Solution Processible Small Molecules for Plastic PV with Long Lifetimes	Next Energy Technologies Inc.	$94,999
NOx Control with Hydrogen Rich Biogas from Two-Phase Digestion	California Polytechnic State University	$94,924
Proof-of-Concept Solar Energy Converter Using Internal Photoemission and Plasmonic Perfect Absorbers	Pacific Integrated Energy, Inc.	$94,328
Non-Optical Concentration of Solar Energy for Low Cost Rooftop CHP	Solar Stream Innovations, LLC	$95,000
Residential Energy Intelligence Software (Res-Intel)©	Policy Consultants, LLC	$49,840
Task Ambient Daylighting	Erik Page & Associates, Inc.	$95,000
Development of a Low Leakage Retrofittable Outside Air Damper	Davis Energy Group	$75,000
Adaptive Power Flow Controls for Distribution Circuits with Renewables	California State University, Long Beach	$49,999
Laser Sensors for Gas Pipeline Explosion Protection	Physical Sciences, Inc.	$94,978
Investigation of a New Process for SNG Production Using Steam Hydrogasification	University of California, Riverside	$94,595
Renewable Energy Integrated Gas Network (REIGN)	Protomatrix.	$94,989
Eco-Routing Navigation System for Electric Vehicles	Ctr. for Environmental Res Technology, University of Calif. Riverside	$94,993
Feasibility Study of a Novel All-in-one Approach for Biofuels Production	University of California, Davis	$95,000
Analytic Tool to Support the Implementation of Electric Vehicle Programs	University of California, Davis	$50,000

Simultaneous Reduction of NOx/CO/CH4 Emissions from Natural Gas Engine	**University of California, San Diego**	**$94,932**
Potential Rooftop Photovoltaic Electricity for Sustainable Transportation in California	**University of California, Santa Barbara**	**$49,898**
Catalysis of Natural Gas for a Diesel Engine	**Discovery Fuel Technologies, LLC**	**$95,000**

CHAPTER 2:
2011 Independent Assessment Reports

The Energy Innovations Small Grant (EISG) program awards numerous grants for innovative energy research projects every year. Independent Assessment Reports (IARs) highlight the project outcomes for each of the EISG projects. This chapter includes the IARs from grant projects that were awarded in 2011 (except where noted) that have not previously been published.

2.1 Solar Electric Power from Heat Pulses to Silicon (2009)

Awardee: Roshan Energy

Principal Investigator: Ramesh Gopalan

2.1.1 Abstract

This project explored a theoretical solid state phenomenon for application to the production of electric power. The intent was to subject silicon to heat pulses, such as provided from concentrated sunlight, to directly produce an electron flux. The proposed mechanism, different from the more well-known thermoelectric effect, uses the phenomenon that the diffusion of electrons/holes produced by a heat pulse in a semiconductor moves faster than the diffusion of the heat pulse itself, leading to an electrical pulse. The researchers developed a stack of semiconductor layers to test the concept. The project team designed the stack of the proposed device to reduce efficiency losses resulting from Shockley-Read-Hall recombination as well as thermal conduction. The researchers developed new methods to produce high purity, crystalline silicon thin film layers using radio frequency (RF) induction heating on a barrier which prevented contamination of the silicon from the processing substrate. The heat absorption by the base layer was found to allow high temperature processing while being electrically conductive. Theoretical research by the team led to the understanding that thermal to electric conversion efficiency is fundamentally limited by Auger recombination, leading to rapid loss of the electrons/holes produced by the heat pulse before they can be collected at opposite electrical terminals. While not an identified goal of this project, potential manufacturing advances from reduced silicon usage and simplified process flow suggest a way produce very low cost (< $0.30/W), high efficiency (> 20 percent) silicon photovoltaic cells.

Keywords: Thin film, silicon-on-substrate, heat engine, photovoltaic, low cost manufacturing, RF induction, diffusion barrier, high efficiency, mc-Si, photovoltaic, PV

2.1.2 Introduction

Meeting California's aggressive goals for renewable energy resources will require development of all viable sources, including approaches that make use of novel physical phenomenon, including direct thermal energy conversion to electricity. While solar technologies like concentrated solar thermal steam production and photovoltaics continue to advance independently, fundamentally different approaches may allow for greater conversion efficiency and lower cost.

The diffusion of electrons and "holes" generated by a heat pulse through a semiconductor such as silicon is much faster than the diffusion of the heat itself. This potentially allows an electrical pulse to be generated before the heat is dissipated through the stack. This principle is distinct from the well-known thermoelectric effect which currently yields poor conversion efficiency (< 5 percent) even in layer stacks made up of complex semiconductor materials.

In silicon semiconductors, exposure to a heat pulse increases the density of electrons (and holes) in the conduction (and valence) bands of the semiconductor. If these electrons and holes can be made to drift, or diffuse, to opposite electrical terminals, conversion of the heat pulse into an electrical pulse occurs.[1] In this project, researchers studied how a device could be designed, fabricated, and optimized to achieve this end. They also investigated whether it could be amenable to low cost manufacturing and to understand the fundamental limits on its performance. The research team worked on two parallel paths: practical construction of the device stack as well as gaining better understanding of the theoretical underpinnings of the proposed concept.

2.1.3 Objectives

The goal of this project was to determine the feasibility of using a novel thin film silicon device to generate electric power from solar radiation, utilizing aspects of transient pulse heat and electrical transport in a semiconductor device. The result would be direct conversion of concentrated solar heat into useful electricity. The researchers established the following objectives, revised after the proposal but before the work began:

1. Acquire materials and fabricate the silicon devices at processing foundries. Metal contamination levels (e.g., Fe) in the active silicon layer must be below 10^{15} cm^{-3}; average crystal grain size in silicon device layer must be 10 um (microns) or larger.
2. Perform device characterization and measurements (e.g., TEM, XRD) to determine and confirm silicon device parameters. Confirm initial devices show total electrical energy output greater than 10 percent of heat energy input in response to a heat energy pulse.
3. Create an optimized device stack and test for device efficiency of net solar input (heat and light) into electric power output at National Renewable Energy Laboratory (NREL). Develop silicon devices that yield area under curve electrical energy output in the range of 20—30 percent of heat energy input.

1 This is similar to photon production of electron/hole pairs in the common solar photovoltaic cell.

4. Propose manufacturing strategy based on the stack developed. Include materials input and processing method. Confirm module cost less than $1/W.

2.1.4 Outcomes

1. The researchers fabricated layers of the proposed device, with exposed silicon layers on heat absorber metal contact stacks. They used radio frequency (RF) induction heating to process the layers and had NREL characterize the layers to confirm metallic contamination levels below 10^{15} cm^{-3}. They measured the average crystal grain size at about one micron.

2. The researchers completed theoretical modeling of the layers' behavior under simulated heat pulses. This led them to alloy the silicon with 20 percent germanium to suppress thermal conductivity losses. The researchers fabricated the high purity silicon thin film *in-situ* through melt re-crystallization. They determined that the heat pulse absorption layer had two other possible functions. It could function as a diffusion barrier during hot processing of the thin film, and it could serve the bottom side electrical contact layer. The researchers calculated the theoretical efficiency of the device to be approximately 1.0 percent.

3. The researchers determined that melt-recrystallization of the silicon on an ceramic alumina substrate using RF induction localized the heating energy, providing a potential yet simple method for processing large area modules. The diffusion barrier prevented contamination from the processing substrate, maintaining high purity of the silicon thin-films. They also determined that Auger[2] recombination would dominate over Shockley-Read-Hall (SRH) recombination, the originally proposed loss mechanism, resulting in low device efficiency. They determined the original concept was not physically feasible, given that Auger recombination increasingly dominated as the density of electron and holes increased, an otherwise necessary condition for electrical flux.

4. The researchers concluded that the innovative silicon processing method developed under Objective 3 could provide for a manufacturing process for creating silicon solar photovoltaic (PV) modules at less than $1/W cost, with an efficiency of better than 20 percent. The researchers hypothesized cost reductions are achievable from reduction of silicon feedstock by about a factor of 10 and from eliminating expensive process steps.

2.1.5 Conclusions

1. The researchers fabricated laboratory-scale semiconductor stacks with low levels of metallic contamination with an average crystal grain size of one micron using RF induction heating, using both silicon and germanium alloys. The crystal size fell short of the objective of larger than ten microns. The researchers did not complete this objective.

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2 In the Shockley-Read-Hall recombination process only two atomic sub-particles are considered, an electron and a hole. The Auger recombination is a process where three particles are involved: two of them in the process of generation or recombination and a third that takes or gives some energy.

2. Alloying with germanium improved the thermal and conductive performance of pure silicon in the proposed device. Physical parameters met the project objectives but fell far short of efficiency, calculated to be approximately 1.0 percent conversion of thermal energy to electricity. The researchers did not meet this project objective.
3. Solid state physical behavior of the device under thermal energy pulses was dominated by Auger effect and precluded the device from operating as hoped. The researchers did not meet this objective.
4. Radio frequency induction heating of high purity silicon into photovoltaic film layers is possible through use of a diffusion barrier which prevents impurity contamination from the cheaper substrate. This may provide a simple process for production of high efficiency silicon solar cells. The researchers proposed a process estimated to produce cells at less than $1/W, subject to further testing and development. The researchers completed this objective.

The researchers have not demonstrated the proposed device is practical or feasible, but have developed a manufacturing process that may reduce the cost of solar PV.

2.1.6 Recommendations

The Program Administrator recommends that the researchers should:

1. Develop a comprehensive research roadmap for the simplified processing method developed as a sidepiece in this project for the production of solar photovoltaics.
2. Subject the research roadmap to peer review by solid state physicists and photovoltaic manufacturers.
3. Begin documenting the photovoltaic properties of the stack produced using their RF induction heating process.
4. Determine the ideal germanium, or other alloy, concentration in cell stacks, taking into account properties and cost.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the technology for the more efficient production of silicon PV, but not the original proposed technology, should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.1.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply or transmission or distribution system. Reduced environmental impacts would result from improving the economical generation of electricity by solar energy. The results of the original project provided important scientific data on the physical behavior of silicon alloys subjected to heat pulses. While not the original goal of the research, development of a simplified, less material intensive method for the production of silicon photovoltaic cells could reduce the cost of solar electric generation using photovoltaics. Given the early stage of development, estimating benefits from such a new method would be highly speculative.

2.1.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers anticipate receiving grant money from United States Department of Energy (SunShot Incubator Grants) to develop prototype and pilot-scale manufacturing line for the photovoltaic production process. Upon completion and demonstration of the pilot plant, they will begin discussions with photovoltaic manufacturers. They have not completed a market assessment nor have they surveyed potential customers.

Engineering/Technical

The researchers estimate they can complete development and demonstration in two to three years with funding of approximately $3 million.

Legal/Contractual

The researchers have filed for patent protection (13/244,509 on 09/25/2011), but no public information is available on the application status at the United States Patent Office website. They have not publically disclosed their innovation, except in confidentially protected grant applications.

Environmental, Safety, Risk Assessments/ Quality Plans

These plans must be accomplished as a product is being readied for manufacturing.

Production Readiness/Commercialization

The concept is not yet ready for production or commercialization. Researchers plan to engage manufacturing partners during or soon after a pilot line is demonstrated.

2.2 Wireless Sensors for Real Time Monitoring of Induction Motors (2009)

Awardee: University of California, Riverside

Principal Investigator: Sundararajan V

2.2.1 Abstract

In this project researchers developed a multi-sensor wireless system for continuous real time performance and condition monitoring of industrial size induction motors. The wireless system was intended to provide a low cost alternative to expensive condition monitoring testing. The system used acoustic, vibration, and electric current sensors. The researchers developed algorithms to discriminate between healthy and faulty motors and to distinguish between various types of motor faults. The faults analyzed included air gap eccentricity, bearing damage, and stator winding faults. The signals from the sensors were analyzed using the Hilbert-Huang transformation and the Fourier transformation to train fault classifiers. The system was shown capable of distinguishing a faulty motor from a healthy motor with a probability of 99.9 percent of correct detection and less than 0.1 percent likelihood of false alarm on the motors tested. It detected different fault categories with an average accuracy of 99 percent. The within-fault classification had an average accuracy of about 95 percent for eccentricity and about 85 percent for different types of bearing faults. The system needs to be developed for different sizes and types (e.g., variable speed) of motors before being considered for wide application.

Keywords: Condition monitoring, fault diagnosis, Hilbert-Huang transform, wireless sensor networks

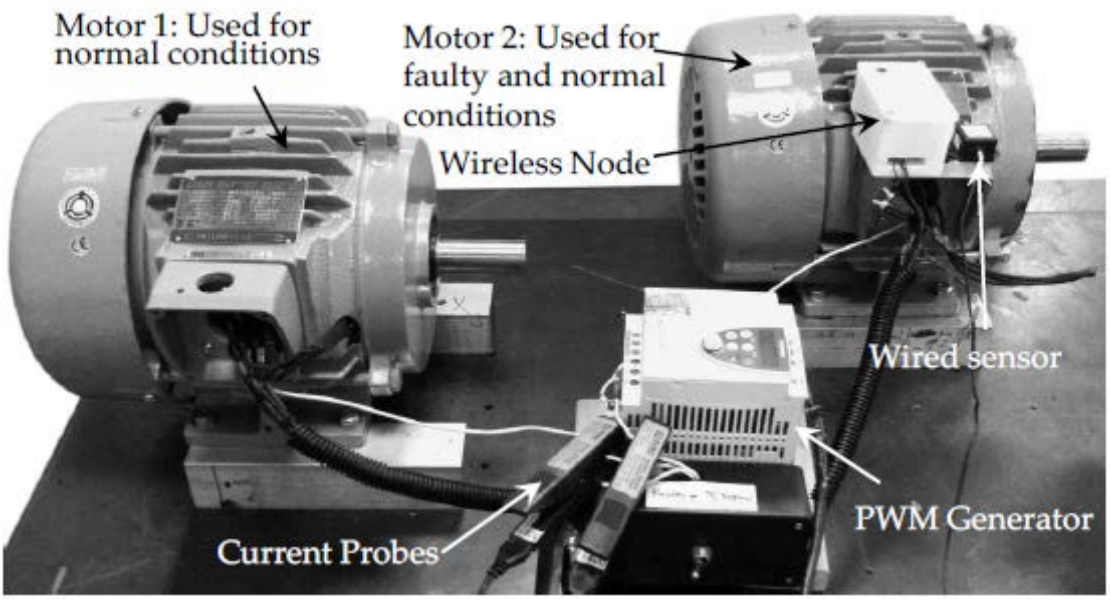
2.2.2 Introduction

Induction motors are widely used in a variety of industrial applications and consume a significant portion of electricity in the industrial sector of California. Environmental stresses in industrial applications, such as vibration and loads applied to these motors, can cause malfunctions, uneven wear, and premature mortality. Motors experiencing degradation operate at lower efficiencies, increasing the cost both to user and to California. Condition monitoring systems that can determine the existence of and type of motor deterioration would increase the productivity of the facility, reduce maintenance costs, and decrease electricity consumption.

The state of the art in condition monitoring of induction motors uses close coupled sensors, usually of a single type, to track faults in an offline test or under special conditions. The installation and maintenance of these sensors increases motor downtime and provides limited condition information.

In this project, researchers developed and tested a stand-alone multi-sensor wireless system for continuous real time performance and condition monitoring of induction motors. The researchers intended the wireless system as a low cost and more informative alternative to expensive condition monitoring technology currently used in industry. Figure 1 illustrates the test setup used by the researchers.

Figure 1: Experimental Setup to Evaluate Fault Detection System



2.2.3 Objectives

The goal of this project was to determine the feasibility of a stand-alone multi-sensor wireless system for continuous real time performance and condition monitoring of induction motors. The problems of interest in this research were:

- Static and dynamic eccentricity
- Damaged bearings (damage on inner race, outer race or cage, and lack of lubricant on bearing)
- Unbalanced stator windings

The researchers established the following project objectives:

1. Achieve sampling rates of 8 kHz on current sensor, accelerometer, and audio microphone and 200 Hz sampling rate on a speed sensor.
2. Detect faults in offline and online mode with a probability of 99.9 percent.
3. Produce false alarms no more than 5 percent.
4. Identify the nature and severity of the fault with high accuracy (> 99 percent).
5. Establish a cost of less than $550 for the prototype and $200 for the manufactured product.

2.2.4 Outcomes

1. The researchers developed a wireless sensor platform and used experimentation to formulate algorithms to distinguish faulty motors from healthy motors and to identify various categories of motor faults. They used a data sampling rate of 256 Hz and did not include speed sensors. They modified one of the motors (see Figure 1) multiple times with known faults to create a database to train the platform to detect faults.
2. The researchers estimated high accuracy in detecting known faults. The researchers developed algorithms that distinguished between healthy motors and faulty motors. They calculated an accuracy of 99.9 percent and a false alarm rate of less than 0.1 percent. They did not validate the algorithms on motors whose condition was actually unknown.
3. The researchers calculated a rate of false alarm in fault detection of less than 0.1 percent even when using just 10 percent of collected data for training the platform. By increasing the amount of training data to 20 percent of that collected, the researchers calculated that false alarms fell to zero. Again, the researchers did not validate the calculated accuracy with motors of unknown condition.
4. The researchers showed the platform capable of discriminating between different fault types (bearing faults , stator winding faults, and eccentricity faults) and subtype (e.g., bearing failure mode) and severity with an average accuracy of 95 percent for the motors tested.
5. The researchers demonstrated the total cost of the prototype was $600. They have not yet identified the relationship between the prototype cost and the potential final manufactured cost of the product.

2.2.5 Conclusions

1. The researchers developed a multi-sensor wireless sensor system to perform real time condition monitoring of induction motors. Sampling rates were less than specified in the objectives, and speed sensors were not used. The researchers mostly completed this objective.

2. The results showed that a combination of specific features of the vibration signal and certain key frequencies of the Fast Fourier Transform (FFT) of the current and sound data yielded the highest accuracy in fault detection, distinguishing a faulty motor from a healthy motor with a calculated accuracy of 99.9 percent and producing false positives at a rate of less than 0.1 percent. The researchers did not validate these results with motors of unknown condition. The calculated accuracy was not consistent with a sample of n=256 (with four condition modes), given that faults were pre-established (e.g., by replacing good bearings with bad bearings) and no blind testing was performed. The researchers did not complete this objective.

3. The system did not provide significant false positives or the identification of faults where there were none, but these results were not validated in actual tests of motors of unknown condition. The researchers did not complete this objective.

4. The researchers showed the system may also be able to discriminate between different types of faults and their severity, with an accuracy exceeding 95 percent. The researchers completed this objective.

5. The cost of the prototype exceeded the cost objectives. The cost of a manufactured system was not calculated. The researchers did not complete this objective.

The researchers demonstrated the technical possibility of a multisensory wireless platform for continuous electric motor condition monitoring. They have not yet demonstrated the sensor platforms' practicability or feasibility. Significant additional development and demonstration is needed before the concept can be considered practical or feasible.

2.2.6 Recommendations

The Program Administrator recommends the following actions:

1. Blind test the sensor platform on multiple motors of unknown condition, first testing and then disassembling and inspecting each motor for detected and missed faults.

2. Include rotor bar damage in the fault detection algorithm.

3. Determine impact of variable loading and speed to make the condition monitoring system more robust for~~to~~ possible uncertainties in motor performance, and evaluate the system for motor designs based on variable speed application. This should include determining learning algorithms for longer term data collection and evaluation of data sample extraction from all data collected to determine if longer learning improves performance.

4. Incorporate power management for wireless sensors through sleep scheduling. Increase distance from sensor platform to base station. Develop user interface to accommodate multiple motor/sensor platforms into a single user base station.
5. Evaluate the system on multiple motors of different design and size and under extended use. This should include cohorts of the same size and model.
6. Determine engineering needs for a system to be used in industrial environments, including noise, vibration, and fumes.
7. Complete a life cycle cost and benefit analysis, including manufacturing cost estimates.
8. Develop a decision tree that compares increasing severity of faults with cost to repair versus monitoring on-going but not serious degradation. Develop a users' guide on when to repair.
9. Conduct experiments with multiple simultaneous faults.
10. Conduct experiments in real world settings where environmental noise or vibrations are present.
11. Adjust or calibrate the fault detection algorithms to individual conditions.
12. Develop engineering and technical specifications.
13. Conduct experiments with increased distance to base station from the motor/sensor platform.

2.2.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research project is increased affordability of electricity in California.

The wireless system enables the continuous condition monitoring and fault detection in induction motors, which can reduce energy consumption and required power. Previous studies have shown that preventive maintenance of motors can increase efficiencies by about 2.0 percent. A 2.0 percent reduction in the annual power consumption by electric motors over 6 hp in California industrial settings would reduce the State's energy consumption by an estimated 1.3 billion kWh per year (0.4—0.5 percent of electricity consumption in 2007). Saving 1.3 billion

kWh per year would translate into a cost savings of approximately $200 million to California industry, with associated demand charge savings.

2.2.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have received expressions of interest from Brithinee Electric, a motor repair company, to commercialize the technology. They have not completed a market assessment.

Engineering/Technical

The researchers estimate the need for about $0.4 million and two years to complete technology development and demonstration.

Legal/Contractual

The researchers had applied for, but had not received, a patent by the conclusion of this project.

Environmental, Safety, Risk Assessments/ Quality Plans

The main environmental, safety, risk, and quality assessment needed would be the engineering specifications for durability and continued accuracy under industrial settings.

Production Readiness/Commercialization

The product is not yet ready for commercialization or production.

2.3 Flameless Combustion in Air-Cooled, Hybrid Solar Central Receivers (2010)

Awardee: San Diego State University

Principal Investigator: Fletcher Miller

2.3.1 Abstract

Current commercial concentrating solar power (CSP) systems are limited to temperatures that are too low for the more efficient Brayton cycle turbines. Due to material constraints, existing CSP systems employ lower temperature, less efficient Rankin cycle engines. In many cases the Rankin systems use wet cooling which requires the consumption of large amounts of water, in short supply at the hot, dry sites where the systems are located. Accordingly, this research investigated the development of a new, air-cooled high temperature receiver that can produce electricity via a Brayton cycle. Importantly, this receiver can operate in a flameless combustion hybrid mode with natural gas as backup during cloud passage.

Specific objectives of this research were to build and test a laboratory-scale solar simulator capable of high fluxes similar to those incident on an actual central receiver and integrate it with a novel, new receiver. With this approach the receiver would absorb concentrated light volumetrically in a suspension of carbon nano-particles entrained on an air stream. By the technique of volumetric absorption instead of radiation absorbed on a surface, many materials problems are circumvented. The researchers used an existing particle generator for this work, although it needed to be modified for the higher pressure used in efficient Brayton turbines. The tests conducted on the receiver examined the process of flameless combustion inside the receiver by comparing results both with and without natural gas present.

During this project researchers successfully designed, constructed, and used the solar simulator with a new receiver. It successfully produced 3 kW of optical power within a 10 cm diameter focal region, with a peak flux of 1.2 MW/m^2. They also designed, constructed, and tested the receiver. In tests of the receiver without natural gas, it produced exit process air temperatures of about 650° C. However time ran out before tests could be conducted in flameless combustion mode. The primary conclusion was that the system worked, since temperatures and fluxes were achieved, but more work needs to be done to prove feasibility with flameless combustion.

Keywords: CSP, central receiver, methane/solar hybrid, nano particle, flameless combustion

2.3.2 Introduction

The World Meteorological Organization has announced that the amount of greenhouse gases (GHG) in the atmosphere reached a record high in 2013 due to a surge in the level of carbon dioxide.[3] To combat the rising levels in GHG and resultant climate change, California has mandated the California's Renewables Portfolio Standard (RPS). This standard requires that investor-owned utilities, electric service providers, and community choice aggregators increase procurement from eligible renewable energy resources to 33 percent of total procurement by 2020.[4] Solar thermal electric technologies are attractive candidates to replace fossil fuel powered generation with renewable solar energy.[5] This approach uses a concentrated solar power (CSP) or solar power tower system which employs a large field of tracking mirrors that focuses concentrated sunlight onto a raised central receiver.[6] The CSP receiver could be supported by a natural gas combustor for transient backup power in the event of interrupted solar.[7] Researchers are also investigating overnight thermal storage. In the United States, for example, more than 700 MW capacity of CSP systems have been installed. Worldwide, there are 17 large utility-scale CSP systems in operation or in the advanced planning stage.[8] Almost all use some form of steam Rankin cycle for power, which is less efficient and has other disadvantages compared to alternatives. The Rankin cycle requires some form of cooling, either wet or dry cooling. Wet cooling is more efficient but results in large consumption of water, an expensive commodity in the hot, dry locations where the systems are sited. Dry cooling uses large fans to reject heat to air, but with a loss in electrical efficiency. Another disadvantage of the Rankin cycle is that its efficiency is only about 30 percent.[9] This requires that the field of concentrating mirrors be larger, adding to system cost and ecological impacts. The high temperature gas turbine Brayton cycle, on the other hand, is 40 percent efficient. When a Brayton topping cycle is combined with a Rankin bottoming cycle overall efficiency can reach 58 percent.[7] Thus a key new development would be to integrate a Brayton cycle gas turbine in a CSP system, ideally hybridized with a natural gas combustor for increased dispatchability. The higher efficiency of the Brayton cycle turbine would require fewer focusing mirrors, reducing the capital cost of the CSP system but still displacing fossil fuel consumption with renewable solar power.

The benefit to the California ratepayer from the integration of a high efficiency Brayton cycle turbine with a CSP system could be substantial in the form of reduced GHG emissions and

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3 https://www.wmo.int/pages/mediacentre/press_releases/pr_1002_en.html

4 http://www.cpuc.ca.gov/PUC/energy/Renewables.

5 http://www.nrel.gov/docs/legosti/fy98/24863.pdf

6 http://en.wikipedia.org/wiki/Solar_power_tower

7 http://www.csp-world.com/news/20131031/001242/new-hybrid-csp-natural-gas-plant-announced-sacramento-us

8 http://www.circleofblue.org/waternews/wp-content/uploads/2010/08/Solar-Water-Use-Issues-in-Southwest.pdf

9 http://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node67.html

lower system cost. As stated, California's Renewables Portfolio Standard (RPS) requires utilities, electric service providers, and community choice aggregators to increase procurement from renewable energy resources to 33 percent of total by 2020. In 2013 in-state system power for California was 200,137 gigawatt-hours (GWh) and 296,983 GWh when imports from out of state were included.[10] California's in-state renewable generation was comprised of biomass, geothermal, small hydro, wind, and solar generation sites that made up approximately 17 percent of the total in-state generational output in 2011.[11] The renewable fraction rose to almost 20 percent in 2013 with a solar contribution of 2.0 percent.[12] At present in-state renewables of all types comprise only 20 percent of in-state generation, well short of the 33 percent goal. The renewables fraction of total state procurements is less at 13 percent, making a larger shortfall of about 20 percent renewables. At the 2013 level of in-state generation, the 13 percent shortfall of the total would be 26,018 GWh. The average CO_2 emission factor for natural gas powered steam-electric generators (2012) is 1.22 Lbs/kWh.[13] Thus the assumed saving of 26,018 GWh would correspond to a yearly savings of up to 14.4 MMT of GHG emissions. The penetration of this new CSP technology into out-of-state generation markets would further increase the potential savings in avoided GHG production.

The advancement of science or technology that was proposed in this project was the development of a new air-cooled high temperature receiver that can operate in hybrid mode with natural gas to produce electricity via a Brayton cycle. Air-cooled receivers have the potential to supply high temperature air in the range suitable for efficient Brayton operation. A laboratory test receiver and associated components are shown schematically in Figure 2. The receiver would receive a continuous supply of small carbon nano particles entrained on the input air stream. The volumetric density of the particles introduced would be high enough to make the air stream optically dense. In this way the radiation input would be absorbed volumetrically rather than by the absorbing wall of the receiver. This approach would reduce many wall materials problems. The approach would also examine integral flameless combustion of fossil fuel, primarily natural gas, which releases energy without the creation of a visible flame.[14] The combustion takes place above the auto-ignition temperature of methane (natural gas) near 600° C and below the lean flammability limit.[15] By avoiding a high temperature flame front, production of oxides of nitrogen is greatly suppressed. A high intensity solar simulator would be constructed to allow laboratory measurement of the effectiveness of the approach under realistic conditions.

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10 http://energyalmanac.ca.gov/electricity/total_system_power.html

11 http://energyalmanac.ca.gov/electricity/

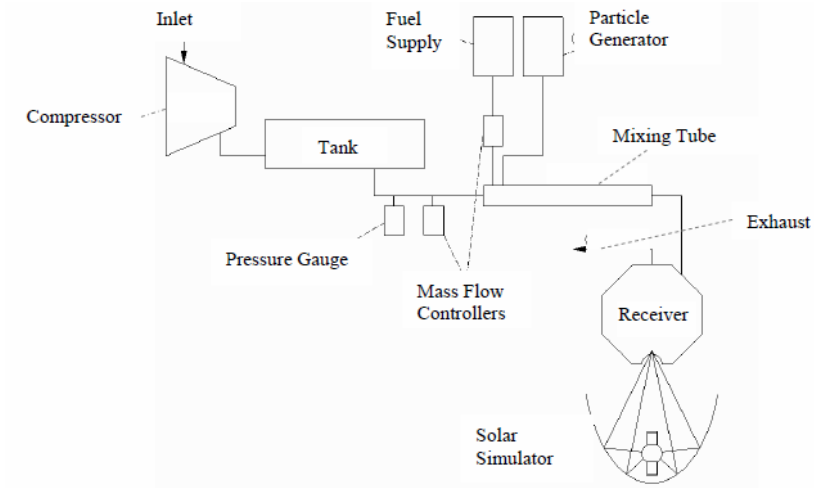
12 http://energyalmanac.ca.gov/electricity/electricity_generation.html

13 http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11

14 http://www.handbook.ifrf.net/handbook/dl.html/index.pdf?id=171&type=pdf

15 http://encyclopedia.airliquide.com/encyclopedia.asp?GasID=41

Figure 2: Schematic of Laboratory-Scale Receiver, Solar Simulator, Particle Generator and Test Bench to Deliver Compressed Gases at 5-10 atm



2.3.3 Objectives

The goal of this project was to determine the feasibility of employing flameless combustion within an air-cooled, solar central receiver to achieve hybrid operation for periods of reduced solar input. The researchers established the following project objectives:

1. Construct an arc lamp-based solar simulator that concentrates at least 2.5 kW within a 6 cm diameter target.
2. Construct a model of a receiver that predicts the behavior of particle seeded air heated by solar radiation. Show that the particle seeded air will absorb 80 percent of solar radiation before the radiation strikes receiver walls.
3. Develop and construct a system supply that will provide measured quantities of air, particles, and natural gas uniformly mixed to the receiver. Control/monitor airflow to +/- 1.0 percent. Control/monitor particle mass flow to within 0.1g/m^3. Control natural gas flow to +/- 0.5 percent.
4. Complete final design and construct receiver. Measure the receiver to be airtight at atmospheric pressures, capable of internal temperatures to 1500° C, and able to withstand peak radiative fluxes up to 2500 kW/m^2. Install thermocouples with temperature and efficiency precision of +/- 2.0 percent.
5. Couple receiver to system supply. Both the solar receiver and the system supply should continue to function according to previously indicated performance objectives after they are coupled together.
6. Operate receiver with solar simulator without natural gas. Produce process gas in excess of 800° C from the receiver with a thermal efficiency above 70 percent.

7. Operate receiver with solar simulator with natural gas and flameless combustion. Control flameless combustion within receiver in a safe and stable manner. Produce air in excess of 1000° C using flameless combustion at a thermal efficiency above 70 percent.

8. Determine receiver exhaust composition at various operating conditions. Measure CO and NO_x concentrations below acceptable levels. Achieve complete combustion of natural gas.

9. Determine temperature and fuel concentration limits of flameless combustion. Determine temperature limit to within 20° C at concentrations varying from 0.1—2.0 percent.

10. Determine time dependence of flameless oxidation for transient solar input. Determine time required to achieve stable hybrid operation to within 0.5 sec.

2.3.4 Outcomes

1. The researchers designed and constructed a high power 15 kW (electric input) solar simulator. The simulator used an arc lamp and ellipsoidal reflector. The researchers developed a calibration technique using a high resolution monochrome camera and radiometer and demonstrated that more than 2.5 kW optical power was absorbed in a 6 cm diameter circle.

2. The researchers developed a simple model of the solar receiver. They used the model to choose the receiver length and particle mass loading so that 80 percent of the radiation, on average, would be absorbed before striking the receiver walls. They defined a new parameter that compared how much energy is provided by the fossil fuel part of the system compared to the solar part when natural gas is first processed to form the carbon particles. The natural gas component was on the order of 2.0 percent.

3. The researchers assembled a full gas supply system to deliver natural gas, air, nitrogen, and the carbon particle stream to the receiver. Calibrated gas flow meters measured flow rates with the desired accuracy. The researchers designed and built a new extinction tube to monitor the particle mass loading being delivered to the receiver. Control of particle mass flow rate was adequate at atmospheric pressure, but many control problems arose at the higher operating pressures needed for Brayton turbine, 5—10 atm.

4. The researchers designed, built, and successfully tested a large, high pressure, high temperature, windowed receiver to withstand the pressure and temperature goals. Internal thermal insulation was rated for about 1650° C. A peak radiative flux of 1900 kW/m^2 was achieved. The high pressure window, after modification of a mounting ring, successfully withstood up to 10 atm of pressure. Thermocouple sensors measured temperature to an accuracy of 0.4 percent.

