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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: 2010 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

The California Energy Commission has been conducting the Public Interest Energy Research (PIER) program through competitive solicitations to advance science or technology in each of the seven PIER program areas to benefit California ratepayers since 1997. The Energy Innovations Small Grant (EISG) program, created in 1998, is a component of the PIER Program. The role of the EISG program is to advance research into new and innovative energy concepts and technologies whose feasibility is not yet sufficiently established to meet traditional research and development (R&D) funding requirements.

The Energy Innovations Small Grant (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 (IARs) are written at the completion of 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 twenty-four independent assessment reports for EISG grant projects awarded during 2010.

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

Please use the following citation for this report:

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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 the need for a program to support the early development of promising new energy technology concepts that are not mature enough to be covered by PIER general solicitations. The Energy Commission has established the EISG program to meet this need.

This report is a compilation of the Individual Assessment Reports (IARs) for grant projects that were awarded in 2010 and that have not been previously published.

All data sources for tables and figures are from the author unless otherwise noted.
### CHAPTER 1: Introduction

2010 EISG Projects with IARs Included in this Section

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CHAPTER 2:  
2010 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 2010 that have not previously been published.

2.1 Development of Flexible Dye Sensitized Solar Cells

Awardee: Miami University
Principal Investigator: Lei Kerr

2.1.1 Abstract

Manufacture of photovoltaic solar cells on flexible and lightweight substrates could lower costs and increase application acceptance. Flexible substrates could reduce costs through automated and continuous processes such as those used in paper manufacturing. This project focused on the production of solar cells on paper substrates. The research team demonstrated the technical possibility of the concept by fabricating a dye sensitized solar cell (DSSC) on a paper substrate, but it achieved only minimal efficiency. The team has also designed a new structured solid state solar cell based on a p-type hole conductor, CdS:Cu, which may enhance the possible application on paper substrates. The team developed a new method to distribute polymer homogeneously into TiO$_2$ nanocrystalline films, which could enhance performance of such a solar cell. Initial cost analysis showed potentially competitive production cost if efficiency can be improved. The researchers have published three peer reviewed journal articles and have submitted two patent applications. Product efficiency and stability need to be improved and demonstrated.

Keywords: Solar cells, paper substrate, flexible, dye sensitized, solid state, CdS

2.1.2 Introduction

Expanding the use of renewable energy remains a central component of California energy policy. Increasing the use of solar photovoltaic (PV) technology for electricity remains impeded due to noncompetitive costs compared to traditional power generation technologies. PV costs must be reduced significantly to compare favorably with grid supplied electricity. Dye sensitized nanocrystalline solar cell (DSCC) technology is one promising research area that might achieve this goal.

Most work on DSCC involves casting a molecular thin layer of a ruthenium-based dye on a porous film consisting of nanoparticles of titanium dioxide (TiO$_2$). The issues with glass substrates are their rigidity and heavy weight. By making DSCCs on a flexible polymer, metal, or paper substrate, the DSCCs can become flexible, portable, and lightweight. The advantage of flexible DSCCs is that they can be manipulated into any size or shape and incorporated into consumer goods. The most significant advantage of flexible solar cells is the potential for low
cost roll-to-roll mass production, which could greatly reduce PV manufacturing cost. Paper is cheaper than other substrate materials and more easily kept to within tolerance for thickness and uniformity. If DSSCs were made on paper, lamination and coating technology could improve their resistance to humidity.

In this project researchers developed and tested three different configurations of ruthenium based DSSC on paper substrates. The laminated structures included a plastic sheet top layer to protect from moisture. The devices are shown in Figure 1.

**Figure 1: Three Solar Cell Configurations Investigated in This Work:**

(a) CdS Coated TiO2 Solar Cell with Liquid Electrolytes

(b) Solid State CdS Coated TiO2 Solar Cell

(c) Control Sample of Ru Dye Sensitized TiO2 Solar Cell with Liquid Electrolytes

### 2.1.3 Objectives

The goal of this project was to prove the feasibility of printing dye sensitized solar cells. The researchers established the following objectives:

1. Demonstrate that good contact is established between the TiO₂ and a p-type hole conductor.

2. Demonstrate control samples on Ti foil and polymer substrate with at least 3 percent efficiency with an error of ±5 percent using a solid state p-type hole conductor for future comparison.

3. Demonstrate that the conductivity of the paper substrate will be comparable with fluorine-doped tin oxide (FTO) glass with sheet resistance lower than of 15 ohms per square millimeter (Ω/mm).

4. Demonstrate the reproducibility of solar cells using paper coating technologies with the cell efficiency within ±5 percent fluctuation, and demonstrate that the flexible solar cells on paper substrates have similar efficiency with the control samples on Ti foil and polymer substrates.
5. Verify the critical parameters in controlling the flexible solar cell performance on paper substrates, and provide the guidelines to improve solar cell efficiency.

6. Confirm that the projected PV cost from using the paper coating technology to make flexible solar cell on paper substrates is less than $1 per watt.

2.1.4 Outcomes

1. The researchers produced solar active layers that exhibited good contact and pore filling between the titanium and conductors. They investigated these two metrics using scanning electron microscopy.

2. The researchers fabricated control solar cells on Ti foil and PET polymer substrate and measured the efficiency at 3.75 percent efficiency (Table 1). The benchmark standard TiO$_2$ on glass substrate measured about 7 percent.

| Table 1: Solar Cell Performance of Flexible DSSCs on Ti Foil and Glass |
|-----------------|-----------------|-----------------|-----------------|
|                | $V_{oc}$ (V)    | $J_{sc}$ (mA/cm$^2$) | Fill Factor | Efficiency |
| Flexible DSSC   | 0.69            | 11.44            | 0.48         | 3.75        |
| Rigid DSSC      | 0.72            | 19.56            | 0.50         | 7.00        |

3. The researchers developed electrical conducting paper and measured the resistance at 8—10 $\Omega$/mm. They selected Nickel (Ni) as the conducting material on the paper substrate. Using scanning electron microscopy (SEM), the researchers demonstrated that a Ni film was uniformly deposited on the paper substrate.