5. The researchers successfully coupled together the existing particle generator, receiver, and cooling tower using high temperature plumbing designed in-house. There were still problems with particle mass flow rate control.

6. This goal was to operate the receiver with a solar simulator without natural gas and produce process gas in excess of 800° C from the receiver with a thermal efficiency above 70 percent. The researchers successfully tested the receiver, although facility limitations, a broken window and a power outage, caused some damage that took extra time. The window mount was modified and fixed the problem. Outlet air temperatures reached about 600° C, not as high as the goal of 800° C. Due to lamp cooling pump limitations, the receiver never reached steady state. Because it was in a transient state, the researchers could not determine the receiver efficiency.
7. The researchers ran out of time before the receiver could be tested with natural gas and flameless combustion.
8. Due to lack of time, tests of receiver exhaust composition at various operating conditions could not be done.
9. Due to lack of time, tests of temperature and fuel concentration limits of flameless combustion were not done.
10. Due to lack of time, the time determination was not made of the dependence of flameless oxidation for transient solar input.

2.3.5 Conclusions

1. This objective was met.
2. This objective was met.
3. This objective was partly met, but problems remained with control of particle mass flow rate at working pressure.
4. This objective was met in large part, but it took much longer to accomplish than planned.
5. This objective was met.
6. This objective was met in part.
7. This important objective was not met.
8. This objective was not met.
9. This objective was not met.
10. This objective was not met.

The main goal of this project was to demonstrate the feasibility of employing flameless combustion within an air-cooled, solar central receiver to achieve hybrid operation for periods of reduced solar input. While the goal of this project was not demonstrated, the approach still appears to be attractive.

2.3.6 Recommendations

The Program Administrator recommends that the issue of particle mass flow control rate at high operating pressure be given high priority in future research. Evidently the problem lies in the particle generator used to entrain nano particles on the input air stream. The generator developed during previous research was not described, so it is not possible to be more specific. The Program Administrator also recommends that the researchers look into the phenomenon of diffusion limited aggregation (DLA).[16,17] DLA or even simple aggregation may be a problem in the particle entrainment process. If that is the case, it may help to minimize localized regions of high particle density due to bottlenecks.

2.3.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is reduced environmental impacts of the California electricity supply or transmission or distribution system. The benefit from the integration of a high efficiency Brayton cycle turbine with a CSP system could be substantial in the form of reduced GHG emissions and lower system cost. California's Renewables Portfolio Standard (RPS) requires utilities, electric service providers, and community choice aggregators to increase procurement from renewable energy resources to 33 percent of total by 2020. To set the scale of the potential opportunity, in 2013 in-state system power for California was 200,137 gigawatt-hours (GWh) and 296,983 GWh when imports from out of state are included.

California's in-state renewable generation is comprised of biomass, geothermal, small hydro, wind, and solar generation sites that made up approximately 17 percent of the total in-state generational output in 2011. The renewable fraction rose to almost 20 percent in 2013 with a solar contribution of 2.0 percent. Since at present in-state renewables of all types comprise only 20 percent of in-state generation, there is a shortfall of 13 percent to meet the 2020 goal of 33 percent. The renewables fraction of total state procurements is less at 13 percent, for a larger shortfall of about 20 percent. At the 2013 level of in-state generation, the 13 percent shortfall of the total would be 26,018 GWh. The average CO_2 emission factor for natural gas powered steam-electric generators (2012) was 1.22 Lbs/kWh. Thus the assumed saving of 26,018 GWh

16 T. A. Witten Jr, L. M. Sander, Phys. Rev. Lett. 47, 1400 (1981).

17 http://en.wikipedia.org/wiki/Diffusion-limited_aggregation

would correspond to a yearly savings of up to 14.4 MMT of GHG emissions. The penetration of this new CSP technology into out-of-state generation markets would further increase the potential savings in avoided GHG production.

2.3.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers are partnering with four industrial companies, one of which is Rocketdyne. Rocketdyne is a major player in the CSP industry.

Engineering/Technical

The researchers have both industrial and United States Department of Energy support to continue work in this general area. Unfortunately none of that support will fund the continuing work on flameless combustion, the subject of this grant. The researchers plan to continue the development of flameless combustion once additional funding has been secured.

Legal/Contractual

The researchers received support from four companies and the United States Department of Energy with a $4 M grant to develop and test a large scale 5 MWe receiver. The researchers have not secured any patents for the technology developed in this project.

Environmental, Safety, Risk Assessments/ Quality Plans

Because of the use of fine particles in this project, the researchers will have to pursue these plans with diligence.

Production Readiness/Commercialization

The researchers have not developed a commercialization plan. It may require eight to ten years of research, development, and commercialization work to produce a product.

2.4 Catalysts for Oxidizing Water to Oxygen for Hydrogen Generation

Awardee: San Diego State University

Principal Investigator: Douglas Grotjahn

2.4.1 Abstract

This project developed and synthesized several new catalysts for the splitting of water into oxygen and hydrogen through photolysis. The intent was to improve direct solar energy capture over indirect methods such as electrical generation and subsequent electrolysis of water. No actual solar energy capture was tested, but oxidation of water was simulated to test the effectiveness of the developed catalysts.

Based on electrochemical characterization of plant photosynthesis, the researchers designed a variety of new catalysts for helping proton transfer during oxidation of water. They characterized catalyst complexes using spectroscopic and crystallographic techniques to verify composition and to determine molecular shape and involvement of hydrogen bonding. The researchers evaluated catalysts for oxygen evolution from water driven by ceric ion or periodate. They saw up to 200,000 turnovers for some iridium-based catalysts and up to 6,000 turnovers for one ruthenium catalyst before the catalyst was rendered ineffective. This work may facilitate further advances in water splitting for renewable energy production. Much of the effort was spent on developing novel chemical synthesis routes for complex organometallic compounds.

Keywords: Oxygen, water oxidation, water splitting, hydrogen, electron transfer, proton transfer, hydrogen bonding, catalysis, bifunctional

2.4.2 Introduction

Meeting California's aggressive goals for renewable energy resources will require development of all viable sources, including highly innovative approaches like using sunlight for direct molecular splitting of water into hydrogen and oxygen. While solar technologies like concentrated solar and photovoltaics continue to advance, quantum leaps in fuel production (i.e., hydrogen) are necessary to make full use of California's tremendous solar resource.

A successful catalyst for splitting water would allow the large-scale, direct use of sunlight to make H_2 and O_2 as opposed to using electricity generated from solar cells to electrolytically split water or highly concentrated sunlight for thermalytic splitting and would revolutionize fuel production. Improving the electron and proton transfer efficiency and activation-energy[18] requirements are necessary to develop this technological concept. Efforts thus far have focused primarily on catalysis using organometallics. Organometallics remain expensive, degrade in use, and remain relatively inefficient.

In natural photosynthesis, proton transfer is a key process in extracting electrons from water and making oxygen. The overall photosynthetic reaction includes harvesting sunlight, the energy source needed to drive an endothermic reaction, and producing hydrogen and oxygen from water. The second step then adds the produced hydrogen to carbon dioxide to produce hydrocarbons. Taking a cue from nature, this project developed and tested a variety of new organometallic catalysts to be used in a novel solar energy system essentially to replicate the first crucial step in photosynthesis, the production of hydrogen and oxygen from water.

2.4.3 Objectives

The goal of this project was to determine the feasibility of developing catalysts for oxidizing water to produce hydrogen as an energy storage medium. The researchers established the following project objectives:

1. Design ≥ 5 ligands[19] and ≥ 10 complexes.
2. Make ≥ 5 ligands, and purify them to > 90 percent purity as determined by nuclear magnetic resonance (NMR), infrared (IR), mass spectrometries, and elemental analysis.
3. Make 10 complexes and purify them to > 90 percent purity as determined by NMR, IR, mass spectrometries, and elemental analysis. The structure of some complexes is to be determined by X-ray diffraction/crystallography.
4. Achieve at least 100 turnovers[20] of oxygen evolution. Measure oxygen evolution using Clark electrodes and/or RRDE experiments.

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18 The fundamental role of catalysts is to reduce the activation energy for a reaction to proceed but does not change the actual reaction energy balance.

19 Ligands are ions or neutral molecules that bond to a central metal atom or ion and act as electron pair donors, while the central atom acts as an electron pair receptor.

5. Measure turnover frequencies and turnover numbers (TON)moles oxygen evolved per mole of catalyst..
6. Measure 10 cyclic voltammetry curves.
7. Determine hydrogen bonding in structures, measure oxygen evolution (if any), UV-vis spectra, and cyclic voltammetry data. Achieve differences in oxygen evolution between proton transfer catalysts and model complexes of at least a factor of two.
8. Deposit at least one catalyst on a solid (e.g., titania) and measure oxygen evolution performance, achieving at least 10 turnovers.
9. Make at least five new contacts for commercializing the work. Depending on the state of catalyst development, establish at least one partnership.

2.4.4 Outcomes

1. The research team designed 12 ligands and > 50 complexes which featured molecular structures with portions considered important for proton transfer or with hydrogen bonding during catalysis. The research team included two new ligands capable of presenting two pyridine nitrogen atoms approximately 4.0 to 4.5 Angstroms apart.
2. The research team formulated 12 ligands, making new molecular building blocks in the process and spectroscopically characterized them.
3. The research team formulated 26 metal ligand complexes (sometimes using more than one metal with the same ligand) to create unique complexes. These included complexes of ruthenium and iridium. The research team synthesized two water oxidation catalysts with trans-spanning pyridine-like ligands designed to provide more durability to the catalyst. The research team determined the hydrogen bonding environment and molecular shape for seven water oxidation catalysts using X-ray diffraction. Using NMR spectroscopy, the research team determined the purity, structure, and in many cases the protonation state or charge on the complexes.
4. The research team measured turnovers of oxygen evolution that ranged from 915 to as much as 200,000 with some iridium-based catalysts. Figure 3 illustrates the oxygen production from one catalyst tested and shows the production tapering off. Table 1 from the researchers' published paper (as Table 6) provides initial and longer term evolution rates, TON, and TOF for five selected catalyst complexes.

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20 In catalysis with organometallic catalysts as described here, turnover number ~~(abbreviated *TON*)~~ is the number of moles of substrate that a mole of catalyst can convert before becoming inactivated. An ideal catalyst would have an infinite turnover number, but in actual practice turnover numbers range from about 100 to 40 million. The term turnover frequency (abbreviated *TOF*) is used to refer to the turnover per unit time.

Figure 3: Oxygen Evolution (Moles) of One Catalyst Complex, Monitored by Omega Pressure Sensor in a Reaction Vessel

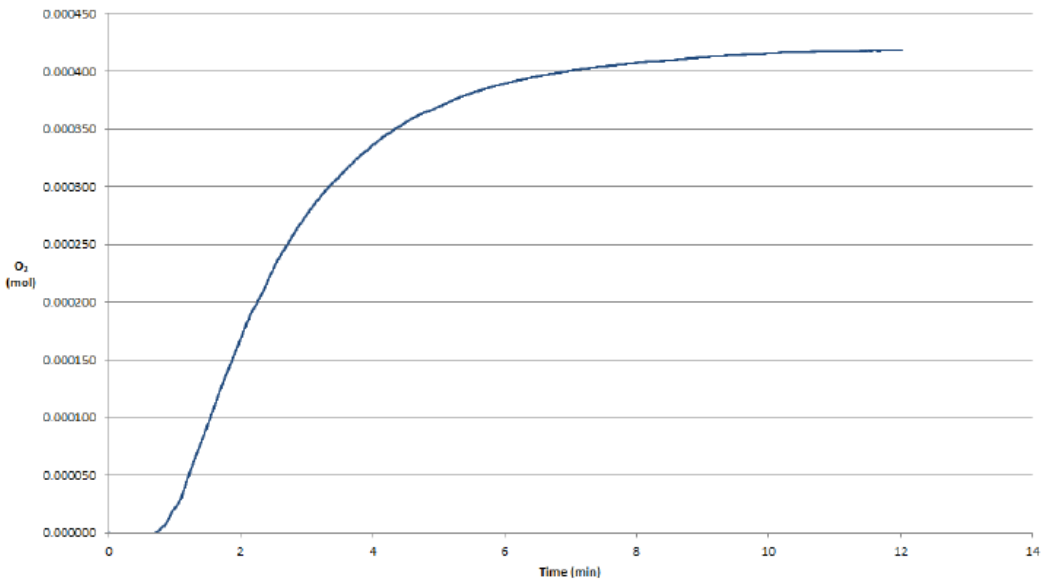


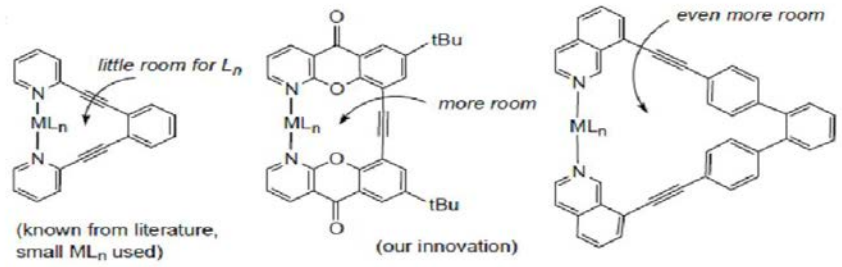
Table 1: Measured Rates, TON, and TOF for Five Selected Catalyst Complexes

	Catalyst		7b	7c	7d	7e	8e
Initial values[a]	Initial Rates (μM/min)		0	0	71.8	130	179
	TON		0	0	5.5	6.4	12.1
	TOF (per min) [b]		0	0	0.58	1.5	2.1
	TOF init (per min)		0	0	1.6	3.1	3.8
Longer term[c]	Catalyst	**8a**			**8d**		**8e**
	TON (at 10 h)	138			215		98
	TOF (per min) [d]	0.23			0.36		0.16

5. The research team compared the water oxidation of catalyst complexes with and without proton transferring or hydrogen bonding groups and found the catalyst with proton transfer to have a TON of 215 compared to a TON of 138 for the same catalyst without transfer ability and a TOF of 0.36 min^{-1} compared to a TOF of 0.23 over the same time period.

6. The research team measured 29 cyclic voltammetry curves for a variety of catalysts in the four schemes. In the case of the trans-spanning ligand catalysts, the trans-spanning ligand with a smaller cavity gave less oxygen evolution (no oxygen reduction wave), whereas the larger cavity catalyst did show an oxygen reduction wave. Figure 4 illustrates different configurations with different cavity size.

Figure 4: Cavity Size and Ligand Spacing Dependence on Molecular Configuration



7. The research team evaluated changes in reduction/oxidation potential (Redox), color, UV-vis absorbance, NMR spectra, and water oxidation efficiency due to changes in pH.
8. The researchers did not deposit catalysts onto solid surfaces nor measure oxygen evolution performance.
9. Objective 9 was abandoned as outside the scope of the project.

2.4.5 Conclusions

1. The researchers showed it is possible to synthesize designer organometallic complexes to meet desired catalysis performance characteristics with high purity. They completed this objective.
2. The researchers demonstrated that using more than one metal provided greater complex design flexibility for any given organic ligand. The researchers developed new synthesis approaches for ligand and organometallic complexes. They completed this objective.
3. The researchers demonstrated that proton transfer capability can provide faster turnover in oxygen production compared to analog complexes without such transfer capability. They completed this objective.
4. The researchers showed proton transfer ability can enhance the oxygen production capability of organometallic complexes. They completed this objective.
5. The researchers determined oxygen production was higher with larger cavity that provided adequate space for organic ligands and for proton transfer. They demonstrated TON approaching 200,000 for some of the catalysts tested with a low value for others of approximately 900. The researchers completed this objective.
6. For some of the catalysts pH sensitive changes in reduction/oxidation potential, color, UV-vis absorbance, NMR spectra, and water oxidation efficiency preliminarily indicated the importance of proton transfer. The researchers completed this objective.

7. The organometallic complexes studied were sensitive to pH, with changes to color, structure, and reduction/oxidation potential. The researchers completed this objective.
8. The researchers did not complete this objective.
9. The researchers did not complete this objective.

The researchers showed the technical potential of developing improved catalysts for oxidizing water to produce hydrogen as an energy storage medium using the concept of proton transfer with organometallic catalysts. They have not yet demonstrated the approach is practical or feasible.

2.4.6 Recommendations

The Program Administrator recommends the following actions:

1. Given the high cost and strategic value of the metals iridium and ruthenium, the researchers should consider alternate metals as the core of their catalyst concepts.
2. The researchers should begin assessing catalyst activity in oxygen formation using sunlight and document spectral response.
3. The researchers should publish a ligand design and synthesis guide based on results, expand on their published paper, and continue exploration for more suitable catalyst(s).
4. The researchers should complete an approximate cost evaluation considering metal cost used in catalysts and catalyst synthesis, cost with catalyst life and deactivation, and approximate end product cost for comparison to traditional approaches.
5. The researchers should carefully document water quality requirements and determine any potential poisoning constituents.
6. The researchers should begin investigating deactivation mechanisms with the aim of developing re-activation processes to save on cost of expensive metals such as iridium and ruthenium.
7. More ligands need to be synthesized with different organic groups, or more importantly the same organic groups but in different molecular location, to help with proton transfer.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.4.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research project is reduced environmental impacts of the California electricity supply or transmission or distribution system. Reduced environmental impacts would result from improving the economical generation of electricity by solar energy, with the added benefit of potentially providing hydrogen for transportation applications.

Given the early stage of development and the potentially disruptive nature of the technology, estimating benefits would be highly speculative.

2.4.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have published a paper in the scientific literature (*European Journal of Inorganic Chemistry*) describing their research and synthesis procedures. This is an important first step toward later and broader based publications to create interest and collaboration by industry and end users. The researchers are actively collaborating with researchers in similar endeavors. Marketing efforts will need to accommodate the potentially disruptive nature of the technology concept.

Engineering/Technical

Developing engineering and technical specifications is premature given the development status of the technology. Researchers are working to demonstrate that proton transfer aids catalysis by at least a factor of 10, up from the demonstrated factor of approximately 2, and that TON and TOF are satisfactory given the cost of noble metal contained in the complexes.

Legal/Contractual

The researchers have filed for patent protection, but have not yet received patents.

Environmental, Safety, Risk Assessments/ Quality Plans

There are no known environmental or safety risks associated with the concept as currently developed.

Production Readiness/Commercialization

The concept is not yet ready for production or commercialization.

2.5 Solution-Processible Small Molecules for Plastic PV with Long Lifetimes

Awardee: Next Energy Technologies Inc.

Principal Investigator: Corey Hoven

2.5.1 Abstract

Printing of photovoltaics can overcome issues of weight, cost of production, and flexibility of traditional photovoltaics. Printed organic photovoltaics suffer from low efficiency and degradation due to environmental exposure.

Soluble small molecule (SSM) organic photovoltaic (OPV) technology may remove development and manufacturing barriers faced by previous plastic photovoltaic technologies. These plastic (organic) solar cells use inexpensive, abundant, use non-toxic raw materials, and they promise low production costs, including low cost production facilities.

In this project researchers validated the morphological stability of several small molecules suitable for use in printed photovoltaic cells. They evaluated morphological stability, and they developed, characterized, and tested new SSM materials that should allow for higher efficiencies and better stability. SSMs are low cost plastic semiconductors that can be printed as an ink or spray painted onto conventional plastic sheets for inexpensive, lightweight, and flexible solar cells. Small molecule-based solar cells may have longer lifetimes than polymer based OPVs for reasons including reduced impurities and a higher resistance to oxidation. The morphological instability of SSMs has been one of the highest impediments to reliability and commercialization of the technology. Using accelerated stress testing, physical spectroscopy, and extrapolation, the researchers demonstrated less than 20 percent degradation in power conversion efficiency (PCE) over 1,000 hours for devices stored in the dark at an elevated stress temperature (60° C, 140° F).

The researchers demonstrated that the selected SSM-OPVs have good morphological stability.

Keywords: Organic solar, building-integrated photovoltaic cell, flexible electronics, stability

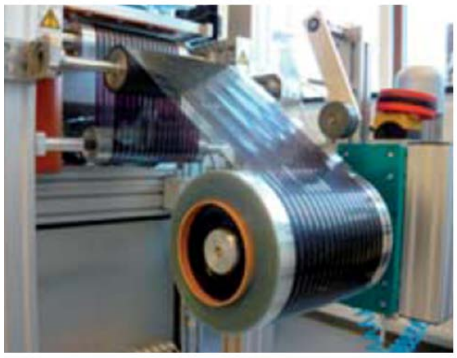
2.5.2 Introduction

Expanded development of renewable energy remains a high priority focus of California's energy and environmental policies. Greater use of photovoltaics, including flexible printed organic photovoltaics, is consistent with those policies and will help meet California's goals, especially in building-integrated applications. Printing photovoltaics can overcome issues of weight, cost of production, and flexibility of traditional photovoltaics; however, printed organic photovoltaics suffer from low efficiency and degradation due to environmental exposure.

Soluble small molecule (SSM) organic photovoltaic (OPV) technology may remove development and manufacturing barriers faced by previous plastic photovoltaic technologies. These plastic (organic) solar cells use inexpensive, abundant, use non-toxic raw materials, and they promise low production costs, including low cost production facilities.

In this project, researchers validated the morphological stability of several small molecules suitable for use as photovoltaics in printed production. The researchers also developed new molecules specifically designed to improve power conversion efficiency (PCE) and stability. Figure 5 illustrates conceptual production of printed cells.

Figure 5: Roll-to-Roll Coating of Organic Photovoltaics



2.5.3 Objectives

The goal of this project was to demonstrate the morphology for SSMs is stable by showing less than 20 percent extrapolated degradation in PCE over 1,000 hours for devices stored in the dark at an elevated stress temperature (60° C, 140° F). The researchers established the following objectives:

1. Determine morphological stability of the researchers' proprietary starting lead SSM by measuring degradation in PCE for devices stored in the dark at an elevated temperature (60° C, 140° F). Determine how this differs from a goal of less than 20 percent extrapolated degradation in PCE over 1,000 hours for devices stored in the dark at an elevated stress temperature (60° C, 140° F).

2. Make new target SSMs that are expected to improve morphological stability.

- Demonstrate though nuclear magnetic resonance (NMR) target molecules were made with ~99 percent purity.
- Determine thermal degradation information using thermogravimetry (TGA).
- Determine the kinetics of samples using differential scanning calorimetry (DSC).

3. Demonstrate that the materials function as expected.
    - Confirm through visual inspection that uniform films are formed.
    - Confirm through visual inspection morphological stability.
    - Confirm Fourier transform infrared (FTIR) signatures are as expected.
    - Confirm that the shape of ultraviolet-visible (UV-Vis) spectrum is not significantly changed by modifications.
4. Demonstrate that the extrapolated lifetime of OPV with new target SSMs is at least two times longer than with starting lead SSM under same conditions (PCE for devices stored in the dark at an elevated stress temperature of 60° C or 140° F). Demonstrate that efficiency is not reduced by more than 20 percent
5. Demonstrate the SSM morphology is stable by showing less than 20 percent extrapolated degradation in PCE over 1,000 hours for devices stored in the dark at an elevated stress temperature (60° C, 140° F).

2.5.4 Outcomes

1. The researchers determined the morphological stability and degradation rate of their proprietary starting lead SSM.[21] The power conversion efficiency (PCE) of the starting lead SSM (i.e., baseline SSM) stored in the dark at an elevated temperature (60° C, 140° F) degraded about 40 percent in less than 36 hours.
2. The researchers made three new molecules based on the starting lead molecule. They also made three additional new SSMs based on an additional molecule identified after project initiation. The researchers conducted thermal gravimetric analysis (TGA) and differential scanning calorimetry (DSC) on the six molecular formulations. In addition, the researchers made two other new SSMs based on a new proprietary strategic approach that was not originally proposed.
3. The researchers produced uniform films using the target molecules. They used visual inspection to confirm that the proposed proprietary molecular modification was able to function as expected under certain treatment conditions. Using Fourier transform infrared (FTIR) spectra, they determined that only minor changes occurred due to proposed molecular modification. However, the shape of the UV-Vis spectrum was

21 Throughout this IAR, reference is made to "starting lead SSM" and "new target SSM" to protect proprietary information regarding the specific small soluble molecules.

significantly altered during the modification, except for the new lead SSM which showed significant stability under the UV-Vis spectrum.

4. The researchers measured the PCE change of the starting lead and new target SSMs. The starting lead SSM, stored in the dark at an elevated temperature (60° C, 140° F) degraded by ~40 percent in 36 hours, while the new target SSM showed ~5 percent degradation in 100 hours. The researchers determined that the PCE of the new target SSM is over 7.5 percent, compared to the starting lead SSM where the PCE was less than 5 percent.

5. The researchers measured the PCE and found 0 to 10 percent degradation (3.8 percent on average) by extrapolation to 1,000 hours for devices stored in the dark at elevated temperature.

2.5.5 Conclusions

1. The starting molecule degraded significantly under storage in the dark at elevated temperature. The researchers completed this objective.

2. It is possible to modify molecules using strategic design and formulation to produce new molecules that provide appropriate physical and spectroscopic properties. The researchers completed this objective.

3. The morphological stability of the new molecules is better than the starting molecule. The approach used to modify promising molecules appears successful. The researchers completed this objective.

4. The new molecules exhibited increased power conversion efficiency and reduced degradation compared to the starting molecule. The researchers completed this objective.

5. The researchers demonstrated through morphological studies and measurement of PCE that small soluble molecules that exhibit improved stability and reduced power conversion degradation can be design formulated. They have demonstrated the feasibility of the concept, but have not yet demonstrated practicality.

2.5.6 Recommendations

The Program Administrator recommends the researchers should:

1. Determine stability and conversion efficiency under extended operational conditions such as prolonged exposure to light and humidity.

2. Continue to modify formulated molecules with the aim of further improving stability and performance.

3. Produce solar modules using the cells produced with the molecules and determine manufacturability and associated efficiency.

4. Determine shelf life of molecules produced prior to film formation as a guide to industrial process needs.

5. Investigate the effect on stability and performance due to choice of substrate materials.
6. Determine the spectral tenability of the molecular film and consider multi-molecule films to enhance efficiency and capture a larger portion of the spectrum.
7. Begin cost estimation once module fabrication considerations are resolved, and refine the early estimate of $65/m^2 for cell material.
8. Enter into non-disclosure agreements with partners to develop manufacturing processes, including molecular formulations and production techniques.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.5.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit of this research is increased affordability of electricity in California. Given the preliminary nature of this research, quantification of benefits is premature. The proposed technology uses less expensive materials, avoids strategically significant rare earths, and allows for simpler manufacturing through use of roll-to-roll printing techniques. All three factors should help to reduce the cost of building-integrated photovoltaic cells.

2.5.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers are working with industrial firms specializing in different aspects of the necessary production process, such as roll-to-roll film coating. Further, they are working with building design firms to identify structural and property needs for building-integrated PV

application, such as windows and roofing. They are focusing initially on niche markets of portable solar application and flexible roofs.

Engineering/Technical

The main technical issues include production of solar modules and production processes for making film cells using the molecules.

Legal/Contractual

The researchers have licenses and/or patents for a number of small soluble molecules or their families. In total, the researchers have eight items of intellectual property.

Environmental, Safety, Risk Assessments/ Quality Plans

It is unclear if unique environmental or safety risks are associated with the technology, given the proprietary nature of the molecules and production process. However, review of the material provided by the researchers does not indicate any special concerns beyond those typical of industrial processes involving worker exposure to chemicals.

Production Readiness/Commercialization

The technology is not ready for commercialization.

2.6 NO_x Control with Hydrogen-Rich Biogas from Two-Phase Digestion

Awardee: California Polytechnic State University

Principal Investigator: Rafael Jimenez-Flores

2.6.1 Abstract

The goal of this project was to prove the feasibility of a two-phase anaerobic digestion system for the production of hydrogen-rich fuel gas to achieve reduced NO_x emissions when used in internal combustion engines. Use of hydrogen-enriched fuel gas provides a low cost method of achieving low NO_x emissions compared to conventional catalyst systems.

The generation of a hydrogen-enriched fuel gas requires separate digester systems for conventional anaerobic digestion and for hydrogen production. While both digester systems operate under anaerobic conditions, optimizing parameters including pH, retention time, feedstock composition, and gas sparging to improve hydrogen production.

Researchers identified optimum feedstocks such as food waste, glycerol, whey, and d-lactose permeate for the hydrogen producing phase. In general, organic wastes containing soluble, readily degradable organics were appropriate for the hydrogen producing phase. Feedstocks such as manures that degrade slowly were not appropriate for hydrogen phase digestion, because they require hydrolytic enzymes for release of biodegradable organics.

The researchers determined optimum conditions for operation of the hydrogen phase digester to be an organic loading rate (OLR) of 23 g/L-day, a hydraulic retention time (HRT) of 12 hours, and a pH range of 5.5—6.5. In addition, they determined the optimum sparging rate to be 0.96 L/L-hr for biogas from the methane producing phase to achieve an overall optimum fuel gas ratio of 15:85 H_2:CH_4.

The researchers used research data to develop a predictive 3-D model to evaluate the hydrogen phase operation and to predict changes in H_2 production with variations in the operating parameters. The model can also be used to guide scale-up efforts and to increase the level of confidence in the two-phase system operation.

Economic models for operation of the two-phase system with internal combustion of the fuel gas estimated a reduction in operating costs by 63 percent over a single phase system with conventional NO_x emissions equipment.

Keywords: Hydrogen, anaerobic digestion, two-phase system, NO_x control, biogas sparging

2.6.2 Introduction

Anaerobic digestion is an established biological process for conversion of a variety of organic wastes. The process operates at moderate temperatures and under low pressures. The anaerobic microbes which are active in the process degrade soluble and insoluble organics to methane and carbon dioxide. The methane end-product is formed either from conversion of acetate or hydrogen. Under normal conditions little or no hydrogen is detected in the biogas generated in this process.

The methane content of the biogas produced in anaerobic digestion is dependent on the feedstock. More oxidized organics result in less methane and more reduced organics result in a biogas with greater methane content. On average, biogas methane content is approximately 60 percent, and thus it is classified as a medium BTU fuel gas. Biogas may be utilized in a variety of conversion technologies, including steam generation, internal combustion engines, and upgrading for use in fuel cells. Common use in internal combustion engines driving cogeneration to electricity and process heat can result in NO_x emissions which must be controlled. Conventional NO_x control technologies involve the use of selective catalytic reduction technologies which require expensive replenishment to maintain effectiveness. Previous research has demonstrated that enriching biogas with H_2 at a ratio of 15:85 as compared to CH_4, results in reduced NO_x emissions in internal combustion engines. Optimum conditions for H_2 production are relatively incongruous, with CH_4 production including lower operational pH and short hydraulic retention times. In addition, methane producing bacteria have a high affinity for H_2, while H_2 accumulation inhibits further H_2 production by hydrogen producing bacteria.

Conventional anaerobic digestion is widely used for the degradation of organic biomass from food processing, animal manures, and municipal wastes. The resultant biogas is commonly composed of 60 percent methane and 40 percent carbon dioxide. This medium BTU fuel gas can be converted to energy in an internal combustion engine system. However, environmental emissions standards require the use of selective catalytic reduction technologies to reduce NO_x emissions. The capital and operating costs for NO_x reductions are substantial. Alternative low cost methods may enhance the use of anaerobic digestion for common organic waste streams.

Previous research has determined that enriching biogas with hydrogen reduces the NO_x emissions in internal combustion engines, reducing the need (and cost) for catalytic reduction technologies. Previous researchers have also identified the ability of two-phase digestion systems to produce biogas with an optimum ratio of 15 percent H_2 to 85 percent CH_4.

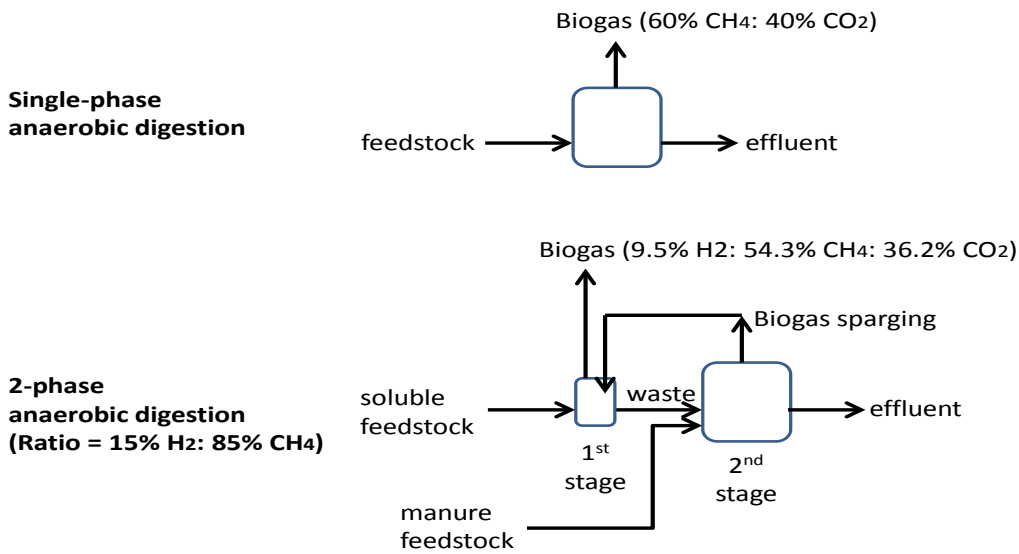
The present study focused on identifying the optimum conditions for operation of a two-phase anaerobic digestion system for the production of a hydrogen-enriched fuel gas. The design of the two-phase digestion system is depicted in Figure 6 below.