4. The researchers fabricated dye sensitized solar cells on paper substrate. They measured the cells’ efficiency at 1.21 percent ($V_{oc}=0.56$ V, $J_{sc}=6.70$ mA/cm$^2$, Fill Factor=0.33). This was less than half the efficiency of the ZnO based DSSC on FTO/glass substrates.

5. The researchers produced consistent conductive paper substrate and produced minimally efficient DSSC on that substrate using a roller coater. The efficiency dropped compared to that described in Outcome 4 above, indicating a less than consistent method for roller coating or some other issue.

6. The researchers completed a life cycle cost analysis and product cost analysis that included consideration of the anticipated three to five year life of the concept product for comparison with standard photovoltaics with expected lives of greater than ten years. The researchers estimated the cost at $2.21$ per watt, including $1.90$ for battery. That compares to the researchers’ stated average cost of $9.20$ per watt for typical rigid structure PV, although the global market has become quite competitive and costs and prices have dropped considerably. Today’s price is in the neighborhood of $1.50$—$2.00/watt. The researchers also estimated the cell efficiency necessary for parity with
grid electricity at $0.10/kWh. They estimated at least 3—5 percent efficiency, depending on lifetime, is required.

2.1.5 Conclusions
1. It is possible to ensure good contact between TiO$_2$ nanoparticles and solar active conductors using the techniques developed by the researchers. The researchers met this objective.

2. The researchers were able to replicate DSSC efficiency on glass and metal foil to use as control benchmarks to isolate systemic from specific substrate issues relative to DSSC performance when cast on paper. The researchers met this objective.

3. Electrical conductive paper has the same or lower resistance than fluorine-doped tin oxide when coated with nickel as done by the researchers. The researchers met this objective.

4. It is possible to fabricate DSSC cells on paper substrate, but efficiency is very low given the state of development to date. The researchers met the objective of producing DSSC on paper but did not meet the objective of comparable efficiency relative to FTO or metal substrates.

5. Consistency of cell performance may be an issue for automated cells on paper. The lifetime of cells has not been tested and may be a further issue and compromised by consistency. The researchers did not meet this objective.

6. The cost of DSSC on paper shows promise with further development but is not yet competitive with either conventional or other DSSC substrate technologies, given the downward pressure on prices seen in the global market. The researchers met the project objective of completing a cost analysis, but they did not meet the broader goal of competitive cost.

The researchers achieved the overall goal of the project, which was to develop dye sensitized solar cells on flexible paper substrates. While they have demonstrated the technical feasibility of producing such cells on paper substrates, they have not yet demonstrated market feasibility.

2.1.6 Recommendations
The Program Administrator recommends the following actions:

1. The research team needs to improve significantly solar cell efficiency of the DSSC on paper substrate. This may include different solid state hole conductors and different treatment processes. Typically treatment processes include high temperature annealing, although that is unlikely practical for paper substrates.

2. The research team needs to investigate the stability and lifetimes of solar cells on paper substrates under various designs and environmental and use conditions. In conjunction with this, the researchers need to improve and document process requirements for
consistency of product performance. Finally, they should begin consideration of application types, as those will affect design and performance requirements.

3. The research team needs to develop prototype PV module on paper substrates including inter-cell connections, battery placement, and controls. The researchers should begin documenting engineering and manufacturing needs. In particular, they need to investigate encapsulation needs and approaches and determine trade-offs between encapsulation and product lifetimes.

4. The research team needs to find industry partner(s) to develop the technology once efficiency is improved and consistency issues are resolved.

5. The research team needs to begin analysis of disposal/recycling options, given the disposable nature of the expected 3—5 year lifetime. This may raise environmental concerns with widespread dispersal of rare earth containing wastes.

6. The researchers need to develop quality plans to ensure product consistency and durability for customer acceptance, even with the anticipated 3—5 year lifetime of the product.

7. The researchers and their production and commercialization partners will need to market their concept more broadly if and when technical hurdles are overcome. The research and development team will need to pay special attention to consumer perception of outdoor products made of paper.

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.

2.1.7 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 from increased affordability of electricity in California. Secondary benefits may accrue to the paper industry in California by
expanding its market for products and to the PV industry in California. Further, California’s economy may benefit overall through domestic manufacturing of the large demand for PV in worldwide markets and the demand required to meet California’s renewable portfolio standard. This benefit derives from avoiding monopoly-like and strategic pricing from dominant countries like China. Specific economic benefits and ratepayer savings cannot be estimated until product efficiency and lifetime issues are clarified.

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 have published three articles in peer reviewed journals. These papers may capture some attention by market makers or investors. The researchers had not performed a market analysis nor talked with potential customers by the end of the project.

Engineering/Technical

The researchers are seeking additional funding to continue their work to increase efficiency and to resolve lifetime issues.

Legal/Contractual

The researchers applied for patent protection through Miami University. They have applied for two separate patents, but neither has yet been awarded. The researchers have not entered into development agreements with any photovoltaic manufacturers or paper product producers.

Environmental, Safety, Risk Assessments/ Quality Plans

The researchers had not developed these plans by the end of the project. Some concern arises from widespread exposure of DSSC on paper substrates that could lead to dispersal of base or heavy metals like cadmium. This issue is potentially worse given that the concept is for disposable PV cells that are replaced after three to five years. In addition, some applications (e.g., clothing) may create safety problems from shock or burn risks.

Production Readiness/Commercialization

The product concept is not ready for production or commercialization. The researchers state that they will need a PV industry partner to commercialize the product.
2.2 High Efficiency LED-based Linear Fluorescent Replacement Lamp

Awardee: Lighting Research Center
Principal Investigator: Nadarajah Narendran

2.2.1 Abstract
The goal of this project was to determine the feasibility of developing an energy efficient LED-based linear lamp that would be a suitable and cost effective replacement for four foot fluorescent lamps in a wide range of luminaire types. The researchers sought to duplicate the form factor of existing fluorescent lamps to allow for retrofit installations where T8 fluorescent lamps were previously used. They developed design specifications using performance measurements and published data for T8 fluorescent lamps as a benchmark as well as Energy Star eligibility criteria. The researchers used high output blue LEDs, low loss optics, a patented remote phosphor scattered photon extraction (SPETM), a linear aluminum finned heat sink, and a standard bi-pin connection. Using commercially available two foot by four foot recessed fluorescent troffers, the researchers were able to demonstrate a 28 percent power reduction and luminous efficacy increase for the LED lamp compared to standard fluorescent T8 lamps. Although the LED lamp did not meet performance criteria for Color Rendering Index (CRI) and would thus not be Energy Star eligible, it met or exceeded most other performance criteria.