In the two-phase system, the first phase is optimized for hydrogen production and relies on biogas sparging from the second phase for hydrogen removal.

The research effort focused on identifying the major design and operational parameters necessary for a two-phase anaerobic system to produce a biogas with a ratio of 15 percent H_2

and 85 percent CH_4. In addition, the researchers determined both the anticipated cost reductions in conventional NO_x emissions systems as well as generating advanced 3-D models to reduce risk in designing and operating larger-scale systems.

Figure 6: The Proposed Two-Phase Anaerobic Digestion System Compared to Conventional Single-Phase Anaerobic Digestion



2.6.3 Objectives

The goal of this project was to determine the optimal parameters for operation of a two-phase anaerobic digestion system for the production of a fuel gas with a ratio of 15 percent H_2 and 85 percent CH_4. The researchers established the following project objectives:

1. Determine the feasibility of using various organic wastes which are available in sufficient quantities and at low cost for the first phase hydrogen-producing digester.
2. Design and operate a two-phase digestion system with biogas recirculation and automated pH control.
3. Conduct experiments to establish the optimum operational parameters for the first phase, including hydraulic retention time, organic loading rate, and pH range.
4. Develop a 3-D predictive model for first phase operation that could be used for further system development.
5. Determine the optimum sparging rate in the first phase digester system to achieve the optimum H_2 content in the biogas.

6. Determine if additives to the first phase are effective or necessary to optimize H_2 production.

7. Estimate the cost/benefits of hydrogen-enriched biogas to reduce NO_x emissions as compared to conventional catalytic systems.

2.6.4 Outcomes

This research project resulted in a substantial number of successful outcomes including the following:

1. The researchers found potential waste streams that contained soluble organics including food waste, glycerol, whey, and d-lactose permeate to be suitable for first phase H_2 production. Wastes including manures were unable to support significant H_2 production under the first phase fermentation conditions.

2. The two-phase, laboratory-scale, continuous anaerobic digestion system demonstrated the ability to sparge the first phase digester with biogas produced in the second phase system, generating hydrogen-enriched biogas. Operation of the two-phase system identified size requirements for both phases, allowing for optimum sparging for production of hydrogen-enriched biogas.

3. The researchers determined optimum conditions for first phase operation to attain the ideal ratio of hydrogen to methane content to be 23 g/L-day organic loading rate, a 12 hour hydraulic retention time, and a pH in the range of 5.5—6.5. In addition, they determined a sparging rate of 0.96 L/L-hr provided optimum hydrogen content in the final biogas product.

4. The researchers used data generated during their studies to optimize H_2 production in the first phase digester to generate a 3-D predictive model which could be applied to both reduce risk in the two-phase system operation and as aid in the design and operation of larger scale systems.

5. With 100 percent of the phase 2 feed coming from phase 1, phase 2 behaved like a conventional methane digester with a neutral pH and methane to carbon dioxide ratio of 60:40 percent v/v. Methane production in the second phase was less than the typical methane digester (~0.2 L/L-day), but this was due to significant consumption of the glucose substrate in the first phase. Data indicated that use of an additional feedstock such as dairy manure would substantially increase the biogas production as well as support maintenance of the correct pH.

6. Researchers determined digester additives to be ineffective at enhancing H_2 production in the first phase digester system. Instead, process data determined that near theoretical H_2 yields were possible without additives.

7. The researchers performed an economic analysis for the optimized two-phase anaerobic digestion system, producing a H_2:CH_4 ratio of 15:85 as compared to the conventional single-phase anaerobic digestion system for NO_x emissions control. Data indicated that a

63 percent reduction in NO_x emissions could substantially reduce overall system costs for the two-phase process.

2.6.5 Conclusions

The present study developed operational data for optimizing a two-phase anaerobic process to generate hydrogen-enriched biogas and estimated the economic impact on NO_x emission control costs. The two-phase anaerobic system included a hydrogen producing first phase and a methane producing second phase. Through the use of serum bottle and continuous digester studies, the researchers determined optimum operational parameters for the hydrogen producing first phase, including an organic loading rate of 23 g/L-day, a 12 hour hydraulic retention time, and an operating pH range of 5.5—6.5. They found waste feedstocks containing soluble, readably biodegradable organics such as food waste, glycerol, whey, and d-lactose permeate, generated hydrogen in the first phase system, while feedstocks such as manures with low levels of soluble fermentable organics produced minimal hydrogen. This was due to the need for hydrolytic enzymes for the breakdown of insoluble organic polymers in manures which require microbes needing longer retention times than in the first phase system.

Removal of hydrogen in the first phase via sparging with biogas from the second phase digester system reduced hydrogen partial pressures and thus enhanced overall hydrogen production. The researchers determined the optimum sparging rate to achieve a H_2:CH_4 ratio of 15:85 be 0.96 L/L-hr.

However, the initial design for the second phase methane generating system utilizing only the effluent from the first phase did not result in sufficient biogas for optimum sparging rates. Therefore, additional organic loading to the second phase is necessary to achieve greater biogas production. Animal manures may provide both greater OLR and increased alkalinity to maintain an optimum second phase system pH.

Researchers applied optimum HRT, OLR, pH, and sparging rate data to generate a 3-D model for the two-phase digestion system. Such a model can be used to ensure optimum operational conditions providing for less risk in maintaining system stability. In addition, the model can be used to guide process scale-up efforts.

Often, optimizing an anaerobic system for hydrogen production results in some methane production. However, researchers determined that additives were not required to eliminate methane production in the first phase when it operated under the optimal H_2 operating parameters.

An economic analysis for reduced NO_x emissions for internal combustion systems due to optimizing the H_2:CH_4 ratio for the two-phase system revealed a 63 percent savings in required NO_x control technology.

While the proposed two-phase anaerobic digestion technology for organic waste holds significant promise to improve NO_x emissions and the economics for commercial-scale systems, the technology is at an early stage and will not transition to commercial development in the near future without substantial funding assistance. Due to the early stage of development, this

funding will likely not come from industrial sources but rather must be supplied by government programs that foster this type of early stage development.

2.6.6 Recommendations

This research project was developmental in nature and thereby requires additional efforts to be considered for commercial application. The following efforts are necessary to demonstrate lower risk in scale-up development. The Program Administrator recommends:

1. Design and test a laboratory-scale, two-phase anaerobic system to produce biogas with an optimized H_2:CH_4 ratio. Confirm optimum operational parameters.
2. Test the laboratory-scale system with actual waste streams including food waste, glycerol, whey, or d-lactose permeate as well the use of an animal manure feedstock for the second phase digester in addition to the effluent from the first phase system.
3. Analyze the optimized hydrogen-enriched biogas compared to conventional biogas in an internal combustion engine to determine reduction in NO_x emissions.
4. Re-evaluate all economic analyses and projections for system capital and operating costs as well as the projected effect on NO_x emissions.
5. Develop further the two-phase digestion system at pilot scale to demonstrate scaleability of the process and further validate operational parameters.

2.6.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California energy supply and distribution system
- Increased public safety of the California energy system
- Increased reliability of the California energy system
- Increased affordability of energy in California

The primary benefit of this research is reduced environmental impacts of the California energy supply and distribution system. This research focused specifically on energy supply. Improving biogas quality by generating hydrogen-enriched fuel gas has the potential to dramatically reduce NO_x emissions caused by energy supply. If conventional single-phase anaerobic digestion systems are modified to include a hydrogen producing phase, reduced NO_x emissions may also be applied to these existing systems. The research team estimated that a 5 MWe facility would emit 40 percent of the NO_x emissions allowed per best available control technology (BACT) guidelines.

Anaerobic digestion has been recognized as a reliable process for conversion of organic wastes to energy. Improving both the environmental emissions and economics of the process would

increase the application to additional underutilized organic wastes. Improving the economics and environmental benefits in applying the anaerobic digestion process to organic wastes would enhance use of this safe, low temperature, low pressure technology.

Early economic projections for the application of the two-phase anaerobic digestion system indicate that reduced NO_x emissions from hydrogen-enriched biogas used in internal combustion engines to generate electrical power and heat could reduce overall process emissions control costs by 60 percent. Reducing process costs may enhance adoption of anaerobic digestion for conversion of organic wastes that are currently underutilized or placed in landfills, thereby increasing the generation of biogas as a renewable fuel source.

2.6.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

A substantial opportunity exists to develop the two-phase anaerobic digestion system for underserved organic waste streams and thereby enhance the commercial market for this renewable energy technology. Currently the researchers are at a very early stage in the process development and have no firm marketing partners.

Engineering/Technical

Researchers estimated that product development and demonstration would likely require 5—10 years. Each potential waste would have to be tested and optimized under continuous/semi-continuous conditions. Wastes tested would depend largely on industry interest.

Legal/Contractual

The research team had previously secured a patent for the two-phase digestion system (2009).

Environmental, Safety, Risk Assessments/ Quality Plans

Environmental, safety, and risk assessments were not part of this project as the technology is still in the developmental stage.

Production Readiness/Commercialization

The two-phase anaerobic digestion technology requires further development and validation at bench and pilot scales.

2.7 Proof-of-Concept Solar Energy Converter Using Internal-Photoemission and Plasmonic Perfect Absorbers

Awardee: Pacific Integrated Energy, Inc.

Principal Investigator: Bala Krishna Juluri

2.7.1 Abstract

Researchers in this project undertook to prove the concept of solar electricity production using photoemission in combination with perfect absorption of light on meta materials. The concept relies on using solar radiation to stimulate internal photoemission in metal semiconductor Schottky diodes that are enhanced by plasmonic absorption. This concept has been evaluated theoretically and determined to have potential to enable solar-to-electric energy at comparable efficiencies and possibly lower costs than commercial crystalline and thin film cells and panels. The researchers' vision was to be able to use inexpensive, non-toxic, abundant materials, and low capital cost film deposition methods to achieve fabrication costs and cell efficiencies competitive with commercial solar conversion equipment.

The researchers set about to develop a suitable fabrication process and use it to produce an experimental device consisting of tiny but electrically active films. They used benchmarks consistent with competitive cost and performance to establish interim and final targets to evaluate experimental results. Device and process design were constrained by time, equipment, and budget available for the project. The researchers changed processing techniques to address these constraints as well as to update device modeling. Despite a detailed project plan and access to extensive experimental and diagnostic tools, the researchers found it necessary to reconfigure the concept, sacrificing some desirable operating characteristics to achieve a simpler, cheaper, and more easily and reliably fabricated device.

Keywords: Internal photoemission, plasmonic, meta-material, thin film solar

2.7.2 Introduction

The emerging field of plasmonics has yielded methods for guiding and localizing light at the nanoscale, well below the wavelength of light in free space and, importantly, well below the physical thickness of solar photovoltaic absorber layers in commercial solar panels. The efficiency and completeness of light absorption is critically important in all solar photovoltaic devices. Thus the potential commercial significance of plasmonics in a solar energy conversion context depends on achieving comparable absorption at the nanoscale.

Perfect absorption is a phenomenon where properly selected materials can be geometrically structured and physically combined to produce a material that exhibits electromagnetic properties that are readily predicted by Maxwell's equations but are not typically found in nature. Such materials are referred to as meta-materials. One property that can be optimized is nearly perfect absorption (very low transmission and reflection) of electromagnetic radiation.

A Schottky diode (named after German physicist Walter H. Schottky) can be formed between a metal and a semiconductor, creating a Schottky barrier instead of a semiconductor–semiconductor junction as in conventional diodes. The metal side acts as the anode and an n-type semiconductor acts as the cathode of the diode. When current flows through a diode there is a small voltage drop across the diode terminals. A normal silicon diode has a voltage drop of 0.6–0.7 volts, while a Schottky diode voltage drop is between approximately 0.15–0.45 volts.

Plasmonic nanoparticles are particles whose electron density can couple with electromagnetic radiation of wavelengths that are far larger than the particle due to the nature of the dielectric-metal interface between the medium and the particles. This is unlike a pure metal where there is a maximum limit on what size wavelength can be effectively coupled based on the material size.

2.7.3 Objectives

The goal of this project was to model, fabricate, and test a proof-of-concept solar energy converter that is a novel combination of two phenomena: internal photoemission in metal semiconductor Schottky diodes and perfect absorption of light based on a meta-material in a thin film structure. The project objectives were to:

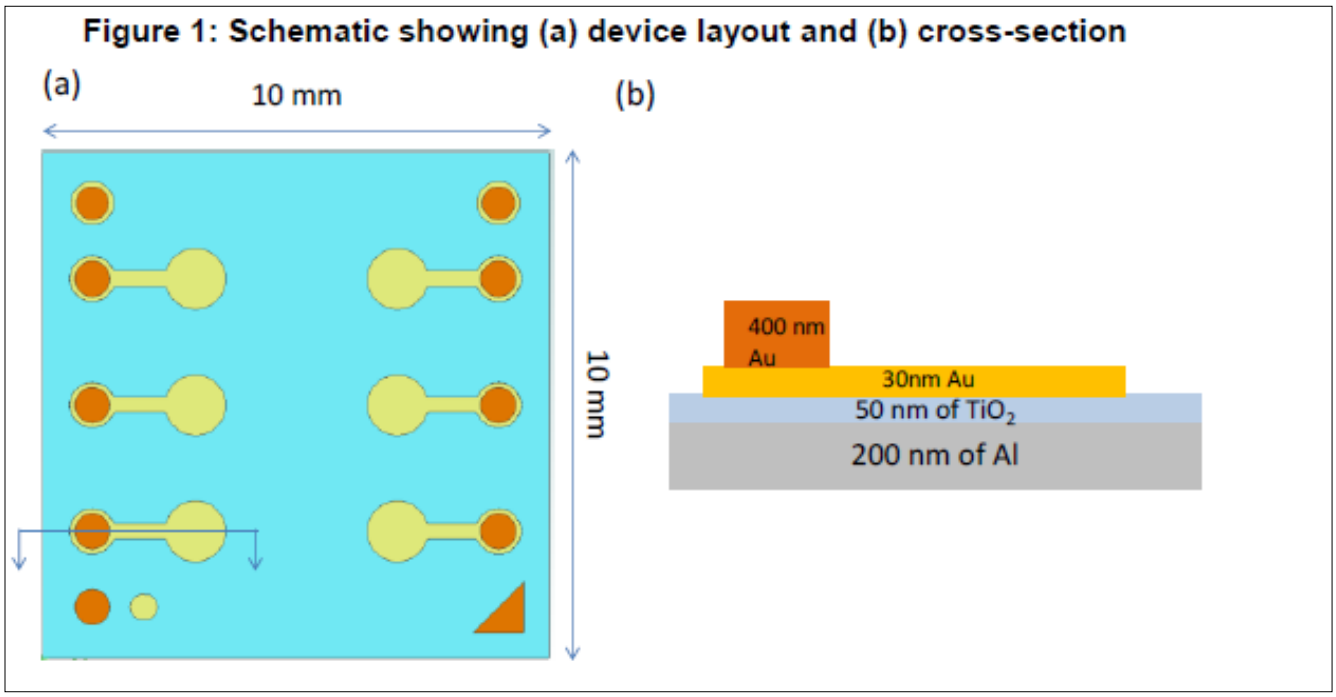
1. Model the PIE internal photoemission solar energy converter device structure to optimize for device geometry and material composition and achieve 95 percent absorption at an initial target wavelength of 633+30nm, with a volumetric power dissipation of $5x10^{21}$ W/m3 in the metal-absorbing structure. The target specification for the absorption peak was changed to 520 nm based on modeling results.

2. Develop a device fabrication process, including process flow and process parameters, for a device with material properties and physical dimensions that matched the design specs determined during the earlier modeling phase.

3. Determine and optimize process flow to enable reliable fabrication of devices with a good yield.

4. Build a working prototype device that matches the device materials and geometries as determined by modeling and simulation (Figure 7 below), build a prototype that exhibits a current response to light, produce a device exhibiting 5.0 percent efficiency at the target wavelength, and build a working version of this device.

Figure 7: Schematic Showing Device Layout and Cross Section



5. Test the prototype device by measuring optical absorption and electrical parameters by conducting wavelength scans of the device from 400 to 1100 nm while measuring the I-V response of the device.

6. Investigate scalability to larger devices, looking at how nano fabrication processes have progressed since the original proposal was submitted and determine how such progress could make the scale-up of the manufacturing of this device more feasible.

2.7.4 Outcomes

The project team addressed all objectives with varying success.

1. Modeling results led to changes in the targeted wavelength. At the revised wavelength, absorption was 90 percent vs. the targeted 95 percent, and volumetric power dissipation was approximately 25 percent of the original target.

2. Development of a fabrication process encountered a number of setbacks related to deposition process choices, material selection, and film geometric uniformity. This resulted in a greater reliance on trial and error than would be appropriate to the

development of a working prototype demonstrating conversion efficiencies of commercial interest.

3. Determination and optimization of process flow would have required a device design that had been demonstrated to meet device performance objectives. The researchers did not meet this condition. Further, suitable processes for fabrication of small area solar photovoltaic research devices provide only partial guidance for the development of economically optimum processes for fabrication of larger area commercial products.

4. Researchers were able to build devices that demonstrated a current response to light, but the current response fell orders of magnitude short of levels consistent with targeted efficiencies.

5. Measurements of specular reflectance demonstrated absorbance patterns consistent with light capture but not consistent with wavelength response according to design predictions. Current and voltage measurements demonstrated detectable power generation at some, but not all, areas of the device where power generation was intended.

6. Regarding scalability to larger devices, researchers recommended selection and development of a nano imprint lithography technique for making larger devices on the order of 10mm x 10mm. However, they also recommended investigation of a number of material, etching process, and deposition process substitutions that would logically precede further devices scale-up.

2.7.5 Conclusions

1. Better and more integrated models are needed if the current line of research is to be continued.

2. Development of fabrication processes is premature until basic materials choices are confirmed and phenomena that could result in power generation are better understood.

3. Determination and optimization of process flow is likewise premature, at least with regard to commercial production.

4. The researchers experimentally demonstrated phenomena predicted by theory, but it was unclear whether and how their findings could be exploited to convert sunlight at efficiencies comparable to current commercial technologies.

5. If further research is attempted to create a device that can produce commercial solar electricity, deviations between theoretical predictions and measured results need to be better explained, and the explanations confirmed. The fact that modeling cannot provide more realistic targets for power production wavelength response is a serious concern.

6. Issues of scalability to larger devices cannot be assessed without firm materials selection and better process definition. Even in cases where high conversion efficiencies are

demonstrated on small areas, progress toward comparable efficiencies on larger products is slow and expensive.

2.7.6 Recommendations

The type of solar energy converter proposed for this project works in a fundamentally different manner than all other semiconductor-based photovoltaic devices. While the original planned product did not meet the technical feasibility test, there is potential that an alternate approach could be developed with more work. The Program Administrator recommends consideration of an alternative, less costly fabrication technique that does not require serial processing. Device design and fabrication should be based on more laboratory experience and a better theoretical understanding of fundamental phenomena.

2.7.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is the potential for increased affordability of electricity in California. If solar photovoltaic devices can be developed that reduce materials usage and cost while achieving competitive conversion efficiencies, this benefit can be captured.

2.7.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have not surveyed potential customers for interest since the version tested in this project is not commercially viable.

Engineering/Technical

The researchers determined that they need to modify the design to produce a commercial product. The new design should absorb broad spectrum light more efficiently.

Legal/Contractual

Adequate patent protection will require further definition of materials and manufacturing techniques. The researchers filed for patent protection prior to applying for this EISG grant.

Environmental, Safety, Risk Assessments/ Quality Plans

These considerations are premature at the current stage of development.

Production Readiness/Commercialization

The original planned product did not meet the technical feasibility test. Therefore there is no production readiness plan.

2.8 Non-Optical Concentration of Solar Energy for Low Cost Rooftop CHP

Awardee: Solar Stream Innovations, LLC

Principal Investigator: Jeffrey Lee

2.8.1 Abstract

The goal of this project was to determine the feasibility of using a vacuum insulated heat pipe to aggregate the small heat inputs of several evacuated tube insulated heat pipes into a single high temperature output to increase the heat-to-electricity conversion efficiency of a rooftop solar combined heating and power system. The researchers proposed to retrofit existing solar installations with a heat pipe manifold (HPM) capable of concentrating solar heat and operating at high temperatures as required for heat-driven electricity generation. In addition to the potential for electricity generation, the researchers hypothesized that the high temperature system would operate more efficiently and be better able to meet heat demand during winter months. The researchers' first prototype leaked under stress and was not testable as planned. The second prototype similarly contained design flaws that hindered performance. Testing of the prototypes failed to produce results supportive of the researchers' hypotheses.

Keywords: Heat pipe, manifold, drainback system, evacuated tube solar water heater, flange, non-condensable gas

2.8.2 Introduction

Solar water heating systems are typically designed to meet 100 percent of summertime water heating needs. Systems that produce more heating capacity than can be used cause accelerated degradation of system components and increased maintenance costs. Consequently, when solar input is reduced during winter months, a typical system is incapable of meeting heating demand.

Excess heating capacity is not produced at temperatures high enough to capture and divert into heat-driven electricity generation and cooling. Thus this unusable excess heat is generally bled off and systems are shut down to preserve the integrity of system components. Systems in harsh environments often use antifreeze to protect pipes in the winter. However antifreeze breaks down at high temperatures, so such systems are similarly unable to provide heating at temperatures needed for energy production. Oil circulation is protective in freezing environments and may be used in high temperature systems. However the requisite copper piping is costly and prone to heat loss, particularly during winter months.

The researchers proposed to retrofit existing solar installations with a heat pipe manifold (HPM) capable of operating at the high temperatures required for heat-driven electricity generation (Figure 8). Additionally, the researchers hypothesized that the proposed technology would provide higher efficiency and better wintertime operating performance as a result of the higher operating temperature. Design errors and prototyping setbacks hindered the completion of all tasks proposed and failed to show a significant advantage of the proposed technology over conventional solar heating.

Figure 8: Retrofit of Sunda Seido 5-16AS Solar Water Heater with a Heat Pipe Manifold

2.8.3 Objectives

The goal of this project was to determine the feasibility of using a vacuum insulated heat pipe to aggregate the small heat inputs of several evacuated tube insulated heat pipes into a single high temperature output to increase the heat-to-electricity conversion efficiency of a rooftop solar combined heating and power system. The researchers established the following project objectives:

1. Confirm from a thermodynamic model that the designed heat pipe will transport >10kW of steam at full scale to a condenser and can handle steam pressures > 400psi operating up to 220° C.
2. Confirm assembly can be performed by Solar Stream Innovations (SSI) without special tools.
3. Demonstrate at ACT (Advanced Cooling Technologies) 400 psi and 220° C threshold of HPM and no trending loss of vacuum recorded by pressure sensor after assembly.
4. Confirm HPM does not leak fluid.
5. Confirm vacuum housing does not have trending loss of vacuum recorded by pressure sensor over a 72 hour day and night monitoring period.
6. Confirm a ¼ scale prototype HPM is capable of outputting >2.5 kW of thermal energy to cooling water with an operating efficiency of approximately 40 percent of gross collector area at steady state operating temperature of 220° C. Extrapolation will be required as current testing equipment is only rated to 150° C.
7. Confirm assembly can be performed away from ACT. Confirm design changes resolved issues.
8. Confirm second prototype will extrapolate to 10 kW capacity.

2.8.4 Outcomes

1. The researchers worked with ACT in Pennsylvania for modeling and design tasks related to the project. ACT modeled five heat pipe limitations including viscous, sonic, entrainment, capillary, and boiling limits to identify design constraints. None of these constraints were determined to limit the ability of the proposed heat pipe to transport > 10 kW of steam at full scale to a condenser. The researchers did not test pressure constraints because Type K copper piping "was known to be able to contain the saturated steam pressure load at 220° C."
2. The original prototype design included a flange connection at the midpoint of the HPM. ACT modified the design and produced a soldered connection. Additional design modifications included lower temperature solder than the researchers anticipated and a support structure that had not been requested. Once the researchers received the prototype, they were unable to assemble it due to a limited temperature range for

soldering and wicking of heat away from the connection. As a result, the prototype could not be fully assembled and was not leak proof.

3. The first prototype could not be tested by ACT because assembly was irreversible and would cause logistical shipping issues. However ACT successfully performed helium leak testing for component parts prior to shipment to the researchers for assembly. The second prototype was not tested because testing expenses would have exceeded the allotted budget. Instead, ACT gave a guarantee that the prototype would be leak proof. The researchers performed vacuum testing after the prototype was assembled as is discussed in Objectives 4 and 5.

4. Soldering issues prevented leak proof assembly of the first prototype. The second prototype was visually inspected and determined to be free of leaks.

5. The researchers fully assembled the second prototype and drew a vacuum which held for 64 hours. Vacuum gauge and visual inspection indicated that the assembly was leak proof. The researchers did not state initial and final gauge measurements.

6. This testing was not performed as stated.

7. The first prototype required a permanent soldered connection and could not be assembled successfully away from ACT. The second prototype had a flange connection originally anticipated for the first prototype that could be assembled and disassembled successfully. The flanged design was capable of maintaining a vacuum and a leak-proof connection at a peak temperature of 200° C.

8. The researchers collected efficiency data before and after manifold retrofit for a Seido 5-16AS solar collector. The HPM was equivalent in efficiency at ambient temperature, slightly more efficient below ambient temperature, and less efficient at high temperature.

2.8.5 Conclusions

1. The researchers met the goal to demonstrate that the proposed design would not be limited by thermodynamic constraints.

2. The researchers did not meet the goal to adequately assemble prototypes produced by ACT. The researchers made conscious decisions to allow ACT to produce both prototypes that were originally planned and critical to the project success without supervision. Although the researchers did travel to Pennsylvania with the intention to meet ACT design engineers, they did not meet with key project personnel. Instead the researchers met with drafting personnel to correct CAD import issues that should have been done remotely well in advance of the visit. After complete failure of the first prototype, the researchers persisted in their hands-off approach by cancelling a planned visit to ACT and providing little to no direction in its efforts. Subsequently, the second prototype was shorter than originally designed, and the flange design prevented full

insertion of the evacuate tube condenser bulbs into the manifold, ultimately resulting in a decrease in efficiency.

3. The researchers did not meet the goal for ACT to demonstrate scientifically that the HPM was leak proof prior to final assembly. The first prototype was leak tested in the component state, but later failed testing once assembled by the researchers. Although ACT issued a guarantee against leakage for the second prototype, no testing was actually done.
4. The researchers met the goal to confirm that the HPM did not leak fluid only for the second prototype. However results were not quantified in a scientific manner. The first prototype leaked and was abandoned for the remainder of planned testing.
5. The researchers fell short of meeting the goal to confirm that the assembly could sustain a vacuum for a 72 hour period for the second prototype. There is no explanation for the reduction in test duration from the proposed 72 hour period to the actual 64 hour period. Additionally, the researchers did not provide actual gauge readings to quantify their findings.
6. Although some related testing was performed on the HPM, the researchers did not meet the objective as stated.
7. The researchers met the objective to allow assembly outside of ACT for one of the two prototypes.
8. The researchers did not meet the objective to provide 10 kW capacity for the prototype. Actual data presented did not provide output power capacity but instead focused on efficiency of the manifold before and after retrofit with the proposed HPM. Although the manifold was capable of operating at high temperatures, this benefit was at the expense of efficiency over the base model. The researchers failed to discuss or demonstrate the benefits of the increased operating temperature that might have countered the loss in efficiency in terms of energy production.

The researchers were unsuccessful in demonstrating the feasibility of using the proposed HPM to increase the efficiency of a solar combined heating and power system. The prototyping process was fraught with mishaps that prevented successful design iteration and improvement in the proposed two-step project approach. The first prototype was produced without supervision, failed to meet the initial design or testing objectives, and was ultimately abandoned. Instead of using a second prototype to implement design improvements based on the first round of testing, the second round was simply a second attempt to produce the initially conceived prototype. Continued lack of supervision and budget management resulted in unexpected design issues and cost cutting measures that prevented successful completion of even the initial round of proposed testing. The scaled down testing of the second, non-optimized prototype was only sufficient to indicate that the HPM was actually less efficient than the original solar collector manifold. The researchers were left to hypothesize whether the demonstration failed due to errors in manufacture and design that prevented proper seating of

the manifold on the evacuated tubes, cost cutting measures that led to a reduction in size of the HPM, heat loss through an oversized flange connection, variability in collector efficiency in socket temperature at a steady state condition, or some other cause.

2.8.6 Recommendations

The researchers proposed additional prototyping to arrive at a solution. However there are so many variables and possible causes for the failure to meet project objectives that the project itself is perhaps too enthusiastic and unbounded and should be broken down into more manageable components. These can then be optimized and later assembled into a final prototype. During the course of additional work, the researchers should take an active role in the prototyping process to minimize the number of variables that will hinder success of the project.

As a part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Identify all potential causes for design errors and system inefficiencies based on current research.
2. Design and implement procedures and sensitivity testing to address all causes identified.
3. Isolate variables and perform testing to optimize each component. Quantify all tests performed and ensure repeatability. For example:
    - Ensure that the HPM design will properly seat in a manifold retrofit.
    - Perform sensitivity studies using various heat exchange fluids.
    - Quantify heat loss as a function of material type, thickness, length, and connection type.
4. Demonstrate quantifiable benefits over conventional solar installations.

2.8.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research project is reduced environmental impacts of the California electricity supply or transmission or distribution system. The

researchers provided a reference to the reduction in CO_2 emissions as a result of using solar electricity as an alternative to natural gas fueled electricity production. However, because the researchers were unsuccessful in meeting project objectives, there was no quantifiable benefit in using the proposed technology over existing solar installations.

2.8.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have not performed a market analysis, but they have surveyed potential customers. The primary market includes commercial and multi-family residential facilities.

Engineering/Technical

Additional prototype iterations are needed to improve performance. The iterations are anticipated to cost approximately $200,000 and to take approximately one year to complete.

Legal/Contractual

The researchers have secured a patent for this technology.

Environmental, Safety, Risk Assessments/ Quality Plans

Environmental, safety, risk assessments, and quality plans have not yet been developed. The researchers do not anticipate negative effects with regard to public safety or the environment.

Production Readiness/Commercialization

The technology is not yet developed sufficiently to pursue commercialization. Once the proof of concept work is complete, the researchers will require assistance to go to market.

2.9 Residential Energy Intelligence Software (Res-Intel)©

Awardee: Policy Consultants, LLC

Principal Investigator: Hal Nelson

2.9.1 Abstract

The goal of this project was to demonstrate the feasibility of developing a residential electricity monitoring and analysis software application that integrates multiple large databases to increase the effectiveness and efficiency of residential demand-side management (DSM) programs. The researchers were unable to obtain billing data from an investor-owned utility (IOU) as originally planned, due to confidentiality issues. Instead the researchers used data from the 2009 Residential Appliance Saturation Survey (RASS), along with publicly available databases from the tax assessor and weather bureau. The researchers extrapolated the statistically significant RASS data to represent all single family homes in Los Angeles County under 3,500 square feet in size. The researchers were able to successfully join and query the various data sources with only nominal data validation errors. Weather and publicly available building data were sufficient to explain approximately 33 percent of the variation in electricity consumption per square foot. The addition of survey data increased this percentage by three points. The Res-Intel software interface used results of statistical analyses on this data to generate usage, energy savings potential, and related charts for zip codes within Los Angeles County. Additionally, statistical functions were provided to generate numerical results based on user input variables.

Keywords: Demand side management, big data, residential energy efficiency, building energy simulation, cost effectiveness, targeted marketing

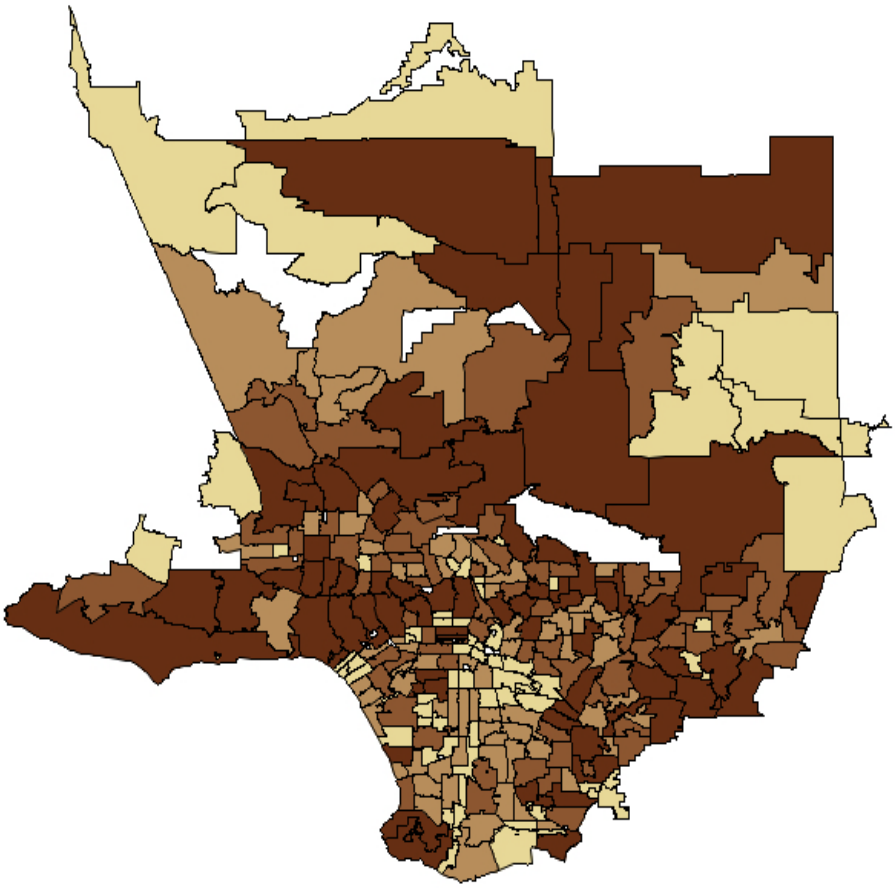
2.9.2 Introduction

The California Energy Commission (CEC) and California Public Utilities Commission (CPUC) have established a goal to reduce residential energy consumption 40 percent by the year 2020. To meet this goal, the CPUC plans to incent retrofits to improve the efficiency of existing homes. Current approaches rely on contractors and homeowners to make energy efficient choices. The researchers posited, however, that voluntary participation in retrofit programs designed to improve efficiency was insufficient to reach the target efficiency goal.