The researchers estimated the cost of each LED lamp to be $142. The lamp would have a useful life of 50,000 hours, which would result in reduced maintenance costs. Energy savings are estimated at $52 over the life of the LED lamp. Without significant rebates and incentives, it is unlikely that the proposed lamp would prove an economically viable alternative to fluorescent lamps.

Keywords: LED, replacement, linear, fluorescent, T8, efficacy, SPE, lamp, retrofit, white, remote, phosphor

2.2.2 Introduction
Four foot fluorescent lamps are the most widely used lighting technology in industrial and commercial settings. Although these lamps are inexpensive and efficient and have useful lives of approximately 20,000 hours, they contain mercury which is harmful to the environment. As LED technologies have improved, LED replacement lamps have been introduced to the market. Acceptance of these lamps has been poor due to inadequate color rendering and appearance, low light output, and insufficient light distribution.

The researchers proposed a linear LED-based replacement lamp that would mimic the performance and form factor of conventional fluorescent lamps, meet Energy Star eligibility criteria, and reduce energy consumption. Figure 2 shows the proposed LED T8 replacement lamp. Because the prototype uses a typical bi-pin connection, it would be suitable for retrofit installations. The researchers proposed using high output blue LEDs with a patented Scattered Photon Extraction (SPETM) technology on low loss optics to improve color rendering and color appearance while providing high intensity output. Reflectors and diffusers would then be
added to the prototype to enhance light distribution. The researchers selected performance criteria for luminous flux, efficacy, Correlated Color Temperature (CCT), Color Rendering Index (CRI), and intensity distribution based on measured and published data for T8 fluorescent lamps, as well as Energy Star eligibility criteria. The prototype was successful in meeting luminous flux, efficacy, and CCT criteria. However it was unable to meet Energy Star eligibility criteria due to low CRI. Although reflectors and diffusers aided in intensity distribution, surpassing current state-of-the-art T8 LED lamps, the prototype was unable to mimic the intensity distribution of fluorescent lamps.

The proposed technology may be used in industrial and commercial settings for new construction or retrofit installations. Although the intensity distribution of the proposed LED replacement lamp is better than current LED lamps, it may not be sufficiently similar to fluorescent lamps to provide even light distribution. The researchers estimate the cost of each LED lamp to be $142. This lamp would have a useful life of 50,000 hours, which would result in reduced maintenance costs. Energy savings are estimated at $52 over the life of the LED lamp. Without significant rebates and incentives, it is unlikely that the proposed lamp would prove an economically viable alternative to fluorescent lamps. Assuming that the distribution of lamps is identical to fluorescent installations and market penetration is 56 percent, the proposed technology could result in an energy savings in California of $413 million and a reduction in carbon emission of 2.2 million metric tons per year.
2.2.3 Objectives

The goal of this project was to determine the feasibility of developing an energy efficient LED-based linear lamp that would be a suitable and cost effective replacement for four foot fluorescent lamps in a wide range of luminaire types. The researchers established the following project objectives:

1. Determine product market needs and performance.
2. Develop lamp performance specifications for optimum luminous flux, luminous efficacy, color appearance, color rendering, and intensity distribution.
3. Identify high flux blue LEDs that provide at least 600 milliwatts at 350 milliamps.
4. Design optical components using SPE™ technology that exhibit optical efficiency providing light output at least 50 percent higher than state-of-the-art white LEDs.
5. Specify electronics that maintain high driver efficiency (92 percent or greater).
6. Design SPE based LED sources that provide white light at 150 lm/W.
7. Design total system efficacy of 110 lm/W or greater.
8. Assess the overall system cost to allow for a payback of less than three to five years through energy and maintenance cost savings.
9. Design the lamp for easy retrofit into a range of existing luminaire types.
10. Study the feasibility of designing a complete replacement lamp with a target retail price of $150.

2.2.4 Outcomes
1. The researchers identified common issues with state-of-the-art LED replacement lamps for T8 fluorescent lamps. To make the proposed LED replacement lamp an attractive alternative, the researchers set a goal to mimic the light output CCT and color rendering indices (CRI) of high performance T8 fluorescent lamps. Additionally, they proposed to use 25 percent less power, provide 25 percent more luminous efficacy, and meet Energy Star eligibility criteria for the LED lamp.
2. Performance specifications were determined as follows:
   • Luminous flux >= 2600 lm
   • Luminous efficacy >= 110 lm/W
   • CCT <= 3500 K
   • CRI >= 80
   • Intensity distribution to emulate T8 fluorescent lamps
3. The researchers tested five high flux blue LEDs. They measured the radiant output from the Nichia LED as 620 mW at 350 mA.
4. The researchers selected NYAG-4 yellow phosphor as a base and R640 red phosphor for layering, based on the peak wave length of the Nichia LED. They tested various optical configurations to minimize radiant power loss. The researchers varied the density of R640 on the optics and tested the efficacy, CCT, CRI, and radiant power as a function of red phosphor density for a single LED with phosphor coated optic. CRI fell outside of design specifications for all iterations. However CCT and efficacy targets were met. The researchers did not report the light output for state-of-the-art white LEDs. They reported efficacy measurements for individual LEDs using phosphor coated optics ranging from 130 to 141 lm/W.
5. The researchers investigated commercially available drivers and identified one with 88.5 percent efficiency.
6. Initial testing of the SPE-based LED package with NYAG-4 yellow phosphor measured output at 155 lm/W, 4400 K CCT, and 60 CRI. To lower CCT, the researchers added layers of R640 red phosphor. Layering of the red phosphor successfully decreased CCT, but resulted in efficacy measurements ranging from 130.1 to 140.6 lm/W.

7. Although Objective 7 only assessed the degree to which measured results met performance objectives for luminous efficacy, all performance objectives will be considered under this objective. The researchers measured the performance of the assembled prototype lamp under various conditions including no reflector, with reflector, reflector/diffusion lens, reflector/commercial driver, and reflector/diffuser/commercial driver. They reported the following results:
   - Luminous flux – Minimum of 1989 lm with reflector and maximum of 2606 lm for reflector/commercial driver.
   - Luminous efficacy – minimum of 98 lm for reflector/diffuser/commercial driver and maximum of 143 for no reflector.
   - CCT – 3500 K for all conditions tested.
   - CRI – 65 for all conditions tested.
   - Intensity distribution – the final report depicts intensity distribution charts for the SPE based lamp and reflector with and without a diffuser.

8. Existing fluorescent lamps cost approximately $2 and last approximately 20,000 hours. The researchers estimate the cost of the proposed LED lamp to be $142 and anticipate a life of 50,000 hours. Energy savings using the LED lamp are estimated to be $52.20. Including replacement costs and energy savings, the cost differential is approximately $85 over the life of the proposed LED lamp. The payback period would be a function of anticipated maintenance cost savings, rebates and incentives available, and retrofit type (more savings would be anticipated for a T12 retrofit than a T8 retrofit). These variables preclude calculation of an exact payback period.

9. The researchers designed and tested the proposed technology in commercially available two foot by four foot troffer luminaires.

10. The estimated cost of the proposed LED lamp was $142 based on a volume of 50,000 pieces.

2.2.5 Conclusions
   1. The researchers met the objective to assess market needs and performance.
   2. The researchers met the objective to establish performance specifications.
   3. The researchers met the LED output objective.
4. The researchers did not meet the objective to provide 50 percent more light output than state-of-the-art white LEDs. Nichia reports a range of 95 to 290 lm/W for cool white LEDs.

Although technological improvements in LEDs are proceeding rapidly, it is unlikely that the output for cool white LEDs was below 100 lm/W at the time the research was performed. Measured output for the LED using phosphor coated optics is within the range of 2013 state-of-the-art white LEDs and likely only slightly higher than estimated output for LEDs from a year ago. The researchers found that efficacy decreased and CRI increased with increasing phosphor density. To approach the CRI target, resulting efficacy was about 130 lm/W.

5. The researchers did not meet the objective to identify a driver that was at least 92 percent efficient.

6. The researchers were successful in designing an SPE-based LED source that provided white light at 150 lm/W. However this LED was unable to meet the target specification for CCT or CRI. Addition of red phosphor improved CCT at the expense of efficacy.

7. The researchers did not meet all of the performance specifications established in Objective 2. The reflector/commercial driver condition was the most successful scenario, meeting three of the five target performance specifications. The conclusions are:

- Luminous flux - Only the reflector/commercial driver condition exceeded the target of 2600 lm.
- Luminous efficacy – Three of the five conditions exceeded the target of 110 lm/W.
- CCT – All conditions met the target of 3500 K.
- CRI – None of the conditions met the target of 80.

Intensity distribution – The intensity distribution of the lamp using the reflector and diffuser provided the best intensity distribution of the two cases tested. However this condition did not meet as many of the other target specifications as did the case without the diffuser. Although the proposed lamp showed improved intensity distribution over state-of-the art LED lamps, neither of the cases tested mimicked the intensity distribution of the fluorescent lamp.

8. The researchers did not meet the objective to allow for a payback period of less than three to five years. Without significant rebates and incentives, it is unlikely that maintenance savings will offset the $85 cost differential between the proposed LED and fluorescent lamps. This cost differential would be exacerbated should uneven light distribution require more LED light fixtures than fluorescent light fixtures. The researchers anticipated that the lamp would become more viable as LED efficiency increases so that fewer LEDs are needed and as LED prices decrease. Increases in energy costs may also lead to improved viability. Given the rapid advancements in LED technology, increasing costs of energy, and proliferation of rebates and incentives for
green technologies, it is reasonable to anticipate that the proposed technology will prove economically viable in the relatively near future.

9. The researchers met the objective to allow for retrofit into existing luminaires.

10. Although the researchers indicated a bulk rate price of $142 for the proposed LED lamp, it is unclear if the calculation was a manufacturing cost or if it included sufficient markup needed to be considered viable as a retail price.

2.2.6 Recommendations

Although the researchers were mostly successful in illustrating technical feasibility of the proposed LED replacement lamp, they were unable to prove economic viability. Rapid advancements in LED technology, increasing energy costs, and government support for green initiatives are likely to improve technical and economic viability in the near future. As part of continued development of this technology, the Program Administrator recommends that the following tasks be completed:

1. Investigate new entrants into the LED market that offer higher output and lower cost.

2. Develop or identify a custom phosphor capable of increasing CRI without diminishing efficacy.

3. Differentiate between manufacturing costs and anticipated retail pricing.

4. Perform a life cycle analysis.

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.

2.2.7 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 public from this research is increased affordability of electricity in California. The proposed technology has a higher capital cost than the alternative T8 fluorescent lamp. However it provides a 28 percent energy savings. Assuming a 56 percent market penetration, the researchers estimate this would result in an energy savings of 3.17 billion kWh, which translates into approximately $413 million per year. This energy reduction would result in an annual carbon emission reduction of 2.2 million metric tons. Given the low CRI and poor intensity distribution, the assumed market penetration is likely optimistic. Additionally, it is unlikely that maintenance savings and government incentives will offset the high capital cost of the proposed technology.

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 not performed a market analysis. This technology is applicable to commercial and industrial installations and retrofits. The CRI is likely to preclude use in residential settings.

Engineering/Technical

Key challenges for user acceptance and market penetration include better color rendering without sacrificing efficacy. Economic viability will require identification of a lower cost, more efficient LED.

Legal/Contractual

The researchers have patented the SPE technology.

Environmental, Safety, Risk Assessments/ Quality Plans

Environmental, Safety, Risk Assessments, and Quality Plans have not yet been developed. The researchers have not identified any potential safety or environmental risks associated with the proposed technology. In part, the researchers proposed the technology to alleviate environmental risks associated with mercury contained in fluorescent lamps.

Production Readiness/Commercialization

The researchers have not developed a commercialization plan. The proposed technology is not sufficiently developed to pursue commercialization.
2.3 Fabrication of Doped CoSb3 Nanowires for High Temperature Thermoelectric Materials

Awardee: NanoRIS
Principal Investigator: Ruxandra Vidu

2.3.1 Abstract
The researchers investigated the fabrication of a new class of high performance thermoelectric (TE) materials for efficient direct conversion of waste heat into electricity. The material targeted in this study was doped CoSb₃, a compound with the skutterudite structure. The technical objective was to grow nanowires of the material with high values of the Seebeck coefficient by electrodeposition into the nanometer pores of templates. The two main goals of the project were to demonstrate the feasibility of this method of growth and to demonstrate the superior TE performance of the material produced.