The researchers proposed to use existing utility billing and other public data to identify residences with the largest energy efficiency potential. This demand-side management (DSM) approach would allow for targeted energy efficiency incentive programs that could strategically identify customers in socio-economic groups that are most likely to participate.
The proposed Res-Intel system was intended to rely on billing data from investor-owned utilities (IOUs) to calculate a Home Energy Intensity Score (HIS). Statistical analyses were performed on the HIS values to identify those areas with the greatest potential to affect change in energy efficiency. The researchers were unable to obtain IOU billing data to test the model due to confidentiality issues. Instead, they used the 2009 Residential Appliance Saturation Survey (RASS) along with publicly available databases from the tax assessor and weather bureau. The researchers extrapolated the statistically significant RASS dataset to represent all single family homes in Los Angeles County under 3,500 square feet in size. Although the RASS data set was statistically significant, it did not provide enough granularity to identify specific homes that could be targeted for incentive programs. Rather, the researchers determined energy efficiency potential on a zip code level (See Figure 9). Only 33 percent of the variation in RASS billing data could be attributed to variables relating to weather and building data.

The researchers noted that the Res-Intel database might be a tool to target high energy efficiency potential regions and improve customer participation through relevant retrofit incentives. However, they assumed that the successful achievement of the goal of 40 percent reduction in energy usage by 2020 may be attributed in part to the Res-Intel software. The researchers assumed the Res-Intel contribution to reduced energy consumption would be from 1.0 to 10 percent, without any kind of scientific basis. Without a demonstration using IOU data, a conclusion that the $60,000 per utility installation cost could be recaptured through energy savings cannot be justified. Further, given the researchers' difficulty in obtaining IOU data, it is questionable that IOUs would be willing to share data with each other, thus requiring separate installations for each utility.

Figure 9: Annual Energy Savings Potentials (kWh) for Los Angeles County by Zip Code



Darker zones exhibit higher potentials

2.9.3 Objectives

The goal of this project was to demonstrate the feasibility of developing a residential electricity monitoring and analysis software application that could integrate multiple large databases to increase the effectiveness and efficiency of residential demand-side management programs by providing specific targets for incentive programs. The researchers established the following project objectives:

1. Demonstrate that 90 percent (+/-10 percent) of the households in the integrated data fields contain the appropriate data and that this data is able to be read by the Res-Intel model. Data quality assurance is critical for decision-making based on analytical results.

2. Demonstrate that building data, electricity sales, DSM program databases, and other databases can be queried by the stored procedures in the model. Eighty percent of data fields (+/-10 percent) should be related by the model, with the balance requiring manual renaming and or relating by the end user. With effective joining/relating of the databases, utilities can monitor the HIS need indicator for a larger share of their customers.

3. Develop regression algorithms to estimate energy demand that explain > 50 percent of the variation in household electricity demand. Develop logistic regression models of predicted probabilities with 95 percent confidence intervals for end-use penetration of key building shell and appliance measures. Explaining variation in energy consumption is critical for developing a valid indicator of customer DSM need.
4. Demonstrate that 90 percent (+/-10 percent) of all households that are detected by the algorithms as having high peak demand are in high electricity usage distributions. The algorithm needs to screen households that have high total kWh usage instead of just high relative usage during summer months.
5. Develop five validation procedures to test relevant model inputs and outputs. Batch validation procedures will find failure rates of < 1 percent. The Res-Intel model integrates data from a variety of sources, and these batch procedures must perform correctly or many households will be lost from the analysis.
6. Develop a GUI that is functionally and aesthetically pleasing to > 75 percent of demonstration model users. Users require a pleasing interface to optimize the functionality of the software.
7. Target 100 percent of critical documentation writing and contextual guidance within the application. The application should meet criteria set out in the IEEE 829 standard for software documentation. Given the complexity of the statistical approaches used to develop the HIS need indicator, as well as the difficulty of joining/relating the databases, users will need to understand how the software obtained its outputs as well as the methodologies employed to derive the outputs.
8. Label 100 percent of output fields for users to self-validate the data. Output labels enable users to understand what they are viewing.

2.9.4 Outcomes

1. The researchers related data from the following databases:
    - 2009 RASS Billing Survey Data
    - NOAA Climate Data
    - 2012 LA County Assessor's Building database
    - CEC weather data by climate zone and city

RASS data for 2009 consisted of 14,263 single family residence (SFR) observations, which were extrapolated to represent 1.47 million SFRs in LA County. NOAA Climate data was joined to the dataset using zip codes. The researchers obtained missing weather data using California Energy Commission (CEC) weather data published by climate zone and city. They eliminated RASS data outliers to reduce errors. Elimination of the thirteenth billing period resulted in 97 percent data completeness. The County Assessor database contained complete records for over 95 percent of single family residences.

2. The databases described above were successfully joined with only 0.13 percent of household data rejected. However the researchers did not use actual IOU billing data during testing, as originally proposed. Rather, they used a published survey to generate extrapolated household billing data. Completeness of this survey database is not relevant to the data integrity of IOU databases. In fact, because the RASS data is the result of a publicly available survey, it is likely that the survey data integrity far exceeds that of the proprietary IOU databases. The researchers were unable to address this objective as proposed.

3. The researchers used regression analysis to evaluate the effect of 16 variables enumerated in weather, building, and demographic data on the baseline energy use. These variables were able to explain 36 percent of the variation in energy usage.

4. Researchers used extrapolated RASS data to generate a map of energy savings potential for Los Angeles County by zip code. Data limitations did not permit identification of individual homes with high peak demand.

5. The researchers developed software procedures to validate the following data:

   - Building service address
   - Building square footage
   - Home energy demand estimates

   IOU data were not available to permit additional validation efforts including:

   - Building energy savings estimates
   - Monitoring module

6. The researchers surveyed the Res-Intel project team to determine if the user interface was aesthetically pleasing. Five of the six team members polled felt that the interface was aesthetically pleasing.

7. The researchers presented software documentation for a significant number of software modules, including chart generation and function syntax. Instructions did not comply with the IEEE 829 standard for software documentation.

8. The researchers verified that interface field labeling errors were identified and corrected.

2.9.5 Conclusions

1. The researchers exceeded the goal to demonstrate greater than 90 percent data completeness.

2. The researchers did not meet the goal to demonstrate greater than 80 percent combined data completeness using IOU data as originally proposed. However, the researchers did demonstrate that building data and weather data were greater than 80 percent complete when joined with extrapolated RASS survey data.

3. The researchers did not meet the goal to explain greater than 50 percent of the variation in household energy demand.
4. Lack of IOU data did not permit the researchers to meet the goal to identify individual residences with high peak demand as originally proposed.
5. Lack of IOU data permitted the researchers to complete only three of the five proposed validation procedures.
6. The researchers did not sufficiently demonstrate achievement of the objective to provide an aesthetically pleasing interface. The results of the survey were not only subjective, but also highly biased and statistically insignificant. Further, the researchers proposed no unbiased quantitative or discrete criteria by which to evaluate the aesthetics of the interface. For example, the researchers could have evaluated intuitiveness of the interface in an unbiased manner by measuring the time needed to complete a task such as generation of the heat map. Bias was also present in both the sample size and sample population.
7. The researchers did not meet the goal to complete all documentation to IEEE 829 standards. However, such documentation is arguably premature for the current level of development and lack of appropriate bench testing. The documentation presented amplified the bias in interface evaluation and assumed that a typical user would be confident or capable to construct the required command line syntax to generate model output. Further, instructions provided appeared to be relevant for analysis within a region, rather than for a specific home or group of homes, as required to achieve the overall objective of this research.
8. The researchers met the goal to ensure that 100 percent of the output fields were correctly labeled.

The researchers were not successful in demonstrating the feasibility of using Res-Intel to increase the effectiveness and efficiency of residential demand-side management programs. Significant setbacks included the inability to obtain IOU data for testing and providing output targeted to individual homes. The researchers failed to demonstrate a direct connection between the proposed technology and a monetary benefit to California ratepayers.

2.9.6 Recommendations

As a part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Partner with an IOU to obtain proprietary billing data and test system integration using original project objectives.
2. Demonstrate the ability to identify and rank individual residences based on energy savings potential.
3. Simplify the user interface to eliminate the need for command line syntax.

4. Bench test the Res-Intel interface using independent, unbiased users.

2.9.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research project is increased affordability of electricity in California. The researchers calculated an energy savings to California by assuming the 40 percent decline in energy consumption targeted by the California Energy Efficiency Strategic Plan would be met by 2020 and arbitrarily assuming that between 1.0 and 10 percent of that reduction could be attributed to the proposed technology. Although the researchers claim that Res-Intel can identify homes with high energy savings potential, the research did not demonstrate this claim. Further, because identification of high usage homes does not necessarily result in implementation of energy saving measures in those homes, the actual energy savings is not directly related to the function of the software, even if this had been demonstrated.

2.9.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have performed a market analysis and intend to license the technology through a lighting manufacturer which has not yet been identified. If the researchers are unable to secure a license agreement, they will pursue commercialization independently.

Engineering/Technical

The researchers have not identified any engineering/technical issues. However, data confidentiality issues hindered the current research and are likely to cause difficulty for a planned beta test without a partnership with an IOU. The planned demonstration will require approximately $10,000.

Legal/Contractual

The researchers performed a preliminary patent search but have not applied for patents.

Environmental, Safety, Risk Assessments/ Quality Plans

There are no potential negative effects from application of this technology with regard to public safety or the environment.

Production Readiness/Commercialization

The researchers will require venture capital to complete development and commercialize the Res-Intel software

2.10 Task Ambient Daylighting

Awardee: Erik Page & Associates, Inc.

Principal Investigator: Erik Page

2.10.1 Abstract

The goal of this project was to test the feasibility of using task plane-mounted illuminance sensors for controlling ambient luminaires in a daylight harvesting system. The researchers developed a prototype task lamp that included a sensor module mounted on top of the task lamp and a controller module mounted to overhead ambient lighting. Measured illuminance levels at the task plane were transmitted wirelessly to the ambient lighting. The researchers tested the accuracy of measured illumination levels and demonstrated reliability in pairing task luminaires with the closest ambient luminaire. They then tested the ability of the prototype to automatically adjust ambient lighting based on the amount of illumination measured at the work surface while applying user-defined minimum levels. The prototype proved reliable in all aspects, with better than anticipated performance. The researchers measured a reduction in operating power of 70 percent when the task light was exposed to an external light source of approximately 250 foot-candles.

Keywords: Daylighting, daylight harvesting, lighting controls, daylight control, automated lighting control

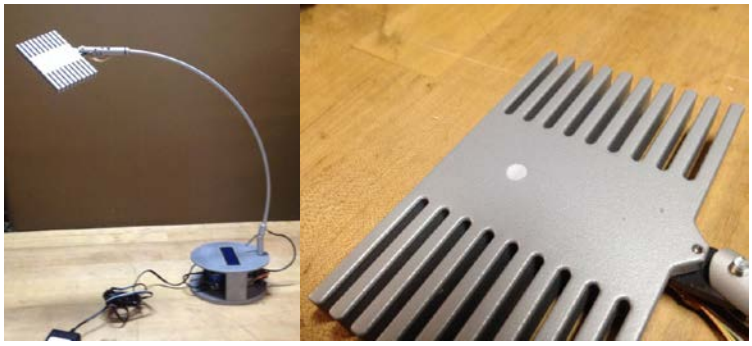
2.10.2 Introduction

Daylight harvesting which reduces electric lighting in response to the amount of daylight available has become widespread in commercial applications. Applications include open-loop and closed-loop systems. Open-loop systems measure the amount of daylight available in the exterior environment, whereas closed-loop systems measure the amount of daylight available in the area in which daylight harvesting is to occur. Most commercial systems are closed-loop and include a photo sensor mounted either on the ceiling or on the ceiling-mounted luminaire to be controlled. Neither of these methods accurately measures light levels at the task plane. Consequently, as many as half of daylight harvesting systems are disabled by users or facility managers because the lighting levels at the task plane are insufficient. Therefore anticipated energy savings are not realized.

The researchers proposed an alternative approach to daylight harvesting that would control ambient lighting based on light levels at the task plane in order to adjust lighting more accurately and gain user acceptance. The researchers developed a prototype that included a sensor module mounted on top of a task lamp and a controller module mounted to overhead ambient lighting. See Figure 10. The prototype included a digital control allowing users to set minimum lighting levels. Light levels measured by a photo sensor mounted to the top of the task lamp were wirelessly transmitted to a photo sensor on a ceiling-mounted ambient luminaire. Computer algorithms paired the ambient luminaire with the task lamp that was most directly impacted by a change in light levels. These algorithms allowed for multiple independently controlled task lamp and ambient luminaire pairs to exist within a single space.

By providing independently controllable luminaires which respond to light levels at the task plane and include user-definable minimum lighting thresholds, the researchers anticipated that users would be unlikely to disable the daylight harvesting system. The successful application of a task ambient daylighting system could result in a savings to California ratepayers exceeding $50 million per year.

Figure 10: Photographs of Final Prototype Task Lamp (left) and Sensor Detail (right)



2.10.3 Objectives

The goal of this project was to determine the feasibility of using task plane-mounted illuminance sensors for controlling ambient luminaires in a daylight harvesting system. The researchers established the following project objectives:

1. Demonstrate that illuminance readings measured at the task plane are received by the ceiling receiver and are accurate within +/- 10 percent.
2. Demonstrate that the ambient luminaire can reliably and repeatedly pair with the task luminaire that is most impacted by changes in light levels provided by the ambient luminaire by initiating an auto-commission protocol on five occasions and confirming that appropriate pairing occurs at least four out of five times.
3. Demonstrate that ambient light levels automatically drop from their maximum light output setting to their minimum light output setting when external illumination at the work surface is increased from 0 fc to more than 250 fc (e.g., a simulation of daylight).
4. Demonstrate that ambient light levels return to their maximum output setting when the external illumination is removed.
5. Demonstrate energy efficiency of the prototype system by measuring a reduction in operating power of at least 70 percent when external illumination is increased from 0 fc to more than 250 fc.

2.10.4 Outcomes

1. The researchers placed a task lamp sensor module in a controlled environment next to a calibrated illuminance meter. They varied light levels across a range typical of commercial day-lit spaces. Initial measurements showed a difference of 5.0 percent between the prototype sensor and calibrated light sensor measurements. Once sensor calibration was added to the prototype software interface, the error fell below 1.0 percent.
2. The researchers performed ten tests where they placed two task lamps beneath two ceiling-mounted ambient luminaires that were separated by approximately one foot. For each test the commissioning algorithms were triggered to reset previous settings and pair with the closest ambient luminaire. The researchers then switched task lamp locations and repeated the test. In all cases both task lamps accurately paired with the closest ambient luminaire.
3. The researchers introduced an external 250 foot-candle light source to simulate daylight. The output power of the ambient luminaire immediately dropped from 40.5 W to 5.2W.
4. The researchers removed the external 250 foot-candle light source to simulate night. Consequently, the output power of the ambient luminaire immediately increased from 5.2W to 40.5 W.

5. The researchers used results from tests for Objective 3 and Objective 4 to calculate the resultant output power savings in a simulated daylight setting. Introduction of the light source resulted in a drop of ambient luminaire operating power from 40.5W to 5.2W, an 87 percent operating power savings.

2.10.5 Conclusions

1. The researchers met the goal to measure task plane illuminance within 10 percent, even during initial prototype testing. Improved prototype algorithms enabled the researchers to achieve accuracy within 1.0 percent, well in excess of the original objective.

2. The researchers met the goal to accurately pair task lamps with the closest ambient luminaire at least 4 out of 5 times. Resulting accuracy over the 10 tests, 20 successful pairings, was 100 percent.

3. The researchers met the goal to demonstrate a light drop with the introduction of external illumination. Ambient lighting accurately dropped from the maximum to the minimum output upon introduction of an external 250 foot-candle light source.

4. The researchers met the goal to demonstrate a light level increase when external illumination was removed. As a continuation of Objective 3, the researchers demonstrated that ambient light levels were restored when the external light source was removed.

5. The researchers met the goal to demonstrate a power savings of greater than 70 percent during the tests completed for Objective 3 and Objective 4. Measured output power savings was 87 percent.

The researchers were successful in demonstrating the feasibility of using task plane-mounted illuminance sensors for controlling ambient luminaires in a daylight harvesting system. This system offered two significant advantages over present daylight harvesting systems. First, because sensors were mounted at the task plane, illumination levels affecting ambient lighting were more relevant than those where sensors were mounted at the ceiling or other locations far removed from the work surface. Second, because users were able to specify minimum light levels, they were less likely to override or disable the system due to insufficient light output. The concept of measuring illumination and controlling daylight harvesting systems at the task plane are novel. However the researchers did not address the possibility of providing a portable system that could be affixed or retrofitted to an existing task lamp. This type of system would provide more flexibility and lower cost. Although the photo sensor and user controls were integrated into the prototype task lamp, the operation of the lamp itself appeared to be irrelevant to the daylight harvesting operations.

The most significant risk to this technology would be the possibility for the approach to be disqualified from Title 24 compliance. Daylight harvesting is one approach to fulfill mandates established by Title 24. Should the researchers not gain acceptance by the regulatory agency, it is unlikely that the technology will be adopted by the user community.

2.10.6 Recommendations

As a part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Pursue regulatory acceptance of this user-controllable system under Title 24.
2. Consider commercialization of a portable system suitable for use with any task lamp, rather than one integrated into a task lamp.
3. Complete larger scale testing in multi-system environments. Optimize the system to accurately auto-commission multiple sensor/controller pairs.
4. Perform long term tests to validate the assumed 40 percent energy savings using the proposed technology.
5. Perform a cost analysis.
6. Perform a detailed market analysis, identify commercial partners, and pursue commercialization.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.10.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research is increased affordability of electricity in California. The researchers calculated a cost and energy savings to California using traditional daylight harvesting systems as a baseline. Traditional daylight savings systems result in an energy savings of approximately 28 percent. Assuming a 50 percent market penetration for these systems, the savings to California using conventional daylight harvesting alone is 1.56 billion kWhr. The researchers anticipated that introduction of the proposed technology would cause market penetration to reduce to 40 percent for traditional systems but would be

supplemented by a 15 percent market penetration for the task ambient daylighting system. Energy savings of the task ambient daylighting system was assumed to be 40 percent because the system was less likely to be under-dim and less likely to be disabled by current users than traditional systems. The savings using the combined approach would be 2.00 billion kWhr, with a differential of 437 million kWh. This translates to $52 million in annual savings to California ratepayers over conventional daylight harvesting systems.

2.10.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have performed a market analysis and intend to license the technology through a lighting manufacturer which has not yet been identified. If the researchers are unable to secure a license agreement, they will pursue commercialization independently.

Engineering/Technical

The researchers plan to self-fund a limited demonstration of one to four systems, requiring approximately $10,000. A larger demonstration of 15 to 25 systems will require outside funds of approximately $50,000 to $75,000.

Legal/Contractual

The researchers have secured a patent for this technology.

Environmental, Safety, Risk Assessments/ Quality Plans

Environmental, safety, risk assessments, and quality plans have not yet been developed. The researchers do not anticipate negative effects with regard to public safety or the environment. Risks include the possibility that Title 24 may not recognize the proposed approach as valid.

Production Readiness/Commercialization

The researchers plan to conduct a small-scale demonstration and field tests of the prototype in a commercial office environment. Results of these tests will be used to seek commercial partners and pursue commercialization.

2.11 Development of a Low Leakage Retrofittable Outside Air Damper

Awardee: Davis Energy Group

Principal Investigator: David Springer

2.11.1 Abstract

The goal of this project was to determine the feasibility of developing a low leakage, low pressure drop outside air vent damper for use with residential cooling systems. This damper was developed for use with the fixed speed SmartVent and variable speed NightBreeze systems. Dampers currently used in the SmartVent system have been found to be easily damaged, require four feet of vertical clearance for installation, and exceed the 6.0 percent maximum duct leakage requirement at 25 Pa as recently codified in Title 24 standards. The researchers designed, prototyped, and tested a damper that would address each of these shortcomings and would be suitable for use in either the SmartVent or NightBreeze system. The prototype system demonstrated negligible pressure loss at 25 Pa and met or exceeded all other project objectives. The researchers anticipate that use of ventilation cooling systems could save a typical homeowner between 383 to 1,040 kWh per year. Application of the proposed damper would allow such systems to be Title 24 compliant. The damper is in the final stages of field testing and is ready for full-scale commercialization.

Keywords: Ventilation, cooling, HVAC, IAQ, economizer, whole house fan

2.11.2 Introduction

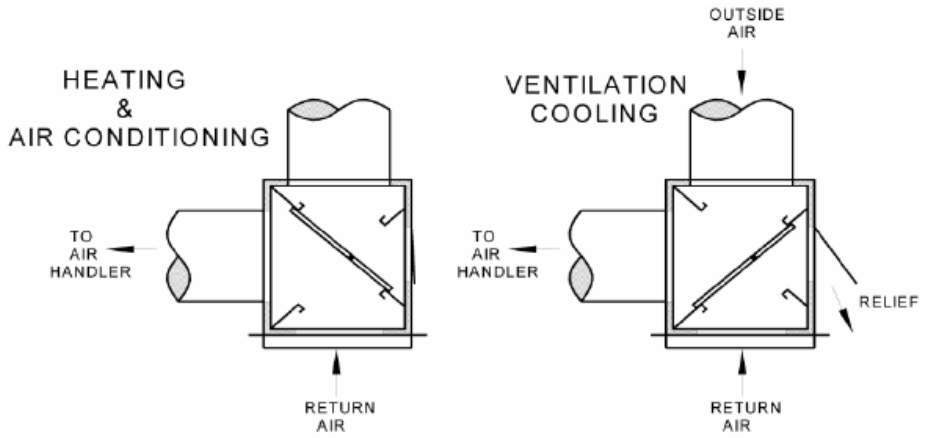
California Institute for Energy Efficiency (CIEE) initiated a project entitled Alternatives to Compressor Cooling in 1994 as a means to reduce peak energy loads caused by residential air cooling. One of the objectives of this program was to eliminate the peak load impact of air conditioned homes located in mild climates. CIEE researchers determined that high quality insulation and ventilation using cool night air could achieve this objective.

Ventilation cooling can be achieved through the use of manually operated whole house fans that typically use a dedicated ducting system or automated central fan systems that use the same ducting as the furnace or air conditioner. Manual systems rely on the homeowner to use judgment in determining the optimal time to run the system. They typically require that one or more windows be opened, posing a security risk. Automated systems do not rely on homeowner judgment or open windows and meet fresh air ventilation requirements prescribed by ASHRAE Standard 62.2. Two automated systems currently on the market include the fixed speed SmartVent and variable speed NightBreeze. Although these systems are currently in production, neither of them comply with recent modifications to Title 24 standards, which have focused on reducing leakage in ductwork to a maximum of 6.0 percent of the system fan flow at 25 Pa.

Dampers currently used in the SmartVent system have been found to be easily damaged, require four feet of vertical clearance for installation, and exceed the 6.0 percent maximum duct leakage requirement at 25 Pa as codified in Title 24 standards. The SmartVent damper actuator has been found to be easily damaged and prone to failure (Figure 11). The researchers in this project designed a unique damper that includes an actuator to operate two damper doors and accommodates a 4" standard sized filter, as shown in Figure 12. The researchers performance tested the prototype damper actuator over 10,000 cycles with no demonstrated degradation in performance. The SmartVent requires four feet of vertical clearance to accommodate duct attachment to the outside air opening located at the top of the damper. The proposed damper repositions the outside air duct to the side of the damper, resulting in a vertical clearance requirement coincident with the height of the damper. The researchers measured the SmartVent damper to have 4.7 percent of the 6.0 percent leakage permitted for the entire duct system under Title 24. The proposed duct measured no leakage at 25 Pa. Given the difficulty in complying with the new 6.0 percent leakage requirement, use of the proposed technology would permit a significant increase in the number of systems considered compliant with Title 24.

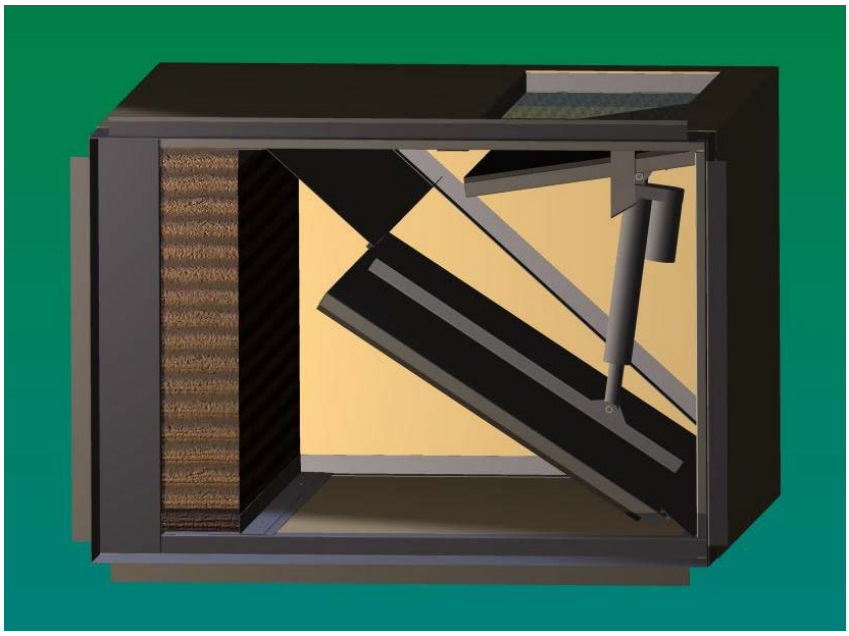
Use of the proposed technology would permit builders to comply with Title 24 requirements for energy efficiency and fresh air ventilation and to earn energy efficiency incentives to offset the cost. The researchers presented a number of studies that indicated the SmartVent and NightBreeze systems can save a typical homeowner 383 kWh/year and 1,040 kWh/year, respectively. The proposed technology would capture this savings while providing Title 24 compliance.

Figure 11: Diagram of the SmartVent Four-Way Damper



Outside air intake is located on the top of the unit.

Figure 12: Diagram Rendering of Final Damper Design Showing Actuator, Two Damper Doors, and Filter



This view is from the underside of the damper where the return air grill would be located. The connection to the furnace is on the left, the outside air intake on the lower side, and the relief opening to the attic on the upper side.

2.11.3 Objectives

The goal of this project was to determine the feasibility of developing a low leakage, low pressure drop outside air vent damper for use with residential cooling systems. The improved damper technology could serve to improve performance, reliability, and installability; facilitate

compliance with 2013 Title 24 standards; and reduce cost and improve cost effectiveness. The researchers established the following project objectives:

1. Measure resistance to airflow less than 0.9″ w.c. (22.5 Pa) at 1,200 cfm. (w.c.- water column).
2. Measure damper leakage equal to or less than 1.0 percent of rated airflow (12 cfm at 1,200 cfm rated airflow) with the damper pressurized to 25 Pa.
3. Verify reliability and durability of the damper, actuator, and linkage by operating it through 10,000 cycles and inspecting it for signs of failure or significant wear or performance degradation.
4. Assure that the actuator meets performance requirements and costs less than $100.
5. Design for a height no greater than 36″ from drywall stop to top of damper.
6. Design the damper to accommodate a 4″ wide 20x30 filter.
7. Demonstrate assembled cost of $450 or less in high volume production.
8. Determine the relationship between air flow and fan energy use for the redesigned damper with 4″ filter and a typical furnace for use in California energy compliance models.

2.11.4 Outcomes

1. The researchers attached a duct blaster to the damper using the outside air position and using the return air position with the secondary return blocked. The duct blaster airflow was set to 1,200 cfm. They measured airflow and pressure from the return side of the damper. Measured resistance to airflow was 39 Pa with the damper in return air position and the secondary return duct sealed, and it was 18.7 Pa with the damper in return air position and the secondary return duct opened.
2. The researchers attached the duct blaster to the damper in the return air position with the secondary return air opening and furnace connection sealed. They measured pressure and airflow with the damper pressurized to 25, 50, and 100 Pa. Leakage was not detected at 25 Pa, and it measured 9 cfm and 10 cfm under 50 Pa and 100 Pa pressure, respectively.
3. The researchers cycled the damper open and closed over 10,000 times during a 72-hour period. They collected data to monitor number of cycles and motor temperature. Upon completion of the testing period, the cycle time remained unchanged, and there were no visible signs of wear on the nylon bushings connecting the actuator to the damper door.
4. The manufacturer of the prototype actuator quoted a cost of $60 per unit for quantities of 100.
5. The researchers configured the proposed damper with the outside air duct on the side of the damper, rather than on top, as done in the SmartVent damper. Thus there was no

additional vertical clearance requirement to accommodate connecting ductwork so that clearance requirements were dictated by the height of the damper box. The height of the box, including insulation, was 35″.

6. The researchers designed the initial prototype to accommodate a 4″ wide 20″ x 30″ standard-sized filter to reduce pressure loss and increase the time required between filter replacements.

7. Martin Metal Fabrication developed the prototype. It was selected for its ability to do precision custom work, rather than production work. Cost estimates submitted by Martin Metal Fabrication were $375 for quantities of 100 and $325 for quantities of 250. Including actuator, labor, and assembly costs, the total cost was $485 for quantities of 250.

8. The researchers depicted measured fan power as a function of maximum airflow and fractional fan power as a function of airflow fraction in graphical format. They then derived equations to fit the data.

2.11.5 Conclusions

1. The researchers met the goal to measure resistance to airflow less than 22.5 Pa with the secondary return duct open. Although the objective was not met with the secondary duct closed, it would be more representative of a typical system to have a secondary return. The 1,200 cfm airflow corresponded to a 3.0 to 3.5 ton air conditioner that would serve a 3,000 to 3,500 square foot home with a secondary return in the master bedroom. Smaller houses would have smaller units, lower airflow, and correspondingly smaller pressure loss.

2. The researchers met the goal to measure leakage equal to or less than 12 cfm with the damper pressurized to 25 Pa.

3. The researchers met the goal to demonstrate damper durability.

4. The researchers met the goal to identify an actuator meeting performance requirements for under $100.

5. The researchers met the goal to design for a required vertical clearance less than 36″.

6. The researchers met the goal to accommodate 4″ wide filters.

7. The researchers did not meet the goal to demonstrate an assembled cost of $450 or less in high volume production. Cost estimates obtained from a specialty manufacturer are likely larger than a production level manufacturer. While it is likely that a production level manufacturer could meet the cost goal, this was not demonstrated.

8. The researchers met the goal to define a mathematical relationship between airflow and fan energy use.

2.11.6 Recommendations

The researchers met or exceeded nearly all of the project objectives. The study successfully demonstrated that the proposed technology could improve damper performance and reliability and facilitate compliance with Title 24 requirements. The researchers are currently field testing the prototype and pursuing commercialization partners. As a part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Complete field testing during peak summer usage.
2. Obtain cost estimates from production level manufacturers for large volume orders.
3. Prototype and test the complete system with a wireless controller.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.11.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from this research project is increased affordability of electricity in California. The researchers presented a number of studies that indicated the SmartVent and NightBreeze systems could save a typical homeowner 383 kWh/year and 1,040 kWh/year, respectively. The researchers anticipate the total cost for the NightBreeze system, including the proposed technology and controller, would be approximately $650. Assuming a typical energy cost of $0.12/kWh, the payback period would be approximately 5.2 years without incentives. The researchers acknowledged that this energy savings was readily available with the existing SmartVent and NightBreeze systems. However, the excessive leakage of existing dampers inhibit current Title 24 compliance. Use of the proposed technology would permit builders to comply with Title 24 requirements for energy efficiency and fresh air ventilation and to earn energy efficiency incentives to offset the cost.

2.11.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have surveyed potential customers and performed a market analysis with the aid of the Wacari Group. Recent regulatory changes setting a maximum permitted system leakage for Title 24 compliance favors the proposed technology. The primary market includes new and existing residential buildings.

Engineering/Technical

There are no obstacles to demonstrating the proposed damper. However the damper is part of a system which includes controls that require further development. The researchers anticipate that an additional $250,000 will be required for control development and documentation.

Legal/Contractual

The researchers have secured patents US #7,398,821 and #7,992,630 for the NightBreeze system. An application for the proposed damper has been submitted under #13,081,019.

Environmental, Safety, Risk Assessments/ Quality Plans

Environmental, safety, risk assessments, and quality plans have not yet been developed. The researchers do not anticipate negative effects with regard to public safety or the environment.

Production Readiness/Commercialization

The researchers have developed a commercialization plan and are pursuing a commercialization partner.

2.12 Adaptive Power Flow Controls for Distribution Circuits with Renewables

Awardee: California State University, Long Beach

Principal Investigator: Hen-Geul Yeh

2.12.1 Abstract

More robust integration schemes are needed for grid stability given the accelerated installation of renewable resources with random output fluctuations into the grid. Renewable generators, such as photovoltaics, inject real power into the system, creating varying phase angles between real and reactive power. This variability can cause power system problems such as the loss of voltage and frequency control. This project evaluated the possibility of a new adaptive control approach for distribution circuits with high levels of renewable energy generators.

The researchers designed and simulated an adaptive VAR control strategy for radial distribution circuits with PV solar energy. They designed for two operational modes: power loss minimization mode (P_Mode) and voltage variation minimization mode (V_Mode). They conducted simulations with defined parameters in a hypothetical radial distribution circuit. The researchers simulated peak power savings of about 10 percent and a maximum voltage variation smaller than 1.2 percent, but not simultaneously. In their modeling, the researchers controlled either power or voltage at one time. Simulated results were robust even with high penetration levels (i.e., 80 percent) of PV cells.

Keywords: Adaptive VAR control, power loss minimization, voltage variation minimization

2.12.2 Introduction

Expanded development of renewable energy remains a high priority focus of California's energy and environmental policies, and photovoltaic installations are a significant contributer to meeting those policies.Integration of renewable resources into the power grid can take place at either the transmission or distribution system. The intermittency and rapid fluctuation of renewable power output require the design of advanced volt-ampere reactive[22] (VAR) control schemes. Given the expanding installation of renewable resources, rapid (seconds to minutes timescale) and random fluctuations of renewable generators with uncontrolled VAR fluctuations create problems such as loss of proper voltage regulation and loss of power quality.

Improved integration of volatile renewable generation is an active research and development area, including using dc-to-ac inverters for voltage and VAR control. Some schemes use fast switching of capacitor banks. Some schemes use smart meter data as the basis for decision-making. In general there are centralized control, distributed control, and mixed methods. Likely to include some of each, the exact future mix of distributed versus centralized control will depend upon the as yet unknown growth of central station solar compared to residential and small commercial solar. Consequently, both transmission level and distribution level control schemes are necessary to enable increased grid connection of photovoltaics and other intermittent and volatile resources while maintaining reliability and power quality. None of the schemes have progressed beyond pilot demonstration, and there is the potential that generation installations may outpace the ability to reliably control the transmission and distribution grid.

In this project the research team developed an adaptive VAR control strategy for distribution circuits with significant connected photovoltaic capacity. The strategy included a two-way switch to minimize power loss or minimize voltage variation. The project was limited to mathematical modeling and simulation.

2.12.3 Objectives

The primary objective of this investigation was to perform a feasibility study by designing and developing an adaptive control scheme for distribution circuits with renewable energy generators, such as PV cells. The researchers established the following objectives:

1. Conduct a current literature search in the VAR control area and develop a mathematical model for the power loss and voltage regulation as the baseline reference.
2. Verify the performance of the adaptive scheme via simulations on a radial distribution circuit by switching between power loss minimization mode (P_Mode) and voltage variation minimization mode (V_Mode) via the adaptive control loop. The voltage variation at each node should be within plus or minus 5.0 percent of nominal regardless in P_Mode or V_Mode.

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22 In electric power transmission and distribution, volt-ampere reactive (VAR) is a unit in which reactive power is expressed in an AC electric power system. Reactive power exists in an AC circuit when the current and voltage are not in phase. This leads to power loss, energy loss, and can affect frequency.

3. Verify the performance of this adaptive scheme via simulations on radial distribution circuit in different PV penetration levels, from 20 percent to 80 percent, and still minimize voltage variation and power loss.

4. Demonstrate that the adaptive VAR control in a high penetration of PV can save at least one percentage point of total energy consumption on the feeder line and reduce the voltage variation of the load by one percentage point simultaneously, compared to the baseline model.

2.12.4 Outcomes

1. The research team developed a VAR control strategy for radial distribution circuits, with two modes of operation: power loss minimization mode (P_Mode) or voltage variation minimization mode (V_Mode). The team formulated the strategy using nonlinear optimization. They neglected the non-linear branch losses and derived a set of simplified power flow equations. They compared the electric power loss with and without the non-linear terms and calculated that the power loss difference is about 2.0 percent at low penetration levels and 1.6 percent at high penetration of variable generation output levels.

2. The researchers evaluated the performance of this scheme via simulations on radial distribution circuits at PV penetration of 20 percent to 80 percent.

3. The researchers compared the scheme's performance with the baseline case and found that the peak power savings was about 10 percent and the maximum voltage variation was less than 1.2 percent of nominal values in both P_Mode and V_Mode, even in high penetration levels (i.e., 80 percent) of PV cells.

4. The researchers modeled energy saving of 2.0 percent to 12 percent for PV penetration levels from 20 to 80 percent in the P_mode operation. Similarly, the voltage variation ranged from 1.8 percent to 1.0 percent for PV penetration levels from 20 to 80 percent in the V_mode operation.

2.12.5 Conclusions

1. The researchers developed a mathematical model, relying on existing literature and modeling, of a control scheme using a two-way switch to manage power and voltage output from randomly behaving electric generators. This two-way switch could be employed to satisfy either the P Mode or V_Mode requirements in a control loop. The researchers completed this objective.

2. In simulated operation, the adaptive VAR control strategy worked to maintain voltage variation within plus or minus 5.0 percent of nominal values regardless of whether it was in P_Mode or V_Mode. Simultaneously minimizing power and voltage variation was not tested. The researchers partly completed this objective.

3. The researchers estimated the hardware to implement the technology to be minimal, but this needs to be verified by hardware testing and prototype design. The researchers completed this objective.

4. In simulated operations, the researchers calculated that the adaptive scheme could save at least one percentage point of total energy consumption on the feeder line and reduce the voltage variation of the load by one percentage point simultaneously in a high PV penetration level, but this should be verified by physical testing. The researchers completed this objective.

The researchers mathematically demonstrated the theoretical possibility of developing an adaptive VAR control scheme for distribution circuits with renewable energy generators. They have not yet demonstrated technical feasibility or practicality.

2.12.6 Recommendations

The Program Administrator recommends the following actions:

1. The researchers should physically test the control scheme under a variety of random and non-random (partially correlated) variability of multiple generators' output. The first test should be performed at laboratory size, and later tests should move to full scale, representing a distribution feeder. This should include consideration of loads (demand) variability under conditions that affect generator output variability, such as transient cloud cover and HVAC compressor start and stops, especially as they affect VARs.

2. The researchers should evaluate simultaneous minimization of power and voltage excursions, recognizing that such may result in Pareto optimums and determine boundaries for full switching to P_Mode or V_Mode.

3. The researchers should design and develop the hardware and sensor package to implement the mathematical models.

4. The researchers should evaluate system performance on primary distribution level, as residential PV systems are generally installed at utilization voltage, and on interconnected distribution networks to complement the work done here on radial lines.

5. The researchers should evaluate the potential for feedback loops or harmonic electric oscillation between output, loads, and control scheme.

6. The researchers, upon completing Recommendation 2, should begin cost estimation and life cycle analysis. This should include determining capability of off-the-shelf components or the necessity of new or novel components.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.12.7 Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit of this research is increased reliability of the California electricity system. As increasing levels of intermittent and volatile generation are attached to the grid at the distribution or the transmission level, increasing challenges are put on grid operators to maintain grid reliability. This concept may help grid operators to maintain harmony on the grid, but estimating quantitative benefits is highly speculative given its current development status. The concept may significantly help California achieve its policy goal of 33 percent of electricity use from renewables, which should provide reduction of greenhouse gas emissions. As such, this concept may represent an enabling technology.

2.12.8 Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

Until the concept develops beyond the mathematical simulation stage, marketing efforts remain premature. Once more fully developed, close coordination with distribution companies and interconnection equipment manufacturers will be necessary. The researchers have not completed any market assessments.

Engineering/Technical

The researchers estimate that they can complete product development and demonstration in two to three years with additional funding of $300,000.

Legal/Contractual

The researchers have not applied for nor obtained any patents. Given the stage of development, performing a patent search would be premature. The researchers do not plan to place the intellectual property into public domain.

Environmental, Safety, Risk Assessments/ Quality Plans

There are no anticipated environmental concerns. Safety and quality plans will need to account for random generator outputs beyond those simulated thus far.

Production Readiness/Commercialization

The concept is not ready for production or commercialization.

2.13G Laser Sensors for Gas Pipeline Explosion Protection

Awardee: Physical Sciences, Inc.

Principal Investigator: Michael B. Frish

2.13.1G Abstract

A catastrophic 2010 natural gas pipeline explosion in San Bruno sparked a need for greater scrutiny regarding inspection and safety requirements for natural gas pipelines. The California Public Utilities Commission (CPUC) subsequently launched a pipeline safety rulemaking proceeding to adopt new safety and reliability regulations for natural gas pipelines, in part based on lessons learned from the San Bruno event.

The goal of this project was to determine the feasibility of deploying permanent laser-based, open path natural gas sensors which can rapidly warn of potentially explosive pipeline leaks as well as detect and report relatively small and non-urgent leaks. Researchers decided to reconfigure an existing handheld Remote Methane Leak Detector (RMLD™) commercial product to test the viability of a permanent laser-based, open path natural gas sensor. The objective was to monitor continuously natural gas pipeline rights-of-way and provide rapid early warning of abnormal gas concentrations which could indicate a leak. Consequently appropriate action to mitigate the potential for a catastrophic pipeline failure could be taken. Test results from this project indicated that the system was responsive, reliable, and practical. The device was also found to be useful for detecting smaller, non-urgent, or intermittent pipeline leaks.

The research team addressed technical requirements for converting the RMLD™ from a handheld leak survey tool into a permanently installed wireless, solar-powered instrument. The team conducted a series of experiments at a PG&E training facility where it created leaks to demonstrate efficacy of the device. A single test unit was easy to install and was able to sense methane along laser paths as long as 580 feet. Laser aiming from a transceiver unit to a passive target at the distal end of the measurement path was stable and required no maintenance during the six month test period. Leak challenges originating at distances up to 70 feet upwind of the laser path demonstrated detection of gas flows as small as 0.5 standard cubic feet per hour (scfh). Real time e-mail leakage alerts were transmitted within one minute of detection.

The positive results of this project provide a foundation for further development work that could lead to commercialization and full deployment by the natural gas industry.

Keywords: Pipeline safety, leak detection, laser sensing, RMLD, natural gas, open path

2.13.2G Introduction

On September 9, 2010, Pacific Gas & Electric's (PG&E) transmission Line 132 in San Bruno suffered a catastrophic failure, resulting in an explosion and fire that killed 8 people, injured 58 others, destroyed 38 houses, and damaged 70 other buildings. This tragic event shed light on the need for greater scrutiny in terms of inspection and safety requirements for natural gas pipelines. The California Public Utilities Commission (CPUC) subsequently launched a pipeline safety rulemaking proceeding to adopt new safety and reliability regulations for natural gas pipelines, in part based on lessons learned from the San Bruno incident. As part of the proceeding, the CPUC ordered the State's four natural gas transmission pipeline operators - Pacific Gas & Electric (PG&E), Southwest Gas, San Diego Gas & Electric (SDG&E), and Southern California Gas Company - to develop plans of pressure testing or replacing all natural gas transmission pipelines which have not yet been tested for compliance with modern safety standards.

The goal of this project was to determine the feasibility of deploying permanent laser-based, open path natural gas sensors to warn rapidly of potentially explosive pipeline leaks, as well as to detect and report relatively small and non-urgent leaks. This project supports an important research goal established by the California Energy Commission (CEC): "The State needs public interest energy research to explore opportunities and apply new and emerging technologies that provide innovative options for natural gas pipeline integrity, operations, and safety."[23] The San Bruno gas pipeline failure highlighted a need for continuous monitoring of natural gas concentrations along transmission pipeline rights-of-way, especially in High Consequence Areas (HCA) or specific areas where a release could have the most significant adverse consequences. Continuous monitoring can provide early warning of abnormal gas concentrations which might indicate a leak and set into motion appropriate action to mitigate a potentially catastrophic pipeline failure. Early warning provides utilities and pipeline operators an opportunity to remedy leaks quickly by automatically shutting off the gas supply (for pipelines equipped with automated shut-off valves) or immediately dispatching crews to the impact zone.

The current pipeline leak inspection industry practice is accomplished by scheduling periodic walking, driving, and/or aerial surveys along pipeline routes. Occasional surveys, however, cannot rapidly detect small intermittent pipeline leaks or failures which could lead to a potentially dangerous, explosive situation. An effective and practical continuous monitoring device must be field-worthy, automated, autonomous, rugged, reliable, fast, and able to distinguish natural gas from other ambient gases. Continuous monitoring of the natural gas content above and around the pipeline is needed over a pre-established period of time and space to detect and mitigate a hazardous condition. Continuous gas measurement requires that the device either sample at many closely spaced intervals or interrogate along continuous lines-of-sight along and around the pipeline. According to researchers, there is no proven sensing system in the market today that meets these requirements.

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23 California Energy Commission (CEC), "2011 Integrated Energy Policy Report (IEPR)", CEC-100-2011-001-CMF, page 175.

The initial goal of this project was to determine the feasibility of deploying permanent laser-based, open path natural gas sensors which could rapidly warn of potentially explosive pipeline leaks. Subsequently the project was expanded to include detection and real-time notification of small and intermittent leaks. The researchers selected a technology based on the Remote Methane Leak Detector (RMLD™), a well-established commercial laser-based handheld pipeline leak survey product developed by Physical Sciences[24] and commercialized by Heath Consultants.[25] The team first converted a RMLD™ unit from a handheld leak survey tool into a permanently installed continuous pipeline monitoring and alarm reporting tool, otherwise referred to as a RMLD™ Pipeline Monitor (RMLD™-pm). The research team that included Pacific Gas & Electric (PG&E) engineers evaluated the technology by installing and operating a RMLD™-pm device at the PG&E training facility in Livermore, California. The researchers intentionally created leaks to demonstrate sensor efficacy, evaluate sensor response to leaks in typical operating scenarios and weather conditions, and verify sensor freedom from false alarms including detection of other ambient gases.

Open path sensor architecture enabled a laser light beam to emanate from the RMLD™-pm and illuminate a remote surface. The RMLD™ unit detected light reflected back from the illuminated surface and was able to deduce the amount of methane in the path the beam traversed. In routine use, the handheld RMLD™ detects pipeline leak rates as small as 2.0 standard cubic feet per hour (scfh), corresponding to less than one-tenth the leak rate expected from a sub-millimeter hole in a high pressure gas pipeline. In this project the RMLD™-pm detected leaks as small as 0.5 scfh, comparable to the gas flow rate of a pilot light.

The remote illuminated surface can be located as far as 1,000 feet from the laser source. Figure 13 illustrates how the monitoring process works. The eye-safe laser beams traverse across and above a pipeline, seeking the presence of gas plumes. When the laser beam detects a potentially dangerous gas leak, the system transmits an alert to the pipeline operator who can either dispatch a crew to the scene and/or send a signal to automatically shut off valves in the impacted area. For smaller non-emergency leaks, the system transmits an hourly signal to the pipeline operator for monitoring purposes. Repetitive small leak alerts indicate a need for further operator investigation and/or repair. The research team believed that sensor units could be spaced at 500 feet to 1,000 feet pipeline intervals, or approximately five to ten units per mile. The sensors are able to ignore temporary disruptions due to passing vehicles and are insensitive to vehicle emissions.

The positive results of this project provide a foundation for a subsequent evaluation of an experimental laser-based leak protection network. The research team recommended installation and demonstration of a small network along a one mile length of an operating gas transmission pipeline. Once installed, the system could transmit leak data to a pipeline monitoring and control facility. Successful demonstration of this technology in a live pipeline environment could eventually result in full deployment along pipelines located in High Consequence Areas.

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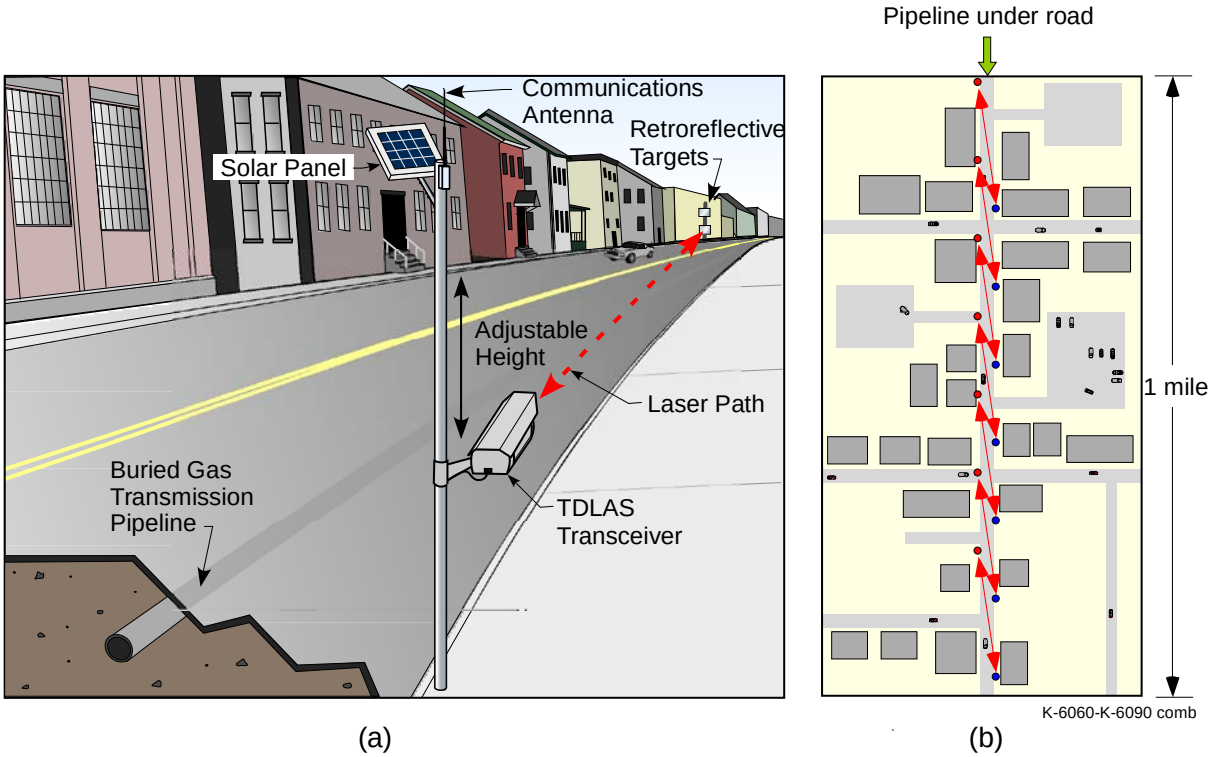
24 http://www.psicorp.com/

25 http://www.heathus.com/_hc/index.cfm

This innovative pipeline protection network, once fully developed and tested, could benefit natural gas customers in California and elsewhere by enhancing early detection of pipeline leaks, improving overall pipeline safety, and reducing the potential of catastrophic events. The network could also help to identify more quickly smaller, fugitive leaks which would reduce greenhouse gas emissions and the overall cost of gas supplies.

Figure 13: (a) Example Installation of Open Path Pipeline Leak Monitor; (b) Bird's Eye View of Network Protecting Extended Length of Pipeline



Red arrows illustrate laser beam paths

2.13.3G Objectives

The goal of this project was to determine the feasibility of deploying permanent laser-based, open path natural gas sensors to warn rapidly of potentially explosive pipeline leaks, as well as to detect and report relatively small and non-urgent leaks. The researchers established the following project objectives:

1. Define test site characteristics and requirements, installation procedures, test duration, controlled leak challenges, weather conditions, and local support needed.
2. Provide an RMLD™-pm unit offering simple installation and optical alignment.
3. Demonstrate an open path laser path length exceeding 500 feet without adjustment for the test period duration (greater than three months).

4. Verify continuous sensor operation under all weather conditions.
5. Demonstrate sensor self-health monitoring and alarm readiness. Observe performance in a realistic operational scenario that includes human and vehicle activity. Report loss of signal due to laser beam blockage or other causes.
6. Demonstrate and evaluate sensor response to challenges by urgent and non-urgent leaks. Verify 100 percent probability of alarm within one minute of detecting urgent leaks. Demonstrate that sensor does not produce false alarms.
7. Evaluate sensitivity to small, non-urgent leaks.
8. Evaluate and explain any deviations from performance expectations.

2.13.4G Outcomes

1. The researchers completed the test plan.
2. The researchers designed, assembled, and installed the RMLD™-pm at the PG&E training facility in Livermore, California. This facility is configured with a set of underground pipelines that, when activated, purposefully leak natural gas at known rates for training leak detection crews.
3. Researchers successfully demonstrated a laser beam path of 580 feet showing continuous operation with no maintenance for the three month demonstration period.
4. The sensor demonstrated proper operation during all weather conditions, including the presence of rain and fog. Extreme heat caused two temporary outages while the unit transitioned to self-protection mode. Solar blinding caused short-lived interruptions near vernal equinox sunsets.
5. Warnings of improper operation due to self-protection shutdown, solar blinding, laser beam obstruction, and interrupted communications were properly reported to the user/operator. Human activity, including people and vehicles blocking the laser beam path, generally interrupted measurement only in the portion of the path beyond the blockage point.
6. The researchers conducted numerous leak detection challenges. Early challenges provided additional data to help optimize automatic leak detection algorithms. Subsequent challenges demonstrated response to leaks and automatic operator notification via e-mail alerts. Leaks originating from upwind or beneath the laser path were detected reliably. Big leaks, defined as those causing the measured path-integrated concentration to exceed a pre-set threshold (generally 300 parts per million of methane gas per meter) for 30 seconds, activated immediate e-mail alerts. Small non-urgent leaks, detected via a statistical analysis algorithm, activated e-mail alerts which were transmitted hourly. There were no known false alarms. There was one significant hour-long methane excursion of unknown origin. System operating data indicated that this was not considered to be a false methane detection.

7. Data results showed an ability to detect leaks as small as 0.5 scfh, comparable to a pilot light, when originating beneath the laser path and about 5.0 scfh when originating as far as 70 feet upwind of the laser beam path.
8. Deviations from expected performance (e.g. overheating, solar blinding) were understood and explained. Corrective action was either implemented or recommended for future implementation.

2.13.5G Conclusions

1. The test plan and location were suitable for this project.
2. The RMLD™-pm unit was relatively easy to install and maintain.
3. The open path laser path length appeared to be very reliable, requiring no adjustment for the test period.
4. The proposed technology appeared to work well with continuous sensor operation in most weather conditions, with the exception of extremely hot temperatures and temporary solar blinding conditions.
5. The continuous monitoring device demonstrated steady, consistent performance and operation.
6. The technology was able to satisfactorily detect large and small methane leaks.
7. Sensor equipment was also able to detect extremely small leaks.
8. The prototype systems demonstrated steady, consistent performance and operation. Installation costs could be higher initially, since installers will not be familiar with this new product and may need specialized training. Performance deviations were satisfactorily corrected and/or mitigated.

This project proved feasibility of deploying laser-based sensors to detect leaks in gas transmission pipes. The researchers demonstrated the RMLD™-pm was sensitive, responsive, reliable, and had the potential to be cost effective and practical. It technically could fulfill the functions of rapid sensing and reporting of sudden and potentially explosive natural gas pipeline leaks, as well as detecting and reporting non-urgent small leaks. Pipeline operators will need a better understanding of how this technology can be successfully integrated with conventional pipeline monitoring and control systems prior to system-wide deployment. This technology will need to be further evaluated in actual operating scenarios to validate performance metrics and ensure that the concept is cost effective compared with other methane detection systems.

2.13.6G Recommendations

Further work is needed to determine how the sensor system will respond to massive leaks and to better understand how plume dynamics could lead to an explosive situation. The Program Administrator recommends that the researchers:

- Evaluate and quantify sensor detection performance in real-world operations. Selected sites should represent critical installations that might include gathering fields (especially around wellheads), compressor stations, municipal environments, High Consequence Areas, and pipelines near geological faults. Performance assessment should include detection, reporting, and interfaces with pipeline operators or Computational Pipeline Monitoring systems.
- Determine how to network multiple lasers and reflectors so issues related to obstruction are minimized or eliminated.
- Determine how this technology could be used for non-urgent leak detection applications.
- Test the proposed concept in several application scenarios and configurations (e.g., higher above ground to limit obstructions and vandalism) and integrated with pipeline operations and controls. A commercial product needs to be configured/developed that incorporates user interface functions now installed on a laptop computer into the RMLD™ controller. A commercial product will need to incorporate an intuitive user interface, hybrid packaging separating the optical subsystem from the control electronics, optics that can accommodate path lengths up to 2,500 feet, and a plan to reduce manufacturing costs.
- Conduct a more rigorous cost analysis and business/marketing plan to verify the market potential for this product and ensure that it compares favorably with other devices in the market.
- Lower the initial cost compared to other options under consideration by the natural gas industry.
- Conduct product optimization and field testing to validate the performance and reliability of the technology in a real-world working environment.
- Test the integrity of the system to ensure that it meets standard industry safety and permitting requirements.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.13.7G Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California energy supply and distribution system
- Increased public safety of the California energy system
- Increased reliability of the California energy system
- Increased affordability of energy in California

The primary benefit to the ratepayer from this research is increased public safety of the California energy system. This project supports an important research goal established by the California Energy Commission (CEC): "The State needs public interest energy research to explore opportunities and apply new and emerging technologies that provide innovative options for natural gas pipeline integrity, operations, and safety."[26] The San Bruno gas pipeline failure highlighted a need for continuous monitoring of natural gas concentrations along transmission pipeline rights-of-way, especially in areas of High Consequence Areas (HCA), or specific areas where a release could have significant adverse consequences.

The current pipeline leak inspection industry practice is accomplished by scheduling periodic walking, driving and/or aerial surveys. Occasional surveys are not able to rapidly detect small intermittent pipeline leaks or failures which could potentially result in a very dangerous, explosive condition. There is currently no proven sensing system that meets these requirements. The proposed system could provide continuous pipeline monitoring for potential leaks, enabling early warning of abnormal gas concentrations which could indicate a leak as a precursor to a catastrophic pipeline, valve, or storage vessel containment failure. Early warning could provide utilities and pipeline operators an opportunity to mitigate leaks quickly and expeditiously. Continuous monitoring capability could also detect sudden and potentially explosive increases in gas concentration which could either activate alarms and automatically shut off gas supply to the impacted area (for pipelines equipped with automated shut-off valves) or dispatch crews to manually shut off valves.

Full deployment of the proposed pipeline protection network could benefit natural gas customers in California by enabling earlier detection of pipeline leaks that could help mitigate the risk of catastrophic pipeline failure. Unaccounted gas leakage in California over 12 years (from 2000 to 2011) represented on average about 8.7 billion cubic feet per year, equivalent to about $44 million, assuming a market price of $5.00 per million British Thermal Units (BTU). This assumes that California's pipeline leakage rate is similar to the national average and that all unaccounted for gas is attributed specifically to gas leaks instead of accounting or metering errors. Continuous leak detector networks, when located judiciously, could help identify sources of intermittent natural gas leaks, resulting in reduced pipeline system leakage rates and increased system safety.

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26 California Energy Commission (CEC), "2011 Integrated Energy Policy Report (IEPR)", CEC-100-2011-001-CMF, page 175.

2.13.8G Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The research team is well positioned to complete development and pursue commercialization of this technology. The team includes both the product developer Physical Sciences, Inc. and commercialization partner Heath Consultants, Inc. Heath Consultants is the world leader in providing products and services for natural gas leak detection. The research team is also working with the natural gas supply industry to help define applications for further product demonstration.

Engineering/Technical

This project successfully demonstrated a prototype. There are no known engineering obstacles preventing further demonstration and/or commercialization. The research team plans to demonstrate the technology in a simulated real-world environment, develop engineering requirements/product specifications, and improve product packaging prior to commercial launch.

Legal/Contractual

The research team filed one new patent application for this new technology and is using existing United States patent 7,075,653. The researchers conducted a patent search and found no conflicts with existing patents.

Environmental, Safety, Risk Assessments/ Quality Plans

There is no obvious safety or environmental risk associated with the system design.

Production Readiness/Commercialization

The concept is not yet sufficiently developed for commercialization.

2.14G Investigation of a New Process for SNG Production Using Steam Hydrogasification

Awardee: University of California, Riverside

Principal Investigator: Chan Seung Park

2.14.1G Abstract

The research in this project involved the development of a unique steam hydrogasification process for conversion of organic waste to methane. In this project, a laboratory-scale steam hydrogasification reactor (SHR) was combined with a water gas shift (WGS) process using high temperature, high pressure, and a catalyst to improve conversion of organic carbon to the end product methane.

The two processes were integrated and tested at laboratory scale using a combined organic waste feedstock including municipal green waste and sewage biosolids. In these experiments milled pine wood and sewage biosolids were combined as feedstock with a moisture content of 63 percent. Reducing the feedstock water content improves processing efficiency and product gas yield and reduces the projected capital and operating costs for the combined process.

Researchers demonstrated successful operation of the combined SHR/WGS laboratory-scale system with the high solids combined feedstock demonstrating a 64 percent higher heating value yield and 80 percent methane content in the product gas. The laboratory-scale process was operated at a 1.0 pound/hour throughput.

Economic scale-up simulation estimates for a 400 TPD plant suggested a production cost of $5 — $6.5 MMBTU for the product gas. At scale, the researchers estimated the combined process produced 17 MMBTU/ton of organic waste. In large-scale system simulations, the estimated ROI was 8 percent.

While the researchers successfully tested the combined SHR/WGS process at laboratory scale, additional issues warrant research prior to full-scale application. Of particular importance is the optimization of equipment configurations and process operating conditions relative to the production of ash and tar produced in the process.

Keywords: Steam hydrogasification, water gas shift, methane, organic waste

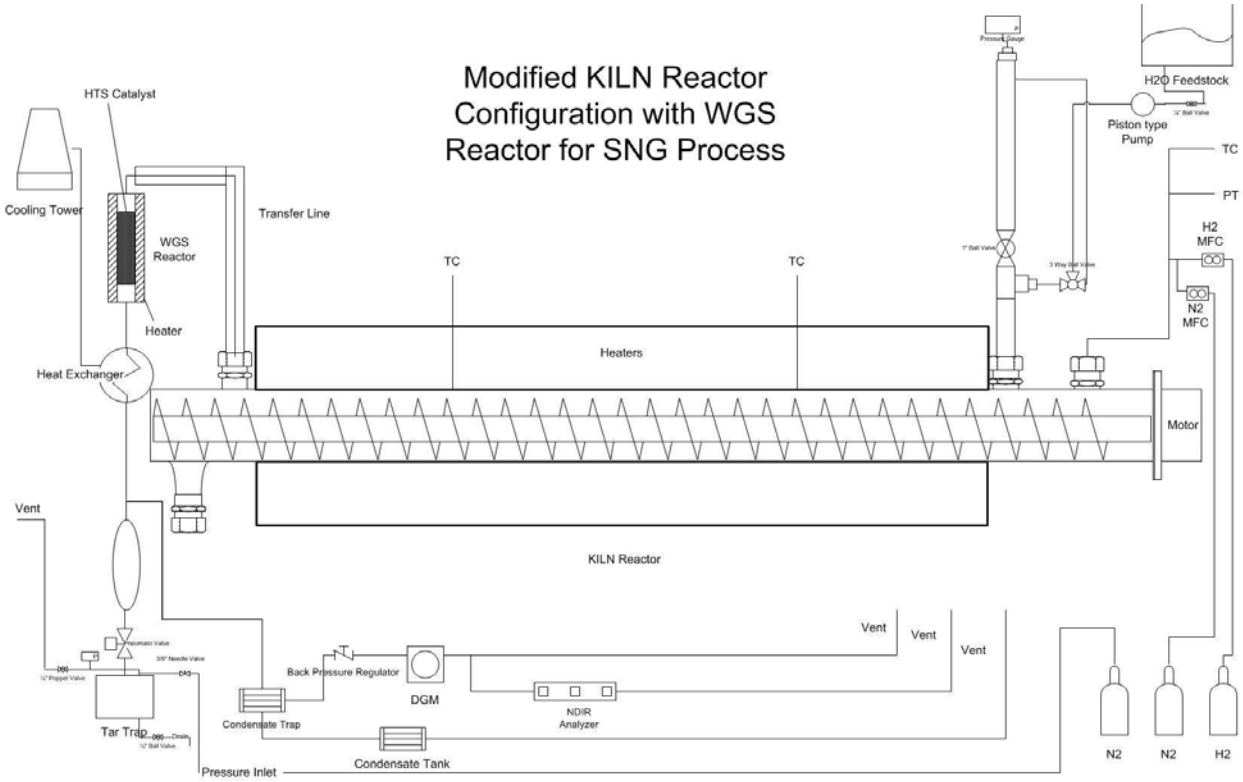
2.14.2G Introduction

The technology developed by the researchers in this project was to combine a steam hydrogasification reactor with a water gas shift process to enhance the conversion of a biomass waste feedstock to high quality fuel gas. The combined technology has the potential to produce a high quality fuel gas product which could be used in conventional electricity generating systems including fuel cells and boilers, or compressed as a transportation fuel. Converting organic wastes reduces disposal costs for both municipal separated organic wastes and sewage biosolids, while reducing the impact of these wastes on the environment. The benefits of commercialization and implementation of this technology would be to reduce disposal costs for these organic wastes while providing a source of fuel gas produced in California, thereby reducing the need for import of fuel.

The proposed advancement in the combination of the SHR/WGS process is enhanced quality of the product gas, thereby reducing the costs for upgrading a lower quality product gas for ultimate market use.

The combined SHR/WGS process was designed to handle high solids organic feedstock, another important aspect of the technology since it reduces the size of the system necessary to treat a given amount of organic waste. The schematic of the combined process is shown in Figure 14.