The templated growth of CoSb₃ nanowires doped with Ni and Te was successful. Growth was by a one-step electrodeposition at room temperature from an aqueous solution containing dissolved dopant compounds. Deposition was into the pores of commercial polycarbonate track-etched membranes with a thickness of 10 μm, pore diameter of 200 nm (density of 3×10⁸ pores/cm²), and pore diameter of 400 nm (density of 1×10⁸ pores/cm²). The 400 nm pore diameter was 12.5 percent pores by area. Aspect ratio of the wires produced was 50. Cyclic voltammetry and electrochemical measurement led to the development of a custom pulsed deposition protocol. The fabrication technology developed is very versatile, and nanostructures with tailored composition can be made on other substrates and templates. The composition of doped CoSb₃ nanowires and nanowire arrays could be further engineered so that the thermoelectric properties could be optimized. Although it was not possible to measure the TE properties of doped nanostructures, the second main goal, the researchers expect that such doping will lead to high performance thermoelectric materials.

Keywords: Skutterudite, CoSb₃, nanowire, electrochemical deposition, template, synthesis, pulse electrodeposition

2.3.2 Introduction
This project addressed the topic of recovering otherwise lost energy from waste heat. In the recovery process, a fraction of the waste heat energy would be converted into electricity. The waste heat arises because energy conversion processes that use a fuel, either renewable or non-renewable, have inherent inefficiencies due to thermodynamic losses, friction, etc. Generally this waste heat is simply released at low temperatures, often below 200°C, which has made it extremely difficult to harvest for practical electricity generation. The waste heat recovery process has to operate, for example, between 200°C and 20°C and extract electrical work energy. The second law of thermodynamics sets an upper limit to the efficiency of this recovery process, the Carnot limit, of 38 percent in this example. Even with this inherent low limit on efficiency of the recovery process, it is still attractive because the amount of waste heat available is so large.
Nationwide, the U.S. consumes about 100 quads of energy a year.\(^1\) A quad is a quadrillion \((10^{15})\) Btu, which is equivalent to about 2.93X10\(^{11}\) kWh of energy. Of the 100 quads of energy consumed per year, 55—60 percent gets lost as waste heat. Thermoelectric generators (TEG) operating between a hot temperature and a cold temperature can generate electricity with no moving parts using the Seebeck Effect.\(^2\) Generally, however, the efficiency of TEG has been low. The figure of merit which defines TEG efficiency is the dimensionless parameter ZT.\(^3\) There is no theoretical upper limit to ZT. As ZT approaches infinity, the thermoelectric efficiency approaches the Carnot limit. However, no known thermoelectrics have a ZT>3. To maximize ZT, a material with large Seebeck coefficient, large electrical conductivity and small thermal conductivity is needed.

If a material with very large ZT could be developed, it would have substantial payoff for the California ratepayer. California now has 12.1 percent of the United States’ population.\(^4\) Based on a per capita estimate, California’s share of the United States’ waste heat is estimated to be in the range of 5 to 10 quads. Ten quads of energy is equivalent to 2.93X10\(^{12}\) kWh of energy. If just 10 percent of this could be converted into electricity with 38 percent Carnot efficiency, it would represent 1.11X10\(^{11}\) kWh, equal to more than 1/3 of California’s annual electricity production in 2011, instate plus imports, of 2.92X10\(^{11}\) kWh.\(^5\) At an electricity price of $0.15/kWh, this would be an annual economic benefit to California ratepayers of $16.7B. Clearly actual benefits would be less than this estimate, which assumes Carnot efficiency of recovery. However it does establish that recovery of even 10 percent of California’s waste heat would have a large economic value.

The advancement of science or technology proposed was to develop a new high ZT material for thermoelectric conversion of heat into electricity based on quantum size effects. The expression for ZT is

\[
ZT = \frac{\sigma S^2 T}{\kappa}
\]

where \(\sigma\) is the electrical conductivity, \(S\) the Seebeck coefficient, \(T\) the absolute temperature, and \(\kappa\) the thermal conductivity. It is clear that for high performance the material should have a high value of \(\sigma\) and \(S\) and a low value of \(\kappa\). However for conventional bulk crystalline materials, \(\sigma\), \(S\), and \(\kappa\) are interrelated in such a way that it is very difficult to change these variables independently and increase the value of ZT. It is often the case that an increase in \(\sigma\) leads to an increase in \(\kappa\) and a decrease in \(S\) and vice versa. As these transport characteristics depend on interrelated material properties, a number of parameters need to be optimized to maximize ZT. Theoretical predictions and experimental studies have shown that ZT can be improved by decreasing the material system size from 3-D crystalline solids to 2-D (quantum wells), to 1-D

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1 http://www.greentechmedia.com/articles/read/tapping-americas-secret-power-source-5259/
2 http://www.daviddarling.info/encyclopedia/S/Seebeck_effect.html
4 http://quickfacts.census.gov/qfd/states/06000.html
5 http://energyalmanac.ca.gov/electricity/total_system_power.html
(quantum wires), and finally to 0-D (quantum dots). The improvement is due to two major factors as the system size decreases and approaches the nanometer scale. First, the introduction of many interfaces that scatter phonons more effectively than electrons results in a large reduction in thermal conductivity without significant lowering of the electrical conductivity. Second, due to quantum size effects, dramatic changes in the density of electronic states allow an enhancement of $S$ somewhat independently of $\sigma$. The compounds known as filled skutterudites have been shown to have promising thermoelectric properties, but they are not yet as high as needed.\(^6\) Unfilled, these materials contain voids into which low coordination ions can be inserted to alter and decrease thermal conductivity by producing sources for lattice phonon scattering.\(^7\)

The binary compound CoSb$_3$ in this class is attractive for further research because it displays interesting electrical properties. Importantly, the thermoelectric properties of CoSb$_3$ are affected by doping. For example, the substitution of Co by Ni is particularly efficient. This project sought to assess the feasibility of fabricating doped CoSb$_3$ nanowires for high temperature thermoelectric (TE) materials to increase conversion efficiency in TE devices and reduce thermal waste. The researchers proposed to grow doped CoSb$_3$ nanowires by electrochemical (EC) methods using template synthesis, as shown schematically in Figure 3. This method is promising for mass production of large quantities of nanowires at room temperature and without the need for vacuum. The researchers investigated electrochemical synthesis as described below.

\(^6\) http://pubs.acs.org/doi/abs/10.1021/ja111199y
\(^7\) http://en.wikipedia.org/wiki/Thermoelectric_materials
2.3.3 Objectives

The goal of this project was to determine the feasibility of fabricating doped CoSb₃ nanowires for high temperature thermoelectric (TE) materials to increase conversion efficiency in TE devices and reduce thermal waste. The researchers established the following project objectives:

1. Determine template synthesis conditions for nanostructure preparation. Recognize the key parameters that apply for electrochemical deposition at nanoscale on different templates.

2. Fabricate dense Ni and Te doped CoSb₃ nanowires using templates. Demonstrate that skutterudite nanostructures can be produced by electrochemical deposition with an aspect ratio of over 25 and having controlled composition. Demonstrate electrochemical deposition of doped CoSb₃ nanowires using templates. Demonstrate that by varying EC parameters, skutterudites with controlled composition and crystalline structure can be obtained.
3. Conduct material and structural characterization. Demonstrate that doping is achieved during the EC growth of nanowires. Demonstrate that the proposed technology is capable of producing complex structures in nanoscale building blocks with improved control over the composition.

4. Conduct tests to assess the thermoelectric properties of both Ni and Te doped CoSb₃ elements. Confirm improved thermoelectric properties of doped CoSb₃ nanowires compared to film. Confirm the electrical and thermal advantage of a reduced transport path. Confirm that high aspect ratio nanostructures outperform the nanostructured thin films.

5. Investigate the nanostructure performance. Confirm superior performance for nanostructure versus film technology. Confirm the decrease of thermal conductivity in nanoscale doped skutterudites by about tenfold as compared to binary CoSb₃. Demonstrate high electrical conductivity not less than 1.0 x 10⁴ ohm⁻¹ m⁻¹. Demonstrate a high thermoelectric coefficient not less than 70 μVK⁻¹.

2.3.4 Outcomes

1. The researchers synthesized nanowires in the pores of commercial templates of polycarbonate track-etched membranes with a thickness of 10 μm, pore diameter of 200 nm pore (density of 3x10⁸ pores/cm²), and pore diameter of 400 nm pore (density of 1x10⁹ pores/cm²). They employed a gold film electrode backing the membrane and an aqueous electrolyte. The researchers characterized the deposition process by electrochemical deposition measurements and cyclic voltammetry. They compared nanowire results with electro deposition of thin films under similar conditions.

2. The researchers fabricated dense Ni and Te doped CoSb₃ nanowires with templates by adding dopants to the electrolyte. They found it necessary to employ pulsed electrochemical deposition (PED). Nanostructures demonstrated in the array format had aspect ratios (height/diameter) of 50, greatly exceeding the objective of 25.

3. The researchers demonstrated that nanostructures containing Ni or Te had good morphology. Doping of nanowires did not change their morphology. The researchers demonstrated complex structures as nanoscale building blocks.

4. The researchers did not test for nor confirm improved thermoelectric properties of doped CoSb₃ nanowires compared to film because they developed no testing method for nanowire samples. They did, however, perform thermo reflectance measurements on film samples as a preliminary step.

5. The researchers did not confirm superior performance for nanostructure versus film technology because of the lack of a measurement technique for nanowire samples.
2.3.5 Conclusions

1. The researchers proved the efficacy of electrodepositing CoSb₃ nanowires in the pores of at least one type of template. This objective was met.

2. The researchers were successful in demonstrating the electrochemical deposition of doped CoSb₃ nanowires using templates. They showed that by varying EC parameters, skutterudites with controlled composition and crystalline structure could be obtained. Therefore this objective was met.

3. The researchers demonstrated that nanostructures containing Ni or Te had good morphology and that doping of nanowires did not change the morphology of nanowires. They also demonstrated the use of complex structures as nanoscale building blocks. This objective was met.

4. Since the researchers did not test for improved thermoelectric properties of doped CoSb₃ nanowires, this objective was not met.

5. Since the researchers were not able to confirm superior performance for nanostructure versus film technology, this objective was not met.

The goal of this project was to determine the feasibility of fabricating doped CoSb₃ nanowires for high temperature thermoelectric (TE) materials to increase conversion efficiency in TE devices. The feasibility goal was partly established since fabrication was demonstrated, but feasibility of high performance for thermoelectric application has yet to be shown.

2.3.6 Recommendations

The Program Administrator recommends that the researchers focus on how to measure thermoelectric properties of nanowire-based samples, especially the Seebeck coefficient. Once it is established that the material has the potential to become useful in a device, attention can be directed to measuring the other parameters in ZT. With these data available, it will be clear what parameters need further optimization for a device. The Program Administrator recommends that the researchers concentrate on measuring material properties important to device performance, particularly the Seebeck coefficient.

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 would be increased affordability of electricity in California through the conversion of currently wasted heat energy to electricity. Nationwide, the United States consumes about 100 quads of energy a year. A quad is a quadrillion \((10^{15})\) Btu, which is equivalent to about \(2.93 \times 10^{11}\) kWh of energy. Of the 100 quads of energy consumed per year, 55—60 percent gets lost as waste heat. If such a thermoelectric material with very large ZT could be developed, it could have substantial economic payoff for the California ratepayer. California now has 12.1 percent of the United States’ population. Based on a per capita estimate, California’s share of the United States’ waste heat is in the range of 5 to 10 quads. Ten quads of energy is equivalent to \(2.93 \times 10^{12}\) kWh of energy. If just 10 percent of that could be converted to electricity with 38 percent Carnot efficiency, it would represent \(1.11 \times 10^{11}\) kWh, equal to more than 1/3 of California’s annual electricity production in 2011, instate plus imports, of \(2.92 \times 10^{11}\) kWh. At an electricity price of $0.15/kWh, it would be an annual economic benefit to California ratepayers of $16.7B. Actual benefits would be less than this estimate, since it assumes Carnot efficiency of recovery. However it does establish that recovery of even 10 percent of California’s waste heat would have a large potential economic value.