Figure 14: Schematic of Process



2.14.3G Objectives

The goal of this project was to determine the feasibility of establishing a combined process steam hydrogasification reactor with a water gas shift process to enhance the quality of the fuel gas produced from a high solids organic waste feedstock. The researchers used a combined municipal waste organic fraction and sewage biosolids with a moisture content of 63 percent.

The researchers established the following project objectives:

1. Estimate the RNG (renewable natural gas) production cost: target value $5.5/ MMBTU.
2. Estimate the plant economic parameters with the target value of 8 percent return on investment (ROI) at minimum 200 ton per day (TPD) plant size.
3. Attain the pumpability of the feedstock with target viscosity of 1.0 Pascal-second at a moisture level of 63 percent.
4. Achieve the process higher heating value (HHV) efficiency of 63 percent.
5. Achieve the process throughput of 1.0 lb per hour.
6. Select the target energy content of the feedstock from the life cycle cost analysis to be at least 10MMbtu/ton.

2.14.4G Outcomes

1. The researchers performed a cost estimate for a full-scale system at 400 tons per day and confirmed the target value of the fuel gas at $5.5/MMBTU.
2. They also estimated that at full scale the return on investment (ROI) would be 8.0 percent, which was originally set as a target for commercialization.
3. The application of the technology was for treatment of a combined waste which has a higher solids content. The researchers were able to demonstrate the ability to adequately handle a combined feedstock with total solids of 37 percent and a target viscosity of 1.0 Pascal-second, thus achieving the objectives.
4. The researchers demonstrated a process higher heating value (HHV) of 64 percent and a fuel gas composition of 80 percent methane for the combined process.
5. The process throughput was only 1.0 pound per hour and thus represented a laboratory-scale process.
6. The energy content of the combined organic waste was determined as 17 MMBTU per ton, which was greater than the original projection of 10 MMBTU.

2.14.5G Conclusions

The researchers met all of the major goals of the project, including engineering and demonstrating the combined steam hydrogasification reactor with the water gas shift process. They successfully operated the overall system at the designed throughput of 1.0 pound per hour. The process demonstrated the anticipated process yields and product gas quality. The

researchers carefully characterized the organic waste streams that are available in California for use in such a process with emphasis on organic wastes which do not represent seasonal variation of supply or composition. The researchers determined the combination of sewage biosolids and municipal separated organics such as yard waste would be most appropriate. In addition, the combination of these wastes would allow for the use of high solids feedstocks which would reduce the size of the system required per ton of organic waste to be treated.

The researchers used modeling software to estimate full-scale system costs for the combined process and determined that a 400 TPD system would provide a fuel cost of $5.5/MMBTU and a return on investment of 8.0 percent, which is consistent with values necessary for commercialization.

Finally, data from the combined SHR/WGS process demonstrated the ability to meet all of the process objectives, including handling of a high solids feedstock with a viscosity of 1.0 Pascal-second, a 64 percent higher heating value (HHV) and 80 percent methane content in the product fuel gas, and continuous operation.

The researchers proved feasibility of the SHR/WGS process at the laboratory scale. The advancement in the technology as developed in this study is an important step in the development of this process.

2.14.6G Recommendations

Subsequent development is necessary to move the technology to the pilot scale and to work out additional engineering issues, including ash and tar quality and quantity. The Program Administrator recommends that the researchers:

- Develop and operate a pilot-scale system requiring the incorporation of a fluidized bed reactor.
- Optimize production and handling by analyzing process ash and tar byproducts.
- Re-evaluate the commercial scale economics as the technology advances.
- Quantify environmental issues relating to process effluents, including ash and tar as well as air emissions.
- Optimize the process to minimize emissions.
- Apply for additional patents to protect intellectual property and to preserve commercial viability.
- Determine product market specifications through market analysis.
- Obtain a partner who will aid in commercialization.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.14.7G Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California energy supply or transmission or distribution system
- Increased public safety of the California energy system
- Increased reliability of the California energy system
- Increased affordability of energy in California

The primary benefit of this technology is reduced environmental impacts of the California energy supply and distribution system. Commercialization of the combined SHR/WGS has the potential to expand the production of renewable methane gas from organic wastes, including municipal organic material and sewage biosolids. Currently these organic wastes are landfilled or land applied, with the potential for biological gaseous emissions into the atmosphere. This technology offers the potential to convert these two wastes to methane in an efficient process which can be used in transportation fuel or for electricity generation.

The SHR/WGS process represents a relatively safe and efficient process for conversion of organic wastes to fuel gas. The moderate temperatures and pressures of the system are considered safe and well within established engineering parameters for continuous process design. In addition, the use of high solids feedstock reduces the overall size of the system, creating a smaller and more manageable footprint. Compared to alternative technologies such as anaerobic digestion or composting, the SHR/WGS process is more efficient with potentially higher yields of fuel gas. In addition the process produces a more consistent quality of product gas and byproducts as compared to biological systems.

Ultimately, commercialization of this technology could provide an economy of scale which would allow the SHR/WGS process to be economical in producing fuel gas from treated organic wastes. At the conclusion of this project the researchers estimated full-scale energy production costs to be $5.5/MMBTU, which is competitive with many forms of fuel gas.

2.14.8G Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers had not completed a market analysis by the end of this project nor had they had any contact with potential customers or users of the product.

Engineering/Technical

The researchers estimated they could complete a pilot-scale demonstration in two to three years with funding of $5 to $10 million.

Legal/Contractual

The investigators have applied for a patent for the subject technology, *UC No. 2011-190 "Method to Produce Methane Rich Fuel Gas from Carbonaceous Feedstocks Using a Steam Hydrogasification Reactor and Water Gas Shift Reactor."* The researchers also claimed they will put the intellectual property into the public domain.

Environmental, Safety, Risk Assessments/ Quality Plans

Safety and risk assessments were not part of this project as the technology is still in the developmental stage. However large-scale systems operating at the temperature and pressures identified for the SHR/WGS process are considered relatively low risk. Scaling up the process would require careful attention to safety.

Production Readiness/Commercialization

The SHR process has made an incremental step forward toward commercialization through combination with the WGS process. While the combined process demonstrated measurable success, it is not currently ready for commercialization.

2.15G Renewable Energy Integrated Gas Network (REIGN)

Awardee: Protomatrix.

Principal Investigator: Kevin E. Mahaffy

2.15.1G Abstract

In this project researchers evaluated the feasibility of a high pressure, air compressing wind turbine using an innovative hydraulic approach for use in energy storage. This was a modification of compressed air energy storage (CAES). This technology, dubbed the Renewable Energy Integrated Gas Network or REIGN, was designed to improve the efficiency of natural gas turbines with compressed air. The compressed air would be generated by wind turbines and stored in underwater constructed reservoirs to offset compression demands of natural gas turbines. The computer model developed for the REIGN system showed the most sensitive variable was the location of the compressed air storage reservoir. The size of the reservoir, operating pressure, losses in pipes, and overall efficiency changed very rapidly with depth of the compressed air reservoir.

Computer modeling of a 1 GW and an 83 MW plant determined an optimal depth of around 1,500 meters leading to an energy return up to 85 percent in optimal circumstances. The physical experiment demonstrated hydraulic air compressors could be used to form the basis of the wind-powered air compressor. The cost analysis indicated the 1 GW plant could potentially make up to $11 million a year in revenue, assuming the ancillary service market continued along current trends and natural gas prices continued to rise. The calculated return of investment was 45—50 years or longer if natural gas prices remain low.

Modeling results need to be verified with physical tests, and operational considerations (e.g., variability of wind impact on performance and thermal loss during air storage) need to be explicitly addressed.

Keywords: Compressed air, natural gas, renewable energy, wind turbine, OCAES

2.15.2G Introduction

Increasing the level of renewable energy generation is a key energy and environmental policy of California. Incorporating increasing levels of renewable energy into a reliable grid is, however, complicated by the intermittent and often volatile nature of renewables like wind and solar. Output not only seldom correlates with grid demand levels and thus requires backup (storage), but the output varies from moment to moment and so requires balancing. Energy storage technologies hold promise to resolve backup and balancing needs, but as yet they are not widely available or they focus mainly on backup and do not address balancing needs well.

Some energy storage technologies, like pumped hydro, may have a time frame for energy charging and discharging that may match backup requirements (e.g., diurnal) but not balancing (sub-60 hertz). Others, like advanced batteries, may react quickly enough for balancing but as yet do not have the capacity for significant backup storage. Turnaround efficiency and ramp rates remain technical issues with energy storage technologies, as are locational constraints. For example, pumped hydroelectric requires adequate elevation differences between upper and lower reservoirs, while compressed air energy storage (CAES) requires both appropriate geology and natural gas or other thermal energy for reheating expanding air on storage discharge.

In this project researchers proposed an innovative variation on compressed air energy storage. Rather than storing compressed air in underground caverns, the researchers evaluated compressing air with wind turbine-driven hydraulic compressors and storing the air in constructed underwater caverns, essentially a concrete reservoir with a moving top to accommodate variable amounts of compressed air, kept at the bottom of the water by its weight and maintaining constant pressure by the depth in the water. The compressed air could be used to improve the energy efficiency of combustion turbines which use a significant amount of fuel to compress air. The air reservoir could be used to store energy for backup and enable more efficient use of a natural gas-fired combustion turbine for grid balancing. This approach could remove some siting limitations for CAES by enabling siting in more grid-convenient locations along California's coast. In addition to enabling grid integration of variable renewable generation, the researchers believed it could also improve the overall efficiency of natural gas-fired generation by reducing the amount of fuel used in compressing air at combustion turbine sites, thus improving their heat rate.

The main feature, the concrete reservoir with floating top, is illustrated in Figure 15.

Figure 15: Section View of a Concrete Reservoir with Open Channels to the Surrounding Water at the Bottom

The rock ballast on top and the weight of the reservoir prevents the air being pumped into it from rising to the surface.

2.15.3G Objectives

The goal of this project was to determine the feasibility of a high pressure, air compressing wind turbine using an innovative hydraulic approach. The researchers established the following project objectives:

1. Demonstrate that the energy return of the Renewable Energy Integrated Gas Network (REIGN) is higher than 60 percent.
2. Determine the feasibility of a wind-powered air compressor through an energy return greater than 25 percent.
3. Demonstrate that with a positive working pressure above 100 psi the chosen design successfully compresses air.
4. Demonstrate less than 10 percent difference in thrust and performance when compared to received air from a turbomachinery compressor.
5. Determine a ROI greater than $500,000,000 in net revenue over 15 years.

2.15.4G Outcomes

1. Using a computer model they developed, the researchers calculated that an 85 percent energy return or higher can be achieved at optimal reservoir depths.
2. The researchers estimated that a wind-powered mechanical turbine with a minimum 25 percent energy conversion is capable of achieving the pressures necessary to pump

air to sufficient depths under optimal conditions.

3. The researchers built a motor-driven multi-stage hydraulic compressor. They used it to demonstrate it would be feasible to pressurize air to above the pressure necessary to pump it to depths up to 3,000 meters. They estimated the optimal depth to be approximately 1,500 meters.

4. The researchers did not calculate the difference, if any, in thrust when compared to a turbomachinery compressor.

5. The researchers calculated return on investment to be $160 million over 15 years. Under various capital costs, configurations, and operational scenarios, they concluded return of investment would take 45—48 years.

2.15.5G Conclusions

1. The estimated energy return for the system theoretically improves natural gas-fired generation's heat rate, but it needs to be demonstrated in real world testing. The researchers completed this objective.

2. Wind-powered air compression may be feasible based on the limited demonstration of a motor-driven hydraulic compressor. The variability of wind and its consequent effect on compressor performance under different power conditions needs to be demonstrated. The researchers partially completed this objective.

3. The deeper the reservoir the more efficient the system can be from an energy return standpoint. Complexity and capital and operating cost increase with added depth, and the optimum depth appeared to be about 1,500 meters. The researchers completed this objective.

4. The potential for different thrust output appears to be moot given the change in system configuration made during the course of the project. The researchers did not complete this objective, but that appears unnecessary at this point.

5. The estimated ROI of $160 million over 15 years did not meet the performance objective of $500 million. The researchers completed the work objective, but not the performance objective. The relative ROI will be significantly affected by changes in natural gas price.

Overall, the researchers demonstrated the potential for the system to store energy effectively, but have not yet demonstrated the feasibility, practicality, or cost effectiveness.

2.15.6G Recommendations

1. The researchers should validate their model with physical tests to confirm performance.

2. The researchers should determine thermal losses that would occur upon lengthy storage of air underwater and determine the effect on turbine performance.

3. The researchers should determine hydraulic air compressor performance under real world wind regimes and determine if pulsing in air compression is a concern.

4. The researchers should document how the underwater storage of compressed air differs from underground storage in traditional CAES in terms of combustion turbine performance. They should also evaluate the practicality of using their air compression scheme for use in traditional CAES application.
5. The researchers should evaluate the effects of humidity in air stream alternately evaporating under decompression and condensing upon compression on materials of construction, especially piping, and on turbine performance.
6. The researchers should document comparative cost and performance using hydraulic air compressors with electrically-driven compressors.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.15.7G Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Reduced environmental impacts of the California energy supply and distribution system
- Increased public safety of the California energy system
- Increased reliability of the California energy system
- Increased affordability of energy in California

The primary benefit to the ratepayer from this research is increased affordability of energy in California.

The current market for this technology encompasses almost all of the natural gas combustion turbines located on or near the coast of California. Mainly the plants are located in Los Angeles, San Diego, and San Francisco. In 2012, 43 percent of all electricity in California was produced from natural gas. More than 25 percent of those plants are located on or near the coast, with approximately 30 percent being combustion turbines and the remainder being steam turbines or combined cycles. If REIGN is implemented in half of the coastal plants using combustion turbines, the savings could be over $100 million dollars a year in natural gas saved at current natural gas prices but at unquantified capital costs. This would be accompanied by reductions in carbon dioxide emissions from power generation, partly offset by increases in cement required for reservoir construction since cement production is a carbon dioxide-intensive process.

2.15.8G Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers have had informal discussions with potential customers. These will need to be formalized, along with development-oriented discussions, with firms knowledgeable in underwater construction. They have not yet published results of their research.

Engineering/Technical

Reservoir construction will need to be closely engineered and take into account potential for buoyant release due to tilting; sea bed leveling; and air pipe movement due to micro-seismic, sand transport, and current forces. Humidity, often high in coastal areas and combined with salt aerosols, will need to be dealt with in materials and performance criteria, as will salt encrustation of wind turbine blades.

Legal/Contractual

The researchers have not applied for patents concerning the proposed technology.

Environmental, Safety, Risk Assessments/ Quality Plans

The researchers will need to work with the California Coastal Commission to determine siting constraints and conditions, if any. The researchers will also need to determine the potential for reservoir tilting if underwater locations are not flat and potential for compressed air release due to uneven buoyancy. Safety concerns associated with hydraulic fluid, assuming hydraulic-driven air compressors, will need to be addressed.

Production Readiness/Commercialization

The concept is not ready for commercialization.

2.16TE Eco-Routing Navigation System for Electric Vehicles

Awardee: Center for Environmental Research and Technology, University of California, Riverside

Principal Investigator: Guoyuan Wu

2.16.1TE Abstract

This research project addressed determining the feasibility of calculating a travel route for an electric vehicle (EV) that required the least amount of energy for the trip, thereby extending the range of the EV. To achieve this goal, the research team demonstrated the accuracy of measurements from the data acquisition system, validated the proposed algorithm in estimating energy consumption of a 2013 Nissan Leaf test EV in real time, and verified the benefit from the prototype system in terms of energy savings for the test EV. The key innovation in this research was the novel eco-routing algorithm that finds a route requiring the least amount of energy for the trip by taking into account real time traffic information, road type, road grade, and passenger/cargo weight. The project results demonstrated that the proposed system can provide up to 51 percent energy reduction compared with conventional navigation strategies of shortest travel distance and least travel duration.

Keywords: Electric vehicle, eco-routing navigation, energy consumption, multivariate regression, map matching

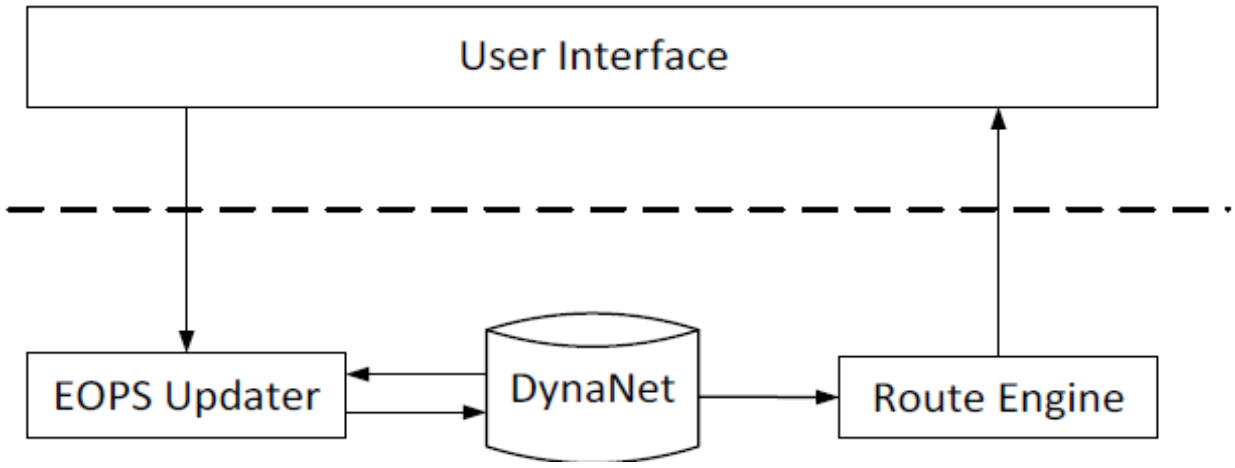
2.16.2TE Introduction

Increasing the use of electric vehicles (EVs) may diminish the environmental and energy impacts associated with conventional petroleum-based vehicles in California. Compared with petroleum-based vehicles, EVs can be powered by electricity generated from divergent and efficient sources that emit no tailpipe carbon dioxide (CO_2), oxides of nitrogen (NO_x), non-methane hydrocarbons (NMHC), carbon monoxide (CO), and particulate matter (PM) at the point of use.

However, one of the major obstacles to the mass adoption of EVs is range anxiety, the fear that an all-electric vehicle may not reach a desired destination before running out of power. The proposed innovation in eco-friendly intelligent transportation system technologies could address this concern and could save approximately 20,736,000 kWh in electricity or $4.15 million in electricity costs each year in California.

Current commercial EV navigation systems provide several functions. Most of them, such as the one on Nissan Leaf, are focused on locating a public charging station in the vicinity, showing the current travel range of the vehicle, and displaying energy use in real time. In terms of routing, the majority of these EV navigation systems still find a route corresponding to the shortest distance or shortest travel time between an origin and a destination. The research team determined that none of them has a capability to incorporate real time traffic information, road type, road grade, weight, and/or weather information in the calculation. The key innovation in this proposed research was the novel eco-routing algorithm that finds a route requiring the least amount of energy for the trip by taking into account real time traffic information, road type, road grade, and passenger/cargo weight. The overall architecture of the eco-routing navigation system is shown in Figure 16.

Figure 16: System Architecture



First, the system receives a request from the driver through the user interface. That triggers the energy-operational parameter set (EOPS) to update EOPS for each link in the roadway network based on the latest set of traffic performance data from DynaNet. In essence, the algorithm is connected to the research team's existing Dynamic Roadway Network (DynaNet) that has road type and road grade information and receives real time traffic information on both freeways and surface streets from various sources. DynaNet can be set to periodically acquire and update traffic performance data or on-demand.

Once the EOPS (in units of watt-hour per unit distance) has been updated, it is multiplied by the distance to yield the total energy estimates that are required for the EV to traverse the link. These energy estimates are then stored in a data table in DynaNet along with other factors like distance and estimated travel time. This data is then used by the Routing Engine in calculating optimal routes according to the minimization criteria selected by the driver. Finally, the calculated routes are sent to the driver via the User Interface.

2.16.3TE Objectives

The goal of this project was to determine the feasibility of calculating a travel route for an electric vehicle (EV) that requires the least amount of energy for the trip, thus extending the range of the EV. To fulfill this goal, the research team originally established the following project objectives:

1. Demonstrate that the calibrated simulation tool is able to calculate energy consumption of the test EV with an average error of ± 10 percent.
2. Demonstrate that the algorithm is able to estimate energy consumption of the test EV in real time with an average error of ± 10 percent.
3. Perform field tests for at least 50 trips on an EV with and without the prototype system on both freeway and arterial roadways with various gradients.
4. Demonstrate that the prototype system saves energy consumption of the test EV by an average of at least 10 percent.

The research team modified the original statement of work due to an unexpected delay in obtaining a test electric vehicle. Also, instead of acquiring the simulation tool as scheduled, the research team cooperated with Nissan North America to obtain the specifically designed data acquisition system, CONSULT III plus Kit, which was capable of collecting data and diagnosing systems for Nissan vehicles such as Leaf. With the availability of CONSULT III plus Kit, the research team accessed a large amount of real world, high resolution data (20 Hz) from the vehicle itself and monitored/recorded its energy consumption. Therefore, instead of calibrating the EV simulation model, the research team developed a new model to estimate the energy consumption of the test vehicle under different speed levels, roadway types, and road grades. The team also calibrated the Energy Operational Parameter Set (EOPS) of the model using the collected field data.

To summarize, the new primary objective was to demonstrate that the data acquisition system was able to provide measurements within an average error of ± 10 percent.

2.16.4TE Outcomes

1. The research team accomplished the objective by demonstrating that the average errors for measurements from the data system were less than 1.7 percent across all study sites, well below ± 10 percent.

2. By analyzing the data from the field testing, the research team identified that the average relative error was near 0.6 percent in terms of trip-based energy consumption. This met the objective goal of ± 10 percent.

3. The research team accomplished this objective through performing field tests for more than 100 trips on the EV (2013 Nissan Leaf) on both freeway and arterial roadways with gradients. The simulation runs to evaluate the benefits of the prototype system for comparison included over 4,000 trips.

4. The extensive tests over different study sites showed the proposed eco-routing navigation algorithm could reduce trip-based energy consumption by 5–25 percent and 25–51 percent, respectively, compared to the shortest travel distance and least travel time algorithm.

2.16.5TE Conclusions

The researchers met the overall objectives and demonstrated that the proposed system could fulfill the objectives and provide up to 51 percent energy reduction compared with conventional navigation strategies.

1. The data acquisition system implemented in this project, including the CONSULT III plus Kit and GPS data logger, are quite reliable and satisfy this objective. The difference in speed measurement between the GPS data logger and dedicated diagnostics system (CONSULT III plus Kit) across all study sites was less than 1.7 percent on average. This established a foundation for further development of the algorithm.

2. The proposed polynomial regression model on the Energy Operational Parameter Set (EOPS), despite its simplicity, was able to estimate energy consumption of the test EV in real time within an average error of ± 10 percent. For example, the mean error in estimation of trip energy consumption was only 0.6 percent.

3. The results demonstrated that the number of trips identified in the scope of work was sufficient and the data set was reliable for algorithm development and validation. In addition, field tests showed that roadway grade plays a significant role on energy consumption for the electric vehicle due to the introduction of regenerative braking, and the eco-mode outperforms the normal mode when the route experiences downhill terrain because the eco-mode is more efficient in energy recovery.

4. Extensive evaluation tests on the selected study sites showed that the prototype system provided significant savings in energy consumption compared to conventional

navigation systems. However, there may be certain penalties in travel time and travel distance.

2.16.6TE Recommendations

This research provided a sufficient basis for further work on the integration of multiple factors in route planning. The Program Administrator recommends the following:

1. Within the completed research, the results are site-specific. System performance may vary significantly with study sites and even travel directions. Therefore, larger scale testing under a more generalized framework using a larger network should be conducted.
2. Additional data such as different vehicle models and driver behavior should be collected to determine the significance of different influential factors.
3. To better understand the characteristics of different route choice, further analysis should be done by incorporating information such as time of the day or day of the week. Drivers' values on the travel time and energy may vary, depending on whether the trip is performed on a weekday or a weekend.
4. The least energy consumption routes for the test EV usually have a penalty on the travel time, but not necessarily on the travel distance. For commercialization, selecting a more rational navigation objective function needs further investigation to achieve a balance between energy consumption and travel time or travel distance and fulfill customers' needs.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.16.7TE Benefits to California

Public benefits derived from PIER transportation research and development projects are assessed within the following context:

- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased use of alternative fuels

The primary benefit to the ratepayer from this research is improved transportation energy efficiency. This would be accomplished through more efficient operation of EVs. There is also

the potential benefit of increasing the use of alternative fuels. As range anxiety is decreased, EV market penetration is likely to increase.

Benefits were determined in the following manner. By the end of 2013, Nissan had sold 42,000 units of Nissan Leaf in the United States and was projected to sell another 30,000 units in 2014. The current Nissan Leaf is estimated to consume 0.24 kWh per mile. Given the average annual mileage of 12,000, one Nissan Leaf will consume 2,880 kWh annually.

The outcome of this project showed that the energy savings could be as much as 51 percent by using the proposed navigation algorithm rather than the conventional least-duration strategy. As a result of using the eco-routing navigation technology and assuming 10 percent of the Nissan Leaf EVs sold in the United States are located in California, 7,200 Nissan EVs would translate to approximately 20,736,000 kWh per year. At $0.2 per kWh and 51 percent savings, the proposed navigation system would result in an annual saving of $2.12 million in electricity costs in California, just by Nissan Leaf EVs. If EVs from other manufacturers also implement the eco-routing navigation technology, the energy and cost savings would be greater.

2.16.8TE Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers did not perform a market assessment nor did they talk to potential customers about this technology. They stated that they would like an automobile manufacturer as a partner.

Engineering/Technical

The researchers have created a development plan for the eco-routing program. The key factor to address is to develop/improve the short-term traffic state prediction for online, real time implementation. The researchers estimate that additional engineering development could be completed in approximately one to two years with a budget near $200,000.

Legal/Contractual

The researchers have no patents or any active applications related to this research.

Environmental, Safety, Risk Assessments/ Quality Plans

There is low to no environmental, safety, or risk issues associated with the research.

Production Readiness/Commercialization

The researchers stated that a key partner for production and commercialization would be an automobile manufacturer or navigation system developer. The researchers had not developed a commercialization plan by the end of this project.

2.17TNG Feasibility Study of a Novel All-in-one Approach for Biofuels Production

Awardee: University of California, Davis

Principal Investigator: Zhiliang Fan

2.17.1TNG Abstract

The goal of this project was to convert biomass to ethanol more efficiently. The proposed one-step conversion process of biomass to ethanol could potentially consolidate pretreatment, cellulase production, enzymatic hydrolysis, pentose fermentation, hexose fermentation, and part of the product recovery into a single reactor if the final product is volatile. The overall goal of this project was to demonstrate the feasibility of the proposed new configuration using *Neurospora crassa* and *Klebsiella oxytoca* as the model microorganisms, focusing on the conversion of cellulose to ethanol as the model system. The feasibility of the proposed new configuration is based on the following hypotheses:

1. Cellobiose will accumulate in the process of cellulose hydrolysis by *N. crassa* if multiple copies of β-glucosidase genes are knocked out.
2. *K. oxytoca* can be engineered to have a slower glucose utilization rate while maintaining the ability to metabolize cellobiose.
3. Ethanol can be produced under aerobic conditions by the immobilized *K. oxytoca.*
4. Cellulose can be efficiently converted to ethanol using the *N. crassa* and immobilized *K. oxytoca* system under aerobic conditions.

This project sought to demonstrate hypotheses 2, 3, and 4 above. The researchers have successfully demonstrated that the glucose utilization rate can be substantially reduced by knocking out the genes encoding for glucose and mannose transporter proteins, while the rate of cellobiose utilization by the mutant remained the same as the wild type strain. The entrapment of cells within the gel matrix can improve ethanol yield from sugars. However, the researchers have not yet successfully demonstrated that ethanol can be produced by the *N. crassa* F5 and *K. oxytoca* consortium.

Keywords: Ethanol, cellulosic biomass, process consolidation, cell immobilization, *Neurospora crassa*, *Klebsiella oxytoca*

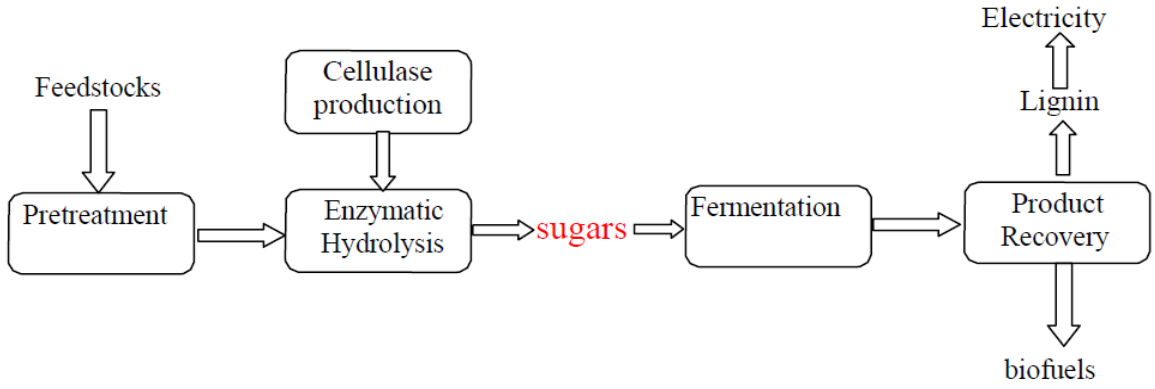
2.17.2TNG Introduction

Research to produce ethanol from cellulosic biomass has a long history of development and optimization and has been the subject of intensive cost analysis. As a transportation fuel, ethanol derived from biomass holds promise both in utilization of waste materials and production within the United States as well as being clean burning and nearly carbon neutral. However, the production of ethanol from cellulosic biomass requires multiple processes which are both capital and operationally expensive. This research project focused on a novel approach to simplify the process by combining hydrolytic enzyme production, cellulose breakdown, fermentation to ethanol, and ethanol recovery. The benefits of such a process are obvious and relate to reduced capital and operating costs for the process. However, the genetic engineering involved in creating and optimizing this microbial co-culture, as well as the need for a physical micro-environment, is daunting.

The conventional method for producing ethanol and other value-added products from biomass feedstock involves a multistep process such as that identified in Figure 17. A variety of processes and technologies must be combined to break down the insoluble feedstock to a soluble form, followed by conversion to the ethanol product and product recovery. The addition of multiple steps increases the complexity of the process as well as the capital and operating costs.

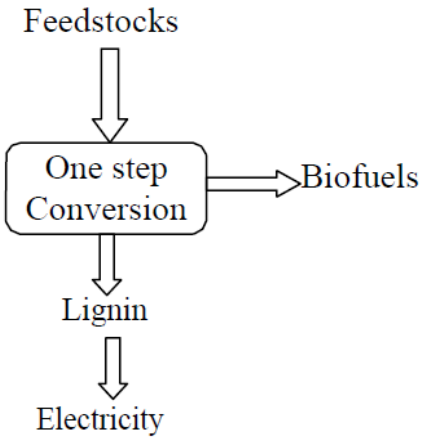
In the conventional process for converting biomass into ethanol, a thermochemical pretreatment is employed to solubilize some of the organics of the biomass while rendering the remaining material more susceptible to enzymatic breakdown. The second step involves the addition of exogenously produced enzymes, generally of fungal origin, which includes cellulases and hemicellulases to break down the insoluble organic polymers to soluble sugars. These soluble sugars are then fermented by specific yeast or bacterial strains to ethanol and byproducts. The development of higher concentrations of the ethanol product to reduce the cost of product recovery by distillation is important. See Figure 17.

Figure 17: Conventional Biochemical Platform for Biofuels Production



The proposed technology would reduce the complexity of the overall process by combining the cellulase production step with enzymatic hydrolysis and fermentation through the use of two microorganisms working in synergy. This process is shown in Figure 18 and includes the use of the microorganisms *Neurospora crassa* and *Klebsiella oxytoca.* Combining hydrolytic enzyme production with biomass enzymatic breakdown and fermentation could dramatically simplify the overall process while reducing capital and operating costs.

Figure 18: Alternative Biochemical Platform for Biofuels Production



However this concept has several potential roadblocks to successful application, including substantial consumption of sugars by the fungal hydrolytic enzyme producing microbe *N. crassa* and a requirement for a reduced oxygen environment for production of ethanol by the fermentative microbe *K. oxytoca.* In general, a shift in metabolism is required whereby the cellobiose produced by *N. crassa* is metabolized by the fermentative microbe *K oxytoca* and the glucose produced in enzymatic hydrolysis is consumed by the enzyme producer *N. crassa*. In addition, the ethanol in the process needs to be stripped out of the system so as to not inhibit either microorganism. The fermentative microbe *K. oxytoca* generally requires low oxygen tensions for fermentation.

Therefore the research requires both metabolic alterations in the two microbes involved in the process, as well as the application of physical methods for microbe immobilization to alter the oxygen tension microenvironment.

2.17.3TNG Objectives

The objective of this project was to develop a new, more efficient method for producing ethanol fromellulosic biomass. The process design sought to combine hydrolytic enzyme production, enzymatic hydrolysis of the biomass with fermentation of sugars to ethanol, and ethanol product recovery into a single step. To accomplish this goal, the project required reprogramming of the microbial catalysts through genetic engineering and use of specialized polymers to generate a microenvironment. The specific objectives were as follows:

1. Construct a mutant *K. oxytoca* strain which is deficient in glucose transportation with the goal of decreasing the rate of glucose utilization by the mutant strain to be less than 0.25 g/L/h.
2. Investigate the effect of immobilization conditions on ethanol production and determine aerobic conditions that achieve an ethanol yield from cellobiose of 75 percent or more using the *K. oxytoca* mutant as the ethanologen.
3. Demonstrate that ethanol can be produced from cellulose using the engineered *N. crassa* F5 strain and the immobilized recombinant *K. oxytoca* strain in aerobic conditions and identify aerobic conditions that achieve a yield of ethanol from cellulose of 50 percent or more.
4. Perform a preliminary energy and ethanol cost analysis. The goal is to achieve an ethanol cost of $0.71/gallon or less and energy efficiency of 63 percent or more.

2.17.4TNG Outcomes

The research project resulted in a substantial number of successful outcomes including the following:

1. The researchers anticipated reducing monomeric sugar utilization by the ethanol producing microbe to increase glucose availability for the hydrolytic microbe of the co-culture. To this end, they constructed the mutant *K. oxytoca* P2*ΔptsGΔManXYZ* with the genes encoding for the glucose and mannose transporters deleted. They found the mutant utilized glucose at a much slower rate (about 0.23 g/L/h) as compared to that of the wild type strain (about 0.83g/L/h). The rate of cellobiose utilization by this mutant strain was unaffected.
2. The ethanol-producing microbe requires reduced oxygen levels for fermentation of substrates to ethanol. However, the hydrolytic microbe requires substantial oxygen for enzyme production. To allow optimal conditions for both microbes in the co-culture, the researchers needed to establish a micro-environment in which oxygen diffusion was limited and reduced for the ethanol producing microbe. To accomplish this, they entrapped the *K. oxytoca* cells within a *k*-carrageenan gel matrix that improved the ethanol yield from sugars. The researchers obtained an ethanol yield of 75 percent from cellobiose when the cells were entrapped in 3 percent *k*-carrageenan and the cell concentration was 15mg/L. The ethanol yield produced by the free cells was only 60 percent.
3. A crucial objective was to investigate and quantify the ethanol production from cellulose by the co-culture. This was required to establish the main objective of the project and to perform a process cost analyses. However ethanol was not produced by the co-culture, while cellulose was efficiently utilized. Therefore this objective was not accomplished. The researchers determined that the hydrolytic enzyme-producing microbe was capable and efficient at metabolizing ethanol produced in the co-culture. The researchers have subsequently identified a strategy for blunting or eliminating ethanol consumption by

the hydrolytic enzyme-producing microbe through altering ethanol metabolizing genes in *N. crassa.* One solution identified by the researchers was to block the ethanol utilization pathway by knocking out alcohol dehydrogenase genes. Furthermore, the researchers stipulated that knocking out *adh1,* one of the two major alcohol dehydrogenase genes, could be effective. Researchers presented preliminary data for knocking out *adh* genes in *N. crassa,* demonstrating that the issue may be resolved. However, the project duration and funding were insufficient to accomplish rigorous evaluation of this new genetically altered microbe in the co-culture process.

4. The final objective was to utilize data from co-culture experiments in which ethanol was produced from the cellulose feedstock to provide the basis for cost analysis for full-scale application. The goal was to achieve an ethanol cost of $0.71/gallon or less with an energy efficiency of 63 percent or more. Since the researchers were unsuccessful in demonstrating ethanol production from the co-culture using cellulose as substrate, this objective was not accomplished**.**

2.17.5TNG Conclusions

The research team successfully completed several genetic and physical engineering goals to develop an appropriate co-culture for cellulose conversion to ethanol. First, they demonstrated that *N. crassa* could be genetically altered to produce hydrolytic enzymes and break down cellulose while reducing consumption of the cellobiose product, presumably gaining needed energy primarily from monomeric sugars such as glucose. In addition, the ethanol-producing microbe, *K .oxytoca* P2, was successfully engineered to reduce glucose uptake by knocking out the genes encoding for the glucose and mannose transporter. This allowed more monomeric sugars to be available to *N. crassa* for growth and enzyme production while cellobiose was used for ethanol production. This partitioning of specific carbon substrates by the individual microbes of the co-culture represented a novel genetic engineering approach.

It is also known that production of ethanol is enhanced when oxygen levels in the fermentation system are reduced. The researchers demonstrated the development of a physical micro-environment in which oxygen tension resulting from aeration was reduced due in part to reduced diffusion by immobilization of *K. oxytoca* cells within a *k*-carrageenan matrix, allowing more efficient ethanol fermentation. Therefore, the researchers realized the initial Objectives 1 and 2 of the project.

However the research team failed to anticipate the consumption of ethanol by the co-culture. The researchers were able to demonstrate that the hydrolytic enzyme-producing microbe *N. crassa* was indeed consuming ethanol. This was anticipated to be the result of genetically engineering *N. crassa* to reduce cellobiose metabolism. *N. crassa* maintains a substantial energy demand not only for cell growth, but also for the production of hydrolytic enzymes. This microbe normally utilizes much of the cellobiose which is produced by hydrolysis of cellulose. Since use of cellobiose has been blunted, alternative energy sources such as ethanol are used along with monomeric sugars. While presumably a greater level of monomeric sugar (glucose) was present due to engineering *K. oxytoca* to reduce glucose uptake, this was not sufficient as an energy source and *N. crassa* then also consumed ethanol produced in the co-culture. The

researchers performed further genetic engineering of *N. crassa* to reduce or eliminate ethanol metabolism through deleting *adh* gene expression. Data demonstrated that this effort was successful. However the application of this further modified *N. crassa* strain was not evaluated in the co-culture system.

The failure to demonstrate ethanol production in the co-culture system from cellulose was disappointing. This was especially true with respect to the researchers demonstrating that ethanol consumption by N. crassa could be genetically altered. Without even preliminary data for ethanol production by the co-culture from cellulose, a cost projection for full-scale development could not be attempted. Therefore, the overall objective of the project was not realized.

This research project was developmental in nature and thereby represented an effort which may require additional efforts to be successful. The original objective of the research effort, to simplify the process of converting cellulose to ethanol to improve the overall economics, is still valid. Furthermore, the researchers now have a good handle on the issues which must be overcome to achieve effective ethanol production in the co-culture system. They have already examined ethanol utilization by the hydrolytic enzyme producing microbe N. crassa and have demonstrated that this microbe has an active ethanol utilization pathway. They have also found that knocking out *adh1* in the wild type *N. crassa* strain can effectively prevent ethanol utilization. The next step is to knock out the *adh1* gene in the F5 strain by targeted gene deletion and re-evaluate the ethanol production by the consortium. If there is still ethanol consumption by the fungus strain, the team would suggest knocking out two additional hypothetical alcohol dehydrogenase genes in the *N. crassa* genome. The research team has therefore identified potential solutions to at least a portion of the ethanol consumption issue.

2.17.6TNG Recommendations

The Program Administrator recommends the following steps to advance the project technology:

1. Continue genetic engineering of the co-culture microbes to prevent ethanol metabolism.
2. Demonstrate efficient conversion of cellulosic feedstock to ethanol by the improved co-culture, including analysis of process rates and yields.
3. Perform a rigorous process economic analysis for full-scale application.
4. Demonstrate pilot-scale testing to confirm process conversion rates and yields.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.17.7TNG Benefits to California

Public benefits derived from PIER research and development projects are assessed within the following context:

- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased use of alternative fuels

The primary benefit of this project is the increased use of alternative fuels.

Since the proposed technology is still at a relative early stage of development, the team has not achieved the goal of producing ethanol from cellulosic biomass. However, the researchers are optimistic about the market and commercialization potential of the technology and believe the problem with the technology identified through this project is solvable through further research. The team will continue work on the project toward commercialization.

The early projection for ethanol production cost by the research team is estimated to be $0.73/gallon for a bio-refinery using the advanced consolidated bioprocessing (CBP) technology, while the ethanol production using the conventional technology is about $1.71/gallon. Since the co-culture process is more consolidated than CBP, the cost of the ethanol production is likely to be similar or lower to what can be achieved in the advanced CBP case. The researchers estimate the ethanol production cost could be about $0.73/gallon which is about $0.98/gallon lower than the cost produced from the conventional technology. The California Biomass Collaborative estimates that about 40 million dry tons of cellulosic materials including agricultural residues, forest residues, and municipal waste are available for ethanol production each year. About 4.79 billion gallons of ethanol could be produced from this material. If this technology could lower the production cost of ethanol by $0.98/gallon, the potential benefit to California could be about $4.7 billion.

2.17.8TNG Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers had not performed a market analysis nor surveyed potential customers for this technology by the conclusion of this project

Engineering/Technical

The researchers estimated that they could complete product development and demonstration in about two years with funding of about $2 million.

Legal/Contractual

The researchers had filed for one patent by the end of the project. They had performed a patent search.

Environmental, Safety, Risk Assessments/ Quality Plans

Safety and risk assessments were not part of this project as the technology is still in the developmental stage.

Production Readiness/Commercialization

While the proposed cellulose to ethanol process holds significant promise to improve the economics for commercial-scale production, the technology is at an early stage and will not transition to commercial development in the near future without substantial financial assistance.

2.18TE Analytic Tool to Support the Implementation of Electric Vehicle Programs

Awardee: University of California, Davis

Principal Investigators: Andrew Burke, Gustavo Collantes, Marshall Miller, Hengbing Zhao

2.18.1TE Abstract

This project developed a lifecycle cost of ownership (LCO) model to support the deployment of plug-in vehicles (PEV) in California. The model was incorporated into a dynamic analytic tool that could be used to understand questions related to LCO. The model used information from a variety of sources. The researchers recorded detailed drive cycle data from various routes in the Sacramento and San Francisco regions. They input the drive cycle data into a dynamic vehicle model, Advisor, which calculated fuel economy values (both electric watt hours/mile and gasoline gallons/mile) for the various drive cycles. The researchers then input the fuel economy outputs to the LCO model along with relevant parameters such as fuel prices, vehicle cost incentives, costs for insurance, parking, and maintenance. The researchers stochastically varied fuel and electricity prices to simulate expected future increases and uncertainties. The output of the model was not a fixed cost, but rather a distribution of expected costs that can have significant variation. The model included results for vehicles similar to the Nissan Leaf (all electric), the Chevrolet Volt (hybrid), and the Chevrolet Cruze (gasoline or diesel ICE). The Advisor model demonstrated that increased accessory loads from heating or cooling can have a large effect on fuel economy and range for vehicles operating in electric mode. The LCO varied up to 15 percent based on the choice of drive cycle.

Keywords: Electric vehicles, vehicle efficiency, lifecycle cost of ownership, vehicle simulations, drive cycles

2.18.2TE Introduction

Present markets for plug-in vehicles (PEVs) are limited by their higher cost and lower perceived utility compared to conventional internal combustion engine (ICE) vehicles. As sales of PEVs expand, more customers will need to evaluate the utility and economics of the increasing number of PEV options. The lifecycle cost of ownership (LCO) tool, after further refinement, would allow potential PEV consumers, both fleet managers and individuals, to gain better information about the various PEV options in the market. This improved information would help to expand the PEV market in California. Increased information could result in more PEV sales in California and less difficulty in meeting the zero emission vehicle (ZEV) mandate for 2015 and beyond. Based on projected sales of EVs in California over the next three years, the researchers estimated that the information from this tool could add roughly 5,000 additional EV sales in California for an accumulated cost of ownership savings of roughly $35 million.

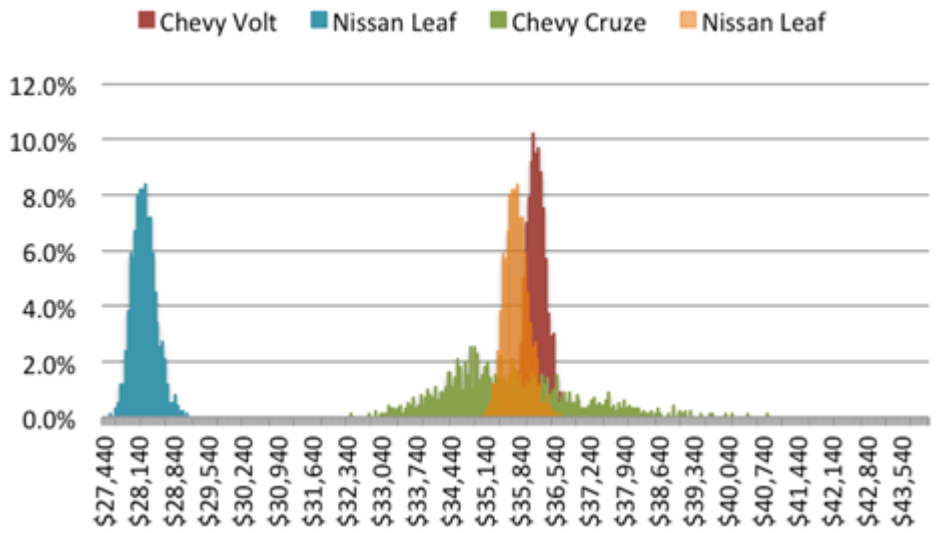
While several groups have published LCO analyses, these suffer from a variety of shortcomings such as not including risks and uncertainties, excluding time effects in key variables, assuming hypothetical vehicle configurations and general vehicle drive cycles rather than ones specific to regions, or excluding real world factors such as road grades, traffic conditions, and ambient conditions. Since LCO analyses are useful in comparing battery electric and plug-in hybrid vehicle ownership costs to those of conventional vehicles, an LCO model which eliminates these shortcomings could be useful to policy researchers, fleet owners, and other people interested in the comparisons of lifecycle ownership costs of PEVs. The overarching goal of this study was to offer stakeholders rigorous, context-specific knowledge about factors that affect the purchase and cost of owning PEVs relative to other vehicles.

This study has extended knowledge in the following ways:

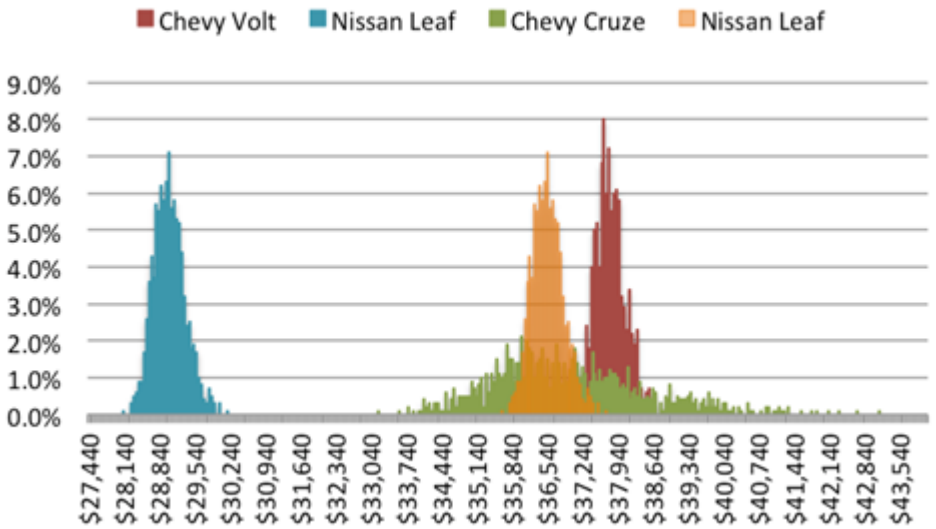
1. The focus centered on vehicles in the market for which sufficient information is available. The study incorporated new information on PEV technology such as updated battery models and data on vehicle accessory loads.
2. Most studies to date have relied on point estimates for all or some of the key variables that affect LCO, such as fuel prices, technology innovation, and traffic conditions. This analysis incorporated variation in input variables, specifically electricity and fuel costs, into the LCO estimates.
3. The study used input variables that characterize key regions within the state.
4. The analysis used validated dynamic vehicle models for the simulation of energy consumption of real (as opposed to hypothetical) vehicle configurations. In addition, the models incorporated actual drive cycles measured from real world driving in the Davis-Sacramento and San Francisco regions.
5. The researchers communicated with key stakeholders for guidance in general analysis direction and to incorporate policy and regulatory variables.

Graphs of the results of the LCO tool are shown in Figure 19 for the Davis-Sacramento trip. The consequences of the stochastic character of the electricity and gasoline cost inputs are shown in the distribution of the ownership costs. The results indicate the magnitude of the standard deviation can vary significantly for the various driving cycles and different vehicles.

Figure 19: Graphic Presentations of the LCO Tool Outputs Showing the Distribution of Ownership Costs (a)



Davis-Sacramento Trip 400W accessory load 60K miles (b)



Davis-Sacramento Trip 4000W accessory load 60K miles

2.18.3TE Objectives

The research team's goal was to offer stakeholders rigorous, context-specific knowledge about the factors that affect the purchase and cost of owning a plug-in vehicle relative to other vehicle platforms. With this knowledge, stakeholders such as electric utilities, state agencies, local governments, and consumers can make decisions and implement programs to support the adoption of plug-in vehicles consistent with extant policy and regulatory frameworks. By using data specific to key regions in California, the research team's intended outcome was to enable stakeholders to develop programs tailored to their areas that target vehicles currently in the market.

To achieve their goal, the researchers established the following project objectives:

1. Develop a list of variables identified in the literature to affect vehicle cost of ownership and develop a model that includes at least this set of variables.
2. Collect five hours of GPS driving data for each of seven days in at least two metropolitan areas in the state of California.
3. Consult with at least one representative of each of the car manufacturers with plug-in electric vehicle offerings in the market at the time of starting this project and each transportation agency with jurisdiction in the metropolitan areas where the team collected driving data.
4. Perform one set of simulations for each of the driving cycles for which data is collected. Validate simulation results for vehicle electric range and energy consumption with United States Department of Energy available test data.
5. Run the stochastic model until the estimates of vehicle lifecycle cost of ownership converge to within 0.1 percent marginal change.
6. Format the analytical tool in a way such that the tool provides estimates of vehicle lifecycle cost of ownership with the need of not more than 15 input values.

2.18.4TE Outcomes

1. The research team met this objective by developing a model incorporating the following variables: vehicle capital cost, vehicle incentives, vehicle taxes, vehicle insurance, parking, maintenance, discount rate, vehicle depreciation, drive cycle and road grade, auxiliary power for heating and cooling, and battery state of charge (SOC) range.
2. Researchers met this objective through collecting drive cycle data for 10 specific routes in the Davis-Sacramento and San Francisco regions. These routes consisted of either urban driving or regional driving from a city to a surrounding suburb or other city.
3. The research team consulted with a majority of the car manufacturers with plug-in electric vehicle offerings in the market at the time of this project and with each transportation agency with jurisdiction in the metropolitan areas where the team collected driving data. The discussions with automakers focused on the battery life and

battery second life, vehicle depreciation, and California markets. The discussion with public stakeholders focused on the potential for disseminating the tool for use with fleets and consumers.

4. The research team completed at least one set of simulations for each of the selected driving cycles. The operation of electric vehicles in real world conditions was done via computer simulations and the examination of vehicle dynamometer data taken under conditions appropriate for real world driving.

5. The researchers verified that repeated runs with many iterations showed means and standard deviations that were very similar. In particular, the means of repeated runs converged as the number of iterations increased.

6. The research team successfully formatted the analytical tool so that it provided estimates of vehicle lifecycle cost of ownership with the need of not more than 15 input values. In its current format the tool allows for the simultaneous analysis of four vehicles.

2.18.5TE Conclusions

The research team fully demonstrated the feasibility of creating an analytical tool that provides estimates of vehicle lifecycle cost of ownership. Each objective was met. Conclusions for each one follow below.

1. Through reviewing the literature on LCO models, the researchers defined a set of relevant variables that captured aspects of driving which contribute significantly to the lifecycle cost of ownership. These variables included vehicle capital cost, vehicle incentives, vehicle taxes, vehicle insurance, parking, maintenance, discount rate, vehicle depreciation, drive cycle and road grade, auxiliary power for heating and cooling, and battery SOC range.

2. To estimate lifecycle cost of ownership for vehicles in specific regions, the researchers concluded they needed vehicle acquisition costs and GPS driving data. Drive cycles must include expected driving patterns in both urban and regional areas.

3. During consultations with car manufacturer and public agency representatives, the researchers concluded that:

    - Battery warranties are likely to last for a significant portion of the vehicle life, for example 8—10 years or possibly up to 150,000 miles. After use in a vehicle, batteries may be sold into a second application.

    - Vehicle depreciation for PEVs is likely to be similar to that of conventional vehicles.

    - The stochastic nature of the tool likely will require more education for stakeholders not familiar with the tool outputs of means and standard deviations.

4. Through performing simulations, the researchers found that the driving cycle, grade, and accessory loads can have a large effect on the electric energy consumed from the battery in an EV, as is the case for the fuel economy of both conventional ICE and hybrid vehicles. The team found that watt hours (Wh)/mi of an electric vehicle can increase close to 100 percent with full heater or air conditioner operation in urban driving and by 25 percent to 30 percent in highway driving. The range of the EV can be reduced by about 50 percent in urban driving and 15 percent to 20 percent on the highway. The reduction in range is particularly significant to customers.

5. Repeated runs of many iterations demonstrated convergence of the mean output. The effect of changes in the trip/driving cycle and accessory load on the accumulated ownership cost distributions seemed realistic in that they were consistent with prior expectations and not excessively large.

6. The analytic tool was formatted in a way such that it provided estimates of vehicle lifecycle cost of ownership with the need of not more than 15 input values.

2.18.6TE Recommendations

The Program Administrator has determined that further research is needed to refine and extend the modeling and formulations on which the tool is based. These tasks should increase its functionality, scope, and benefits for potential users.

1. Include additional vehicles in the tool. The tool presently includes data for vehicles similar to the Nissan Leaf, GM Volt, and Chevrolet Cruze. There are, however, many other conventional and plug-in or electric vehicles that fleets or consumers will want to compare.

2. Include other stochastic parameters in the LCO tool. Adding additional variation to the input parameters would allow the tool to estimate ownership costs that more accurately reflect actual vehicle use.

3. Provide more realistic modeling of the effect of ambient temperature and HVAC operation on PEV energy consumption. Additional work is needed to model the heating and cooling of the vehicle, including the effect of changing cabin temperature in response to the operation of the heating, ventilation, and air conditioning (HVAC) unit and the heat gain or loss to the ambient environment as the vehicle moves along the road.

4. Provide more extensive calculations using the LCO tool. With the improved auxiliary load model and the inclusion of additional stochastic variables, the LCO tool can be run for a large number of vehicles, regions, and economic conditions to determine the effect of the various parameters on the economic attractiveness of different PEV designs to consumers having different needs.

5. Evaluate the impact of greatly reduced prices of gasoline and diesel fuel and the likelihood that the retail price of fuel will remain low for 5 or 10 years.

6. Expand the tool to include other regions in California such as the Los Angeles and San Diego regions.

2.18.7TE Benefits to California

Public benefits derived from PIER transportation research and development projects are assessed within the following context:

- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased use of alternative fuels

The primary benefit to the ratepayer from this research is the increased use of alternative fuels. This work has added to an understanding of PEV ownership in California and in other states following the California Zero Emission Vehicle (ZEV) mandate. The present markets for PEVs are limited to early adopters who are willing to purchase PEVs in spite of their higher cost and limited utility compared to conventional internal combustion engine vehicles. As the sales of PEVs expand into the mass market, it will be necessary for more customers to be able to evaluate the utility and economics of the increasing number of PEV options. The lifecycle cost of ownership (LCO) tool developed in the present project is intended to be a tool for potential PEV consumers, both fleet managers and individuals. This could result in more PEV sales and lower vehicle emissions in California and less difficulty in meeting the ZEV Mandate for 2015 and beyond.

While it is difficult to project the effect of the tool on consumer decisions and sales, fleet managers and individual consumers having access to better cost of ownership information are likely to purchase more plug-in vehicles. Assuming that the added information increases the number of EVs sold over the three year period from 2015 to 2017 by 5.0 percent, roughly 5,000 additional vehicles could be sold in California. The value of these sales would be about $125 million. Using the LCO results, the five year cost savings of a Leaf purchaser would be about $7,000 compared to owning a Cruze. Hence additional sales of EVs would result in a total ownership savings of about $35 million over five years in California.

2.18.8TE Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers claim that they have described the project work to stakeholders.

Engineering/Technical

The researchers claim that no further work is necessary.

Legal/Contractual

The researchers had not applied for nor received a patent on this project work. In fact, they claim that there is no patentable intellectual property. They report no partnerships to distribute the results of this project.

Environmental, Safety, Risk Assessments/ Quality Plans

The researchers reported nothing in this area.

Production Readiness/Commercialization

Having the tool available on appropriate sites, along with educating stakeholders about the tool, is all that is necessary. The researchers have determined that the tool may require targeted education to ensure that the outputs and potential benefits are understood.

2.19TNG Simultaneous Reduction of NOx/CO/CH4 Emissions from Natural Gas Engine

Awardee: University of California, San Diego

Principal Investigator: Robert Cattolica

2.19.1TNG Abstract

In this study the researchers tested a system using three-way catalysts to reduce emissions of nitrogen oxides (NO_x), carbon monoxide (CO), and total hydrocarbons (THC) on a compressed natural gas engine. The researchers measured the emissions using a Cooperative Fuel Research engine equipped with a three-way catalyst. They measured emissions before and after the catalyst using a Horiba gas analyzer. The principal focus was hydrocarbon emissions, which were mostly methane (CH_4) and therefore the most difficult to be reduced in the catalyst. The researchers tested different equivalence ratios, compression ratios, and control strategies and found that higher compression ratios lead to higher engine-out emissions of THC. This not only led to higher post-catalyst THC emissions but also made reduction of CO and NO_x more difficult. The researchers also conducted tests with steady engine operation as well as with fuel dithering, the modulation of the equivalence ratio using a square wave. Fuel dithering did not provide quantitative advantages. As a control strategy, the team inserted a second lambda sensor between two catalysts to minimize CO or NO_x excursions when the overall operation drifted toward rich or lean. Here fuel dithering provided some qualitative advantages as the signal of the second lambda sensor was in a more optimal range. The strategy worked better for preventing NO_x excursions than for CO excursions, and the lowest emissions were found during the phase when the stoichiometry changed from lean to rich. Finally, the researchers evaluated advanced emission reduction with hydrogen injection and plasma electrode before the catalyst was tested. The only measurable effect was a 9.0 percent CH_4 reduction during lean operation using a plasma electrode but no improvement with the catalyst operation. Overall, while the control system using the dual catalyst showed benefits in controlling emissions, additional advanced CH_4 cleanup did not prove feasible.

Keywords: Methane emissions, dual catalyst, dithering, transient plasma

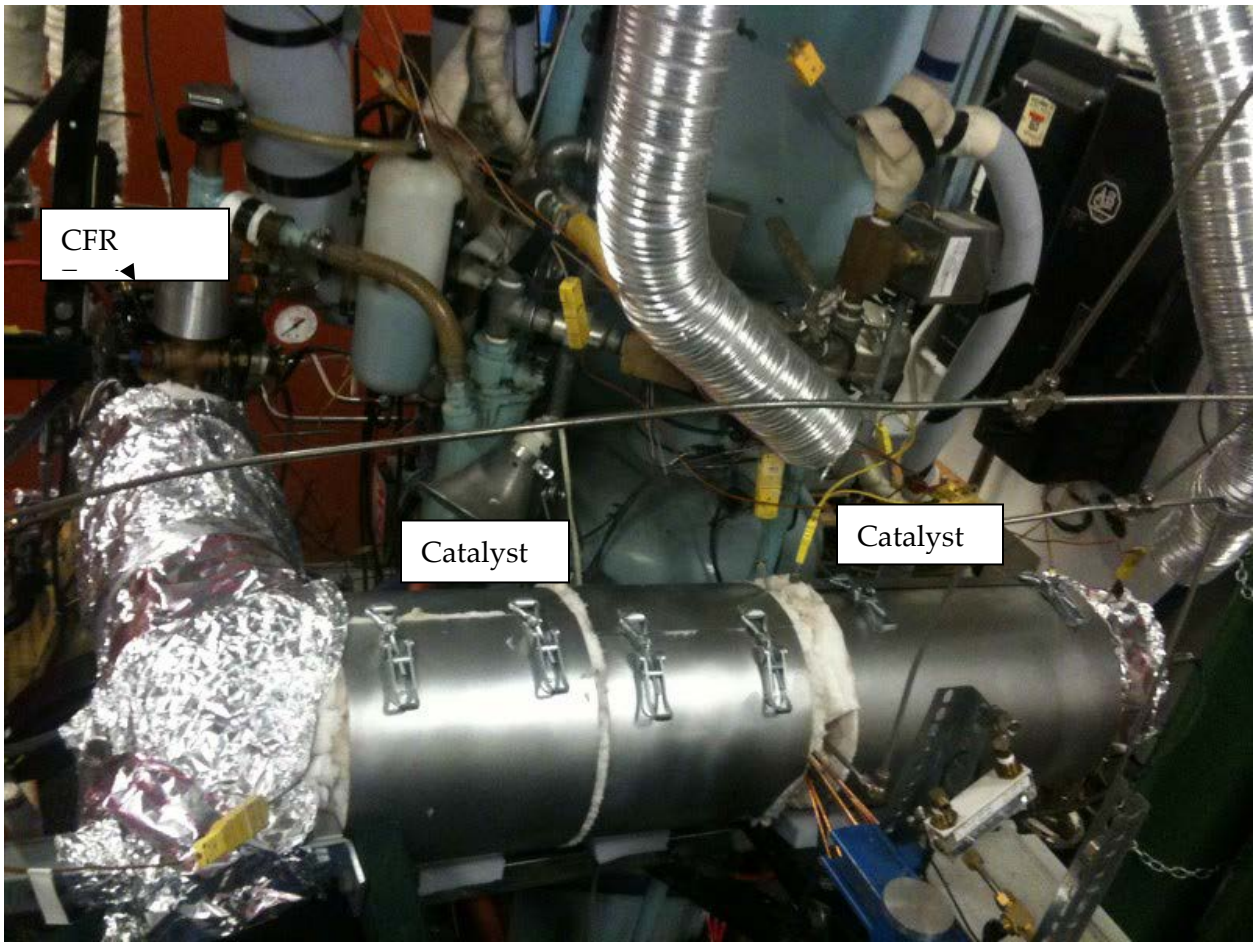
2.19.2TNG Introduction

The goal of this project was to reduce petroleum consumption by increasing the percentage of natural gas-powered vehicles in use and thereby to reduce greenhouse gas and tailpipe emissions. In California the share of compressed natural gas vehicles in buses and fleets is large (> 20 percent), but its share among passenger vehicles is still negligible. For California, the United States Energy Information Administration estimated an annual consumption of 25.7 trillion Btu of natural gas for transportation and transportation related uses. This may be compared with a motor gasoline consumption of 1770.1 trillion Btu. Increasing the share of compressed natural gas (CNG) vehicles by 10 percent would allow those consumers who purchase CNG vehicles to save on fuel costs. Based on a fuel consumption equivalent of 1.7 billion gallons for those CNG vehicles and a $1/gallon less fuel cost, those consumers would save $1.7 billion annually.

In addition, the researchers found that lower emissions could be obtained by using dithering and a second lambda sensor. A 10 percent improvement in emissions may allow CNG engines to operate at higher compression ratios, yielding an additional $50 million in fuel savings from efficiency gains. Finally, larger emission reductions may be possible with improved sensors and the associated improved feedback control. This could lead to even larger benefits for adopting CNG vehicles and the associated fuel and fuel cost savings. This method of emission reduction, however, must compete with other emission control techniques.

The primary advancement of science in this project was to create an effective process to reduce emissions associated with the operation of compressed natural gas vehicles. The main reason that CNG engines have higher emissions lies in the catalytic converter and is not fully understood. The reason could be the accompanying methane (CH_4) emissions, the higher water emissions, or the absence of other molecules. This study targeted two types of experiments for the purpose of reducing emissions from CNG-fueled engines. The first experiment was conducted using a control system that maximized the performance of a three-way catalyst by monitoring the catalyst conversion process and using the data to prevent excessive emissions of NO_x or CO during lean or rich cycle excursions. This was accomplished with a lambda sensor located between the two catalyst portions that monitored when the conversion wave left the first catalyst. Using a Cooperative Fuel Research (CFR) engine, the catalyst system had two catalysts in series, with NO_x sensors before, after, and between the two catalysts. This is shown in Figure 20. The catalysts and pipe sections were insulated to maintain the temperature at elevated levels.

Figure 20: Heated and Insulated Catalysts on CFR Engine



The researchers made two types of modifications in addition to the catalyst system. One was to inject additional compounds into the exhaust stream to react with the unburned methane or with species adsorbed on the catalyst. Even if the compounds would not react directly, they could possibly create an environment of radicals that would promote the reactions. The second modification was to insert a plasma electrode before the catalyst to create reactive species by non-thermal plasma.

2.19.3TNG Objectives

The goal of this project was to determine the feasibility of pollutant reduction from CNG engines in a three-way catalyst using a novel control system. The researchers established the following project objectives:

1. Identify at least five preliminary test cases that lead to further understanding of the difference between gasoline and CNG performance.
2. Verify that measuring equipment is capable of measuring emissions with a standard deviation less than 5.0 percent.

3. Achieve tailpipe emissions below 0.064 pounds per megawatt hour (lb/MWh) NO_x, 0.091 lb/MWh CO, and 0.88 lb/MWh CH_4.

4. Identify at least five advanced test cases that lead to a reduction of CH_4 emissions.

5. Implement hardware and measuring equipment necessary for advanced tests. Verify that post injection of at least three reagents is within 5.0 percent accuracy.