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 have surveyed potential customers for interest in the product. They claim they have performed a market analysis.

Engineering/Technical

The researchers plan to complete the technical work in two to three years if they receive the required funding. They anticipate a prototype in 18 months.

Legal/Contractual

The researchers have a patent pending. The application was filed 16 months before the project started.

Environmental, Safety, Risk Assessments/Quality Plans

It is premature to begin testing in environmental, safety, risk, and quality areas.

Production Readiness/Commercialization

Thermoelectric data are needed prior to commercialization.
2.4 Microwave System for Hydrogen Production From Dairy Digester Biogas

Awardee: CHA Corporation.
Principal Investigator: Chang Yul Cha

2.4.1 Abstract
The goal of this project was to determine if microwave based production of hydrogen from dairy biogas could be used for pre-combustion control of NOx in reciprocating internal combustion (IC) engines. The researchers investigated microwave induced steam-methane reforming reactions with a nickel catalyst with and without oxygen. They conducted water-gas shift reaction tests using a copper oxide and zinc oxide catalyst. They then integrated a microwave reforming reactor with water-gas shift and hydrogen sulfide removal reactors. This integrated microwave system ran for 11 hours with methane containing 2,350 ppm hydrogen sulfide to simulate dairy biogas. Over 75 percent of the methane was converted into hydrogen. The ratio of hydrogen produced per mole of methane was 3.8, which substantially surpassed the project target of 3.0. The addition of oxygen to the reformer increased the methane conversion but did not increase total hydrogen production. A double quartz tube microwave reactor with pre-heating of inlet gas increased methane conversion significantly, eliminating the need for the oxygen addition. The copper oxide and zinc oxide catalyst was very effective for microwave induced water-gas shift reaction and provided over 90 percent carbon monoxide conversion at very low microwave power. This catalyst, combined with low microwave power, also eliminated hydrogen sulfide completely and prevented sulfur poisoning of the nickel catalyst. The researchers estimated the total annualized treatment cost for a 500 kW internal combustion biogas engine to be $0.01 per kWh. NOx removal costs were estimated at $10,200/ton and $22,960/ton for the exhaust gas NOx concentration of 100 ppm and 50 ppm, respectively.

Keywords: Biogas, hydrogen, microwave, steam reforming, water-gas shift, pre-combustion, NOx control

2.4.2 Introduction
This project addressed environmentally preferred advanced generation. The project focused on the recovery of energy from the biogas of California dairy cattle waste. Agricultural products in general and dairy products in particular are large, very important components of California’s economy. California is the top producer of agricultural products in the nation. Its single most valuable commodity is dairy products which account for 16.9 percent of the State’s commodity total. California leads the nation in the production of dairy products overall, accounting for 19.6 percent of the United States total (2004) with a value of $5.37 billion to the State. It is the largest milk producer state with 39,512 million pounds in 2009. California is fourth in the nation in the

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8 http://www.stuffabouthate.com/landscape/livestock/dairy.htm
number of cattle at 5.3 million head (Texas leads with 11.9 million). In 2012 there were 1.82 million dairy cows in California. These dairy herds were spread across the state in 1,650 licensed dairies. The biomass waste they produce is a significant energy resource since a single dairy cow produces about 120 lbs of wet manure per day. In so doing they generate approximately 3.6 million bone dry tons of manure per year. Potentially, California dairies could generate nearly 14.6 billion cu.ft. of methane each year, which corresponds to 140 megawatts of electrical capacity. If this significant biomass resource could be converted to methane on site and combusted on site in biogas IC engines, it would be a significant resource of distributed electrical capacity. A problem for the use of biogas fuel, however, is the CARB 2007 Guidelines to the Local Air Districts of tight NOx control requirement of 11 ppmv NOx. Post-combustion NOx controls are both expensive and defeated by the H2S sulfur in the fuel. However since NOx production rate is highly dependent on combustion temperature, a pre-combustion means of lowering combustion temperature could eliminate the need for post-combustion treatment for NOx. Operating methane engines in the lean limit can indeed lower combustion temperature enough, but engine operation becomes unstable. Hydrogen assisted lean operation (HALO) for natural gas fired engines, however, allows stable engine operation to be achieved at ultra-lean conditions and achieve NOx emissions of 10 ppm. It would be expensive and inconvenient to deliver the hydrogen from off site. Therefore the main goal here was to develop an inexpensive means of producing hydrogen on site from the available biogas resource.

The production of on-site hydrogen would allow the economic value of some of the 140 megawatts of electrical potential to be recovered. At full utilization this capacity corresponds to 1.23X10⁹ kWh per year. At a value of $0.10/kWh, the economic value would be $123 million. There could be several other advantages. Since it is a distributed source, this new energy could displace new grid infrastructure for more remote locations, as well as displace required new generating capacity. If the issue of sulfur could be completely eliminated, there would be the option of employing hydrogen produced on site in fuel cells for even greater efficiency. Finally, other sources of biomass, such as landfills and cattle feedlots, could use the same technology for generation.

The advancement of science or technology proposed in this project was to take a small portion (5—10 percent) of the biogas stream and convert it into a hydrogen rich stream by the application of microwave energy. A schematic of an example biogas system is shown in Figure 4. The well-known steam-methane reforming process is used industrially to produce hydrogen,
carbon monoxide (CO), and their mixture. The system consists of several stages, including a desulphurization unit, a steam-methane reformer, and a shift reactor. This work would build on the success of the researchers on applying microwaves to chemical reactions. In previous work they showed that microwave energy can destroy H2S in a carbon bed. Those results were applied to the desulphurization unit. Most steam-methane reformer reactions are highly endothermic, and they produce high gas outlet temperatures in the range of 750—1,000° C. This high reforming temperature creates difficulties for small-scale reformers such as for dairy biogas. Since microwave energy enhances chemical reactions by reducing activation energy, it could require much lower temperatures for steam-methane reforming. Results obtained from preliminary steam-methane reforming experiments show that greater than 80 percent methane conversion was obtained by using microwave energy in a bed containing the mixture of SiC and Pt based oxidation catalyst using the mixture of methane, steam, and air. A bed temperature for this preliminary test was about 500° C. In the third step, the process increased the hydrogen product by shifting the H2/CO product gas at temperatures in the range of 200—400° C in the presence of an iron-chromium or a copper alloy catalyst. Since microwave energy reduces the activation energy, the shift reaction can occur at much lower temperature than 200—400° C. Overall the goal of this project was to determine the effectiveness of microwave enhanced production of hydrogen from biogas.