6. Determine if CH_4 emissions can be lowered at least by 50 percent compared with the preliminary test results. Tailpipe emissions below 0.064 lb/MWh NO_x, 0.091 lb/MWh CO, and 0.44 lb/MWh CH_4.

2.19.4TNG Outcomes

1. The researchers selected four different CNG gasoline mixtures and two different stoichiometries as preliminary test cases. These cases indicated differences in the catalyst performance depending on the fuel and the stoichiometry.

2. O_2, CO_2, CO, and THC analyzers showed a standard deviation of 0.09, 0.18, 0.12, and 0.74 percent, respectively, of their calibration value. The NO_x analyzer showed a standard deviation of 5.94 percent of its calibration value and was therefore calibrated several times per day.

3. For a low compression ratio (6.5), the target emissions were achieved. The values obtained were 0.059 lb/MWh NO_x, 0.063 lb/MWh CO, and 0.24 lb/MWh CH_4. Non-methane hydrocarbon emissions (NMHC) were approximately 3.0 percent (0.007 lb/MWh). For a high compression ratio (10), the target emissions could not be met, because high CH_4 engine-out emissions of the CFR engine (~7000ppm) overwhelmed the catalyst and control system. Modern engines have much lower engine-out emissions and should therefore meet the target emissions even at higher compression ratios.

4. The researchers set up advanced tests by modifying the exhaust stream before the catalyst. They included a plasma electrode, H_2 injection, and, for reference, CH_4 injection. The researchers considered lean, stoichiometric, and rich conditions.

5. The researchers installed a plasma electrode in the exhaust stream. The electrode was capable of generating plasma up to 20 kV, 2000 Hz, with pulse duration of 10 nano seconds (ns). The researchers calibrated the gaseous injection into the exhaust with a wet test meter with an accuracy of 0.5 percent and yielded a coefficient of variation of 0.61 percent.

6. Under lean operating conditions the plasma electrode reduced CH_4 emissions by 9.0 percent. Other operating conditions, as well as the injection of H_2 before the catalyst, did not achieve the CH_4 emission reduction target of 50 percent. The emissions of 0.059 lb/MWh NO_x, 0.063 lb/MWh CO, and 0.24 lb/MWh CH_4 were, however, already below the emission objectives.

2.19.5TNG Conclusions

1. The researchers met this objective by identifying six operating conditions to characterize the catalyst for engine operation on gasoline and CNG.

2. All analyzers except the NO_x analyzer met the criterion of standard deviation less than 5.0 percent. Therefore, the reseachers calibrated the NO_x analyzer more frequently. The objective was met by successfully installing a non-thermal plasma electrode before the catalyst. The electrode was able to generate plasma at 20 kV and a pulse frequency of 1500 Hz.

3. The goal of reducing the CH_4 emissions by an additional 50 percent by using an advanced emission control system was not met. Hybrid operation with 10 percent gasoline did not reduce CH_4 emissions more than proportionately. The use of hydrogen did not affect the catalyst measurably. The use of a plasma electrode did reduce CH_4 emissions slightly but not the cost or energy efficiency. The plasma was less efficient near stoichiometric conditions where the oxygen content was low.

4. The researchers generally met this objective.

5. For low compression ratios, the set emission targets (0.064 lb/MWhr NOx, 0.091 lb/MWhr CO, and 0.88 lb/MWhr CH_4) were met, while for higher compression ratios they were not.

6. Analysis of the preliminary data showed that the CFR engine generated very high CH_4 emissions especially at higher compression ratios. This served as a stringent test for the after-treatment devices. In addition, the researchers found that large CH_4 emissions make it much more difficult to reduce CO and NO_x in the catalyst. Both are two important regulated emissions. The objective was met by identifying more than five operating conditions for testing an advanced pollutant reduction system. It included two different compression ratios.

The researchers reached several other conclusions from the current study that may help others in judging aspects of emissions from CNG engines.

- Even with redundant sensors, not all the data could be obtained. Both the O_2/NO_x sensors and the injection system could only provide feedback control on the order of seconds. The O_2/NO_x sensors are also sensitive to other species, such as ammonia (NH_3), which is reported as NO_x. These emissions may need to be monitored in the future.

- The researchers concluded that improvement to the experimental setup could be made in the following areas: increasing the response time of the O_2/NO_x sensor by properly setting up the CAN-bus protocol or using an analog signal, adding a small injector with custom pulse width modulation for adding fuel components instead of the flow controllers, and refurbishing the NO_x analyzer for more stable output and more ranges of calibration gases.

- The engine-out emissions of CH_4 should be reduced as much as possible for the present palladium-based catalyst to work better. Contrary to that, engines with higher compression ratios for operation on CNG may have higher engine-out emissions of CH_4. The emission reduction of CH_4 on the catalyst was excellent only at the stoichiometric point when transiting from lean to rich but relatively poor at all other operating conditions.
- The use of dithering the fuel in combination with a second oxygen sensor between two catalysts helped to derive a control strategy for keeping emissions low. This may help to control older retrofit engines or in operating conditions where engines deviate from stoichiometric conditions. If many currently operating engines are identified as equipped with a three-way catalyst but not meeting the emission limits, the use of two catalysts and sensors could have the potential to be marketed as an inexpensive solution for the operators. With further experience gained from these engines and the testing on modern CNG engines, researchers may be able to evaluate if this system has a commercial advantage over existing technologies.

Overall the researchers were not able to meet all their objectives. The increase in compression ratio to a value consistent with maintaining the efficiency of a competitive engine created a significant increase in CH_4 emissions, along with an increase in NO_x and CO. As a result, the project did not meet the technical feasibility test. The control system using the dual catalyst showed benefits in controlling emissions. However additional advanced CH_4 cleanup did not prove feasible. Therefore a field test plan will not likely show any improvement over the test cell results already obtained.

The researchers did not establish the feasibility of the simultaneous reduction of NO_x/CO/CH_4 emissions from a natural gas engine as proposed. Substantial additional research is needed, but it may not produce cost effective results unless there is an assumption that the benefits of CNG use (reduction of greenhouse gases, lower non-methane hydrocarbon emissions, domestic fuel) at least equal the negatives (higher vehicle cost, lower fuel range, higher CH_4 emissions).

2.19.6TNG Recommendations

The Program Administrator recommends that the researchers:

1. Investigate the use of an improved sensor between the catalysts for better detection of both lean and rich excursions.
2. Cross check the performance of commercial automotive catalysts or newer non-proprietary catalyst formulations.
3. Conduct theoretical modeling of the catalyst to better understand the reactions occurring temporally (time dependant) and on the catalyst surface including oxygen storage and catalyst oxidation.
4. Quantify NH_3 (ammonia) emissions during the operation of a CNG-fueled engine.

5. Conduct tests with non-thermal plasma in the 50 kV range with shorter pulse times in a smaller flow cell to see if CH_4 emissions can be reduced more efficiently.
6. Conduct field studies on CNG-fueled engines with three-way catalysts using the knowledge gained from the current study. This includes measurement of CH_4 in engine-out and tailpipe emission for various engine technologies.

2.19.7TNG Benefits to California

Public benefits derived from PIER transportation research and development projects are assessed within the following context:

- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased use of alternative fuels

The primary benefit to the ratepayer from this research would be the increased use of alternative fuels. Lowering the emissions of CNG vehicles would support a transition toward a 10 percent market share of CNG vehicles which in turn could save $1.7 billion in fuel annually. Time to market could be 5 to 10 years.

The researchers found that lower emissions could be obtained by using dithering and a second lambda sensor. A 10 percent improvement in emissions may allow CNG engines to operate at higher compression ratios, yielding an additional $50 million in fuel savings from efficiency gains. However these benefits may take significant time to reach the market.

Larger emission reductions may be possible with improved sensors and the associated improved feedback control. This would lead to even larger benefits for adopting CNG vehicles and the associated fuel and fuel cost savings. This method of emission reduction, however, must compete with other emission control techniques.

2.19.8TNG Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers did not perform a market analysis nor did they contact potential customers. They suggested automotive manufacturers may have advanced catalyst and control systems that are not in the public domain. The researcher did disclose using a dual catalyst in a technical paper.

Engineering/Technical

The researchers plan to focus on the dual catalyst control including a better lambda-type sensor. They project a period of not less than two years to improve the sensor.

Legal/Contractual

There is no indication that the researchers have sought patent protection.

Environmental, Safety, Risk Assessments/ Quality Plans

Because of the state of development, these plans are not relevant.

Production Readiness/Commercialization

Because of the state of development, commercialization planning is premature.

2.20TE Potential Rooftop Photovoltaic Electricity for Sustainable Transportation in California

Awardee: University of California, Santa Barbara

Principal Investigator: Roland Geyer

2.20.1TE Abstract

This investigation was a model study into important questions about PV-powered electricity for sustainable transportation in California. The study asked: If every California household adopted electric vehicles for their total annual vehicle miles traveled and installed photovoltaic panels on their rooftop to power them, would there be enough rooftop area in California to provide the necessary amount of electricity? A second question asked: Would such panels be effective at smaller geographical areas such as the community level? A third question was: Would it be cost effective to power individual household vehicle miles traveled by rooftop PV?

For this analysis, the researchers developed a statistical regression model which uses United States Census demographic variables to predict the total amount of rooftop area at the Census block group level. The researchers established quantitative relationships between total rooftop area, rooftop area suitable for PV, and potential annual rooftop PV electricity output. Importantly, the researchers validated values predicted by the regression model with data from the CH2M-Hill Solar Automated Feature Extraction (SAFE) model which is based on LIDAR measurements for all built structures in Los Angeles County. The model estimated that potential all-electric household transportation electricity demand statewide was between 23 percent and 27 percent of total potential rooftop PV electricity supply. Thus California's estimated rooftop PV electricity potential is about four times larger than needed for its potential all-electric household transportation electricity demand.

In addition to determining the possibility of replacing all household driving with rooftop PV-powered electric vehicles, the researchers also evaluated the feasibility of three different battery electric/plug-in hybrid electric vehicle (BEV/PHEV) adoption scenarios within California. The study concluded with estimates for rooftop PV electricity cost per vehicle mile traveled as compared to conventional gasoline, as well as development of a web-based map portal where all results could be interactively explored. The model predicted that, amortized over a 30 year PV life, the cost per vehicle mile traveled at present prices was lower for a BEV than a gasoline powered vehicle.

Keywords: Renewable energy, electric vehicles, sustainable transportation, rooftop PV electricity

2.20.2TE Introduction

Due to California's mix of electricity sources, plug-in electric vehicles charged from today's electrical grid offer an attractive effective emissions mpg equivalent to a gasoline powered vehicle with 78 mpg.[27] Since 53 percent of California's in-state electricity is derived from natural gas (2010), a fossil fuel-free source of electricity such as PV would be an improvement in emissions.[28] However, since a large-scale switch to grid-provided electricity could lead to an overloaded grid, a distributed rooftop PV supply would be especially attractive. Ideally a distributed system at the local neighborhood or community scale would minimize grid problems. Answers to the three researched questions required data on a fine-grained geographical scale, such as a Census block group. A Census block group is a geographical unit used by the United States Census Bureau which is between the Census tract and the Census block.[29] The Census block group is the smallest geographical unit for which the bureau publishes sample data, i.e., data which is only collected from a fraction of all households. Typically block groups have a population of 600 to 3,000 people. Important questions still need to be answered: Is there sufficient insolation at the local level, is there enough suitable roof area for PV, is the PV supply well matched to the driving habits of the local users, and is the approach cost effective for the users? A transportation model giving answers to these questions would be a valuable community resource for reducing California's GHG emissions from transportation.

A successful transportation model would yield large payoffs in reduced emissions. In 2012, total California greenhouse gas emissions (GHG) were 459 million metric tons equivalent (MMT).[30] Importantly, the transportation sector was the largest source of California emissions, accounting for approximately 37 percent of the total, and on-road vehicles were responsible for more than 90 percent of the transportation emissions. Accordingly, up to 150 MMT of annual emissions from fossil fueled on-road vehicles could be eliminated by the adoption of PV-powered electric vehicles. With such a transportation model, individual communities could evaluate the reductions available in their GHG emissions. In response, solar businesses could focus their marketing to those areas where the benefits are greatest and most attractive to their customers.

The advancement of science or technology proposed in this project was the development of a model based on the available rooftop area and potential PV energy within Census block groups (CBG). The researchers' modeling approach sought to generate a reasonable estimate of the available rooftop area and potential supply of distributed PV energy for the 30,258 CBGs in California. The researchers approach would be to:

- Model available rooftop area and potential PV energy within CBGs.

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27 http://www.ucsusa.org/sites/default/files/legacy/assets/documents/clean_vehicles/electric-car-global-warming-emissions-report.pdf

28 http://energyalmanac.ca.gov/overview/energy_sources.html

29 http://en.wikipedia.org/wiki/Census_block_group

30 http://www.arb.ca.gov/cc/inventory/pubs/reports/ghg_inventory_00-12_report.pdf

- Validate the model of total and available rooftop area.
- Model the vehicle miles traveled per block group and electric energy required.
- Compare rooftop area available for solar PV with the area required for the vehicle miles traveled.
- Estimate cost per vehicle mile traveled for PV BEV and internal combustion vehicles for all CBGs.
- Disseminate spatial results on the web for all CBGs in California.

To validate the model of total and available rooftop area, the goal was a level of agreement > 80 percent between the model results for rooftop area with measured values for 30 block groups (a 0.1 percent sample). The model incorporated estimates of the vehicle miles traveled per block group and electrical energy (available rooftop area) required to fuel it. The researchers then estimated transportation energy demand from electric vehicles for all the CBGs in California under different renewable portfolio standard scenarios of electric vehicle adoption rates. It compared the rooftop area available for solar PV with the area required to meet the demand for transportation. The researchers determined ratios of potential distributed rooftop PV supply over forecast transportation fuel demand in some or all renewable portfolio standard scenarios. They estimated the cost per vehicle mile traveled for PV BEV and compared it to gasoline powered internal combustion vehicle transport for all the CBGs in California and demonstrated in which communities PV may become cost competitive with gasoline. Finally, the researchers' model provided spatial results on the web with a mapping site to display interactive maps of solar potential, driving demand, and associated variables like rooftop area by CBG.

2.20.3TE Objectives

The goal of this project was to determine the technical feasibility of generating sufficient solar PV power for battery electric vehicles to meet local demand in sustainable communities across California. The researchers established the following project objectives:

1. Model the available rooftop area and potential PV energy within CBGs. Demonstrate that the modeling approach is capable of generating a reasonable estimate of the available rooftop area and potential supply of distributed PV energy for 30,258 CBGs in California.
2. Validate the model of total and available rooftop area. Demonstrate a level of agreement > 80 percent between the model results for rooftop area with measured values for 30 block groups (~0.1 percent sample).
3. Model the vehicle miles traveled per block group and the available rooftop area required to provide the required energy. Estimate transportation energy demand from electric vehicles for 30,258 CBGs in California under different renewable portfolio standard scenarios of electric vehicle adoption rates.
4. Compare the rooftop area available for solar PV with the area required to meet the

demand for transportation. Demonstrate that distributed rooftop PV is capable of meeting the transportation fuel demand in some or all renewable portfolio standard scenarios.

5. Estimate cost per vehicle mile traveled for PV BEV and compare it to gasoline internal combustion vehicle transport in all CBGs in California. Demonstrate in which communities PV may become cost competitive with gasoline.

6. Disseminate spatial results on the web. Create a mapping site with interactive maps of solar potential, driving demand, and associated variables (e.g., rooftop area) by CBG.

2.20.4TE Outcomes

1. The researchers developed model estimates of the available rooftop area and potential PV energy within CBGs. In the aggregate, they estimated that the total amount of available building rooftop area over all Census 2012 block groups was 5,754 km^2 which was 1.36 percent of the total physical area of California, and the total amount suitable for the installation of PV panels was 1,482 km^2. The researchers estimated total potential PV electricity supply from a full utilization of the suitable rooftop area to be 346 – 462 terawatt hours per year. In comparison, California's total in-state electricity production is currently about 200 terawatt hours per year.

2. The researchers developed a model which could predict total and available rooftop to a level of agreement of 64 percent for rooftop area with measured values for 30 block groups in LA County, not 80 percent. The fact that measured block groups data contain not just residential but also commercial rooftops limits the predictive power of demographic data.

3. The researchers estimated that the total distance traveled by the vehicles of all Census 2012 block groups in California households to be 324 billion miles per year. If all household vehicle miles traveled were in electric vehicles, they estimated the total transportation electricity demand to be 94—107 terawatt hours per year depending on assumed electric vehicle efficiencies.

4. The researchers found that the potential all-electric household transportation electricity demand was between 23 percent and 27 percent of total potential rooftop PV electricity supply aggregated across all Census 2012 block groups. Thus California's estimated rooftop PV electricity potential is about four times larger than needed for its potential all-electric household transportation electricity demand.

5. Over all Census 2012 block groups, the researchers estimated PV-based transportation electricity to be 4.9 cents to 7.0 cents per vehicle mile traveled, assuming $8/W DC installation cost, 30 years PV system lifetime, and 0.29 to 0.33 kWh/mile BEV electricity. Gasoline-based internal combustion vehicle fuel cost was 13.3 cents per vehicle mile driven, assuming $4/gallon gasoline and 30 mpg internal combustion vehicle fuel

economy.

6. The researchers created interactive web mapping sites for model results : http://cdb.io/1oJatwm (suitable rooftop area); http://cdb.io/1oJbWTs (potential rooftop PV output); http://cdb.io/1oQYmM1 (VMT); http://cdb.io/1nYUAlv (transportation electricity demand); http://cdb.io/1vhpn2v (demand over supply ratio); http://cdb.io/UtFxW8 (PV transportation electricity cost).

2.20.5TE Conclusions

1. The available rooftop area and potential PV energy for California has a whole are more than sufficient to meet transportation needs, and they are adequate within CBGs.
2. The researchers demonstrated the model of total and available rooftop area has a level of agreement of 64 percent between the model results for rooftop area with measured values for 30 block groups. They identified the shortfall in agreement as due to the inclusion of commercial rooftops in the measured data.
3. The researchers concluded that for the vehicle miles traveled per block group there is adequate electrical energy (available rooftop area) required to fuel it.
4. California's estimated rooftop PV electricity potential is about four times larger than needed for its potential all-electric household transportation electricity demand.
5. Amortized over a 30 year PV life, the cost per vehicle mile traveled at present prices is lower for a BEV than a gasoline internal combustion vehicle.
6. The researchers established web sites for suitable rooftop area, potential rooftop PV output, transportation electricity demand, demand to supply ratio, and transportation electricity cost.

In general, all objectives were substantially met. In particular, the researchers proved the technical feasibility of generating sufficient solar PV power for battery electric vehicles to meet local demand in many communities across California.

2.20.6TE Recommendations

The Program Administrator recommends that the researchers establish contacts with electric utilities, very large stakeholders in this development, to get their input. Successful implementation of the sun-to-wheels program will require their cooperation. The researchers should explore and evaluate the question of local or on-site storage of electricity. It could be a subject of great interest to utilities. The economic benefits to both individuals and utilities of growing the rooftop PV and BEV industries through a dedicated PV-based sun-to-wheels program could be substantial. The researchers also should investigate and promote policy measures which could help at the early stages of rooftop PV and BEV diffusion until learning curve effects and economies of scale have reduced investment costs to a point where mass adoption can be expected.

After taking into consideration (a) research findings in the grant project, (b) overall development status, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for subsequent funding within the PIER program.

Receiving subsequent funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

2.20.7TE Benefits to California

Public benefits derived from PIER transportation research and development projects are assessed within the following context:

- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased use of alternative fuels

The primary benefit to the ratepayer from this research is reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use. A successful transportation model could yield large payoffs in reduced emissions. In 2012 total California greenhouse gas emissions (GHG) were 459 million metric tons equivalent (MMT). The transportation sector was the largest source of California emissions, accounting for approximately 37 percent of the total. On-road vehicles were responsible for more than 90 percent of the transportation emissions. Up to 150 MMT of annual emissions from fossil fueled on-road vehicles could be eliminated by the adoption of PV-powered electric vehicles. With such a transportation model, individual communities could evaluate the reductions available in their GHG emissions. Solar businesses could focus their marketing to those areas where the benefits are greatest and most attractive to their customers.

2.20.8TE Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The researchers did not indicate that they are connecting with the market.

Engineering/Technical

The researchers did not suggest that they planned additional engineering/technical efforts.

Legal/Contractual

The researchers plan to put the results of their research in the public domain.

Environmental, Safety, Risk Assessments/ Quality Plans

There does not seem to be a need for such plans at this time.

Production Readiness/Commercialization

The researchers plan to put the results of their research in the public domain and publish the results of this study, which will aid in its adoption.

2.21TNG Catalysis of Natural Gas for a Diesel Engine

Awardee: Discovery Fuel Technologies, LLC

Principal Investigator: David McCann

2.21.1TNG Abstract

Transportation engines burning natural gas fuel can be 25 percent more efficient using compression ignition (diesel cycle) compared to spark ignition. Currently this is not possible because the heat of compression is not sufficient to ignite natural gas fuel. The addition of small amounts of dimethyl ether to the natural gas fuel allows the fuel mix to ignite with the heat of compression. Researchers in this project proposed to develop a prototype catalytic reactor to provide on-board formation of dimethyl ether (DME) using natural gas as an input to the reactor. This project consisted of the design, fabrication, characterization, and testing of a micro-channel reactor. The oxygenate reactor is one component of a system for operating transportation engines fueled with natural gas in a compression ignition mode.

The researchers analyzed a prototype catalytic reactor for heat flow, reactant flow, performance characteristics, manufacturability, and cost. During the course of the project the researchers made significant changes to the design to ensure manufacturability, durability, catalyst activity, and protection against physical catalyst loss.

The research team demonstrated that a micro-channel reactor is a potential platform for oxygenate (DME) production from syngas. The researchers did not meet a number of performance targets during the research effort. Performance objectives for catalyst coating and adhesion became moot due to a design change incorporating catalyst micro pellets into the micro-channel device. Conversion efficiency was low, and the platform exhibited significant temperature swings under transient operation. The researchers documented several areas of necessary improvements before the concept could be deemed technically feasible.

Keywords: Combustion, natural gas, oxygenate, catalysis, diesel, automotive, fuel delivery

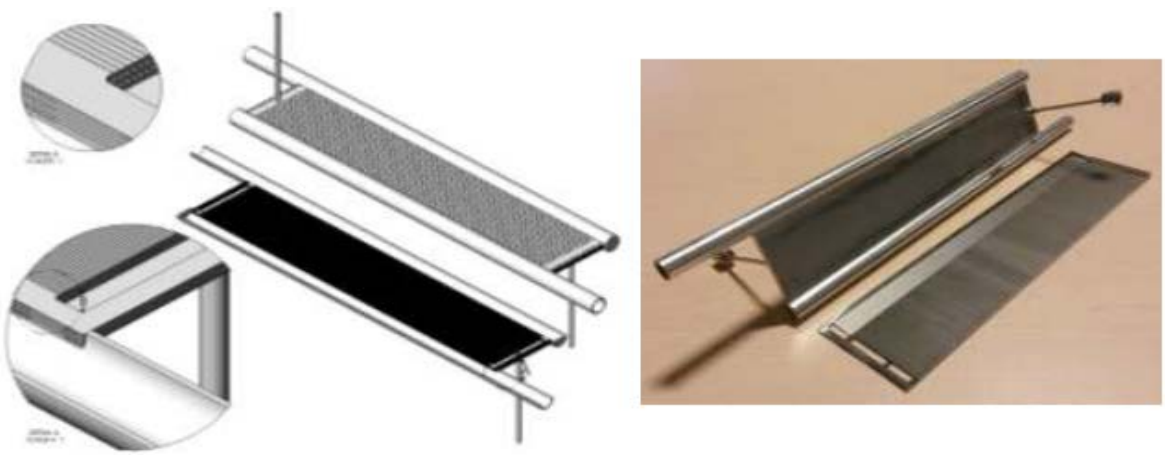
2.21.2TNG Introduction

Natural gas is readily available and priced competitively to traditional and alternative transportation fuels. Natural gas has been used in transportation applications for decades, but it has been limited to spark ignition engines. Advances in diesel engine technology with respect to emissions have re-invigorated the market for diesel engines in California, largely because of their high inherent efficiency. A method to allow compression ignition of natural gas could take advantage of both the supply and price of natural gas and the efficiency of diesel technology in transportation applications.

Diesel engines are approximately 25 percent more efficient than their spark ignition counterparts. Diesel engines rely on the temperatures produced from compression within the engine cylinder as the source of the combustion, versus a spark plug for ignition in gasoline engines. At the temperatures produced by compression, diesel fuel readily ignites. However natural gas does not and cannot be used in a diesel cycle engine by itself.

The researchers in this project proposed a solution to the source of ignition for natural gas in a diesel engine that adds another chemical/fuel. The aim of this EISG project was to evaluate the feasibility of one part of a system to produce a compression ignitable fuel on-board from a portion of the natural gas. The prototype has cross flow channels containing catalyst. The channels accommodate heat exchange and fuel flow catalyst exposure. The prototype reactor developed in this project is shown in Figure 21.

Figure 21: Prototype Oxygenate Synthesis Device Reactor



2.21.3TNG Objectives

The goal of this project was to determine the feasibility of production of an oxygenate fuel directly from syngas with a micro reactor approach. This is one part of a system to allow natural gas use with a diesel engine. The researchers established the following objectives:

1. Demonstrate the size of the reactor is 20 percent smaller than a reactor containing catalyst pellets.

2. Achieve a cost of less than $10,000 per device.
3. Demonstrate the acetone/ultrasound test does not lose more than 10 percent of catalyst loading.
4. Demonstrate mass loss is less than 5.0 percent for the Scotch® tape test.
5. Confirm through imagery there are no visible deficiencies in the catalyst surface.
6. Demonstrate steady-state efficiency equivalent to that of bench (75 percent).
7. Achieve a steady-state pressure drop less than 20 percent of desired operating condition.
8. Demonstrate steady-state 100 hour lifetime at greater than or equal to 80 percent of maximum conversion efficiency.
9. Demonstrate temperature swings to be less than 10° C (20° F) during transient testing.
10. Demonstrate 75 plus or minus 10 percent conversion during transient testing.
11. Demonstrate that less than or equal to 4.0 percent energy use of a diesel engine is possible.
12. Confirm that the produced oxygenate fuel has preferential ignition characteristics by comparison to literature.
13. Demonstrate a target system cost of within 20 percent of a current base system (less than $4,000 on a $20,000 vehicle).

2.21.4TNG Outcomes

1. The researchers fabricated the prototype Oxygenate Synthesis Device. They calculated its internal volume to be 4.86 milliliters (mL) which was more than 20 percent smaller than the 6 mL simple laboratory reactor for comparison. The original design using catalyst coated on plates was abandoned in favor of the cross channel design depicted in Figure 21 and the use of small pellets of catalysts.
2. The researchers estimated a cost of under $9,000 per device including materials and fabrication based on a manufacturing level of 100,000 units.
3. The researchers switched catalyst incorporation from coating to pellets, minimizing concerns for adhesion. They tried approaches with coatings but did not demonstrate effective adhesion. The researchers did not complete acetone/ultrasound tests for catalyst loading loss.
4. The researchers tested catalyst loading loss on coated samples using Scotch® tape which was greater than 5.0 percent, exhibiting essentially zero adhesion of catalyst to substrate.
5. The researchers did not perform imagery evaluation of the catalyst. They instead used catalyst performance in terms of conversion efficiency and selectivity to evaluate catalyst incorporation into the prototype.

6. The researchers measured conversion efficiency of the prototype using the pellet and channel design to be 23.8 percent at 50 mL/min 240° C (464° F) and 30 bar of pressure compared to the laboratory reactor's value of 86.2 percent CO conversion at 50 mL/min, 240° C (464° F) and 30 bar of pressure.
7. The researchers measured the prototype's pressure drop to be less than 0.03 bar when operating at 6 bars.
8. The researchers measured the conversion performance of the catalyst, showing it maintained at least 80 percent of maximum for 60 hours and then dipped slightly below 80 percent of maximum.
9. The researchers measured temperature swings of up to 15° C (27° F) in the prototype when switching from low to high fuel flow.
10. The researchers determined that the conversion efficiency under transient conditions stayed within plus or minus 10 percent of the 75 percent of the CO conversion efficiency (>80 percent) under steady-state testing.
11. -The researchers calculated that the device scaled to a full-size engine would require 1.5 kW of energy to operate.
12. The researchers compared properties of dimethyl ether (DME), the produced oxygenate, to properties of diesel fuel (cetane number and auto ignition temperature) and concluded that the production of DME and injection along with natural gas would perform in a diesel engine. However they performed no physical tests showing this.
13. The researchers estimated a unit cost of $1,593 at a production level of 100,000 units sized to a $20,000 automobile.

2.21.5TNG Conclusions

1. The concept of coating a catalyst onto a substrate was not effective, and the original design was abandoned. The researchers did develop an alternate design using micro pellets of catalyst that was more than 20 percent smaller than an equivalent reactor with normal sized pellets. The researchers completed this objective.
2. The calculated cost to manufacture the reactor was below the established metric of $10,000. The researchers met this objective
3. The catalyst coating approaches demonstrated essentially zero adhesion. The researchers did not complete this objective, but this objective became moot with the alternative design.
4. The Scotch® tape test confirmed little to no catalyst adhesion. The researchers completed this objective, but the test showed failure of adhesion.
5. The researchers did not complete the objective of imaging the catalyst.

6. The catalyst loading and design under test conditions converted under 24 percent of the feedstock to DME. The researchers did not complete this objective.
7. The reactor had a pressure drop of 0.03 bars when operated at 6 bars, or about 0.5 percent. The researchers completed this objective.
8. The catalysts maintained conversion efficiency for 60 hours of steady-state operation. The researchers did not complete~~d~~ this objective.
9. Transient operation of the reactor (changes in feedstock flow) produced significant temperature swings due to the exothermic nature of the reaction of CO+H2 to form DME combined with insufficient heat management. The researchers did not achieve this objective.
10. Under transient operation (changes in feedstock flow) the reactor maintained conversion efficiency converting syngas to DME. The researchers achieved this objective.
11. Operation of the reactor as tested consumed nearly 4.0 percent of the power of the hypothetical engine. The researchers completed this objective, but without much room to spare.
12. The produced DME should allow for compression ignition of natural gas in a diesel cycle engine. This needs verification under physical testing. The researchers completed this objective.
13. Cost estimates for material and fabrication indicate reasonable costs under mass production assumptions. The researchers completed this objective.

The research team demonstrated that a micro-channel reactor is a potential platform for oxygenate (DME) production from syngas. During the research effort a number of performance targets were not met. Performance objectives for catalyst coating and adhesion became moot due to the design change of incorporating catalyst micro pellets into the micro-channel device. Conversion efficiency was low, and the platform exhibited significant temperature swings under transient operation. The researchers documented several areas of necessary improvements before the concept could be deemed technically feasible.

2.21.6TNG Recommendations

While the researchers did not obtain many of their original objectives, they did show a potential design that might prove effective. To prove this new concept, the Program Administrator recommends that the researchers:

- Improve the design with a focus on improved conversion efficiency and heat management. Catalyst loading, reactor size for heat management, and flow properties all need improvement. Flow properties should move toward turbulent flow, which may be difficult given the small diameter channels containing the catalyst.
- Work on methods for on-board conversion of natural gas (methane) to syngas (CO+H2), an endothermic reaction typically achieved through steam reforming.

- Verify that DME satisfactorily allows compression ignition of natural gas in diesel cycle engines under physical testing.
- Determine the percent-of-fuel charge (DME/methane) required for operation, including the effect of different percentages on pre-ignition and late ignition.
- Investigate cold start needs and begin mapping engine performance under differing loads and conditions (e.g., cold start, hot start).

2.21.7TNG Benefits to California

Public benefits derived from PIER transportation research and development projects are assessed within the following context:

- Improved transportation energy efficiency
- Reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use
- Increased use of alternative fuels

The primary benefit to the ratepayer from this research is from improved transportation energy efficiency.

Use of a natural gas fuel system in diesel cycle engines could provide direct price savings for California ratepayers of approximately $780 per year/per vehicle, assuming current natural gas and gasoline prices and automobile efficiencies. A modest 18,000 vehicle penetration could provide California ratepayers an annual savings of $14 million dollars. A secondary benefit to California could be a cost effective reduction in transportation related greenhouse gas emissions.

2.21.8TNG Technology Transition Assessment

As the basis for this assessment, the Program Administrator reviewed the researchers' overall development effort, which includes all activities related to a coordinated development effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

There are a number of marketing and commercialization risks, including but not limited to the fueling infrastructure. While natural gas fueling stations are becoming more prevalent, they remain dispersed and often restricted to fleet use. The researchers have not completed a market assessment or survey of potential customers. The market in California represents approximately 22 million vehicles, with perhaps 1.5 to 2.0 million new vehicles per year. The researchers received expressions of interest from a manufacturer of medium-sized diesel engines.

Engineering/Technical

The researchers are working to identify optimal engine fueling, full-size efficient reactors, and the integration for a complete system. Engineering will follow.

Legal/Contractual

The researchers applied for a patent, number US 2013/0220239 A1. They have completed a patent search and found no conflicting patents.

Environmental, Safety, Risk Assessments/ Quality Plans

Production of DME onboard vehicles poses a potential safety risk. While remote under good engineering and manufacturing practices, the possibility of leakage (post reactor flow) of DME warrants special attention.

Production Readiness/Commercialization

The concept is not ready for production or commercialization.