Figure 4: Process Flow Diagram for CHA Microwave Steam-Methane Reforming with Water-Gas Shift and H2S Removal Reactors
2.4.3 Objectives

The goal of this project was to determine the feasibility of microwave based production of hydrogen from dairy biogas for the pre-combustion NOx control of reciprocating engine exhaust and fuel cell applications of biogas.

The researchers established the following project objectives:

1. Assemble a 3 kW microwave generator and microwave reactor for converting methane to hydrogen through steam reforming reactions. Create a bench scale microwave treatment system for producing hydrogen from biogas at minimal cost utilizing existing equipment.

2. Test silicon carbide (SiC) to decompose methane into hydrogen by microwave energy. Find the methane flow rate and microwave power for best conversion efficiency. Find the effect of added air on steam-methane reforming. Demonstrate that a SiC bed can produce three moles of hydrogen from one mole of methane in the presence of hydrogen sulfide (H2S) by using microwave energy. Demonstrate the microwave SiC bed provides methane conversion efficiency comparable to the conventional thermal steam-methane reforming conversion efficiency of 75 percent.

3. Prepare and test steam-methane reforming catalysts. Find the effect of H2S on the methane conversion efficiency. Also test various ratios of air to steam flow rates to determine best process conditions for the maximum amount of hydrogen. Demonstrate that the nickel catalyst and SiC mix provides greater methane conversion with microwave energy than conventional thermal steam reforming conversion efficiency of 75 percent. Demonstrate the microwave based nickel catalytic conversion method produces greater than three moles of hydrogen from one mole of methane in the presence of H2S.

4. Identify the best microwave catalyst and process conditions for destroying H2S and producing the maximum amount of hydrogen from one mole of methane in biogas. Compare the microwave method with conventional steam reforming for hydrogen production from biogas. Demonstrate that microwave based hydrogen production from biogas for pre-combustion NOx control and fuel cell applications of dairy biogas are superior to conventional steam reforming.

5. Estimate capital and operating costs of the microwave hydrogen production from biogas for pre-combustion NOx control and fuel cells. Demonstrate that the microwave process for converting methane to hydrogen will provide treatment cost of $0.01/kWh for pre-combustion NOx control while meeting CARB 2007 emission standards.

2.4.4 Outcomes

1. The researchers modified an existing 2 kW helix based microwave laboratory unit to carry out the methane reforming reaction with water injection. They also built a 6 kW microwave double quartz tube reactor that was integrated with the existing microwave
oxidizer to conduct tests combining steam reformer (SR), water-gas shift (WGS), and H₂S decomposition reactions. Both systems performed effectively.

2. The researchers conducted steam-methane (CH₄) reforming tests with SiC beds. The SiC test results showed negligible CH₄ conversion with SiC alone. Additionally, SiC impregnated with nickel catalyst was not effective enough for reforming.

3. The researchers adopted a new nickel catalyst supported on alumina mixed with SiC beads and heated with microwaves. They conducted a series of steam-methane reforming tests with the addition of oxygen (O₂) using both the 2 kW helix based microwave reformer and the 6 kW reactor. The target of conversion of over 75 percent of methane was achieved with the addition of O₂. The required ratio of steam to methane flow rate was in the range of three to four. The researchers found that when the inlet CH₄ and steam mixture was pre-heated in the double quartz tube reformer, conversion efficiency was over 75 percent without the addition of O₂ and the reaction produced more than three moles of H₂ from one mole of converted methane. The researchers integrated the microwave reformer with the microwave water-gas shift (WGS) and H₂S removal reactors. The integrated microwave system ran for 11 hours over two days. The methane conversion remained around 78 percent, and 3.9 moles of H₂ was produced from one mole of CH₄, confirming that the H₂S was completely removed in the copper oxide (CuO)-zinc oxide (ZnO) catalyst, thus avoiding nickel catalyst poisoning.

4. The researchers found that CuO and ZnO catalyst reacted with H₂S by microwave energy to produce CuS and ZnS. Microwave energy could also be used to effectively regenerate the used catalyst with the mixture of air and steam. They found that the double quartz tube microwave reactor provided much higher CH₄ conversion than a single quartz tube reactor and that pre-heating of the inlet gas prior to entering the microwave reformer increased the CH₄ conversion significantly. They determined that steam-CH₄ reforming in the double quartz tube reactor with pre-heating of the inlet gas did not require adding O₂ and is preferable for H₂ production. They found that microwave based H₂ production for the pre-combustion NOₓ control is superior to conventional steam reforming (SR). It is capable of handling biogas containing a high concentration H₂S without poisoning the SR catalyst. It is economically feasible to install the microwave based H₂ production system for small biogas engines, and the cost is much cheaper than trucking H₂ to a dairy. It could also provide hydrogen for fuel cells for power generation from biogas.

5. The researchers chose a 500 kW IC biogas engine for estimating capital and operation costs for pre-combustion NOₓ control. They assumed a 15 year useful life and 300 days of operation per year. The capital cost for the pre-combustion NOₓ control system was estimated to be $197,660 ($395/kW or $295/hp) for the assumed case of the 500 kW biogas engine. The NOₓ removal operating cost depends mainly on the NOₓ concentration to be removed. The NOₓ removal cost is $10,200/ton when the NOₓ concentration is 100 ppm but increases to $22,960/ton when the NOₓ concentration
decreases to 50 ppm. The NOx treatment cost in terms of engine power is estimated at $0.0093/kWh, which meets the project target of $0.01/kWh.

2.4.5 Conclusions
1. The task to assemble a 3 kW microwave generator and microwave reactor for converting methane to hydrogen through steam reforming reactions was successful. A bench scale microwave treatment system for producing hydrogen from biogas at low cost was successful. Therefore the researchers met this objective.

2. The task to demonstrate that a SiC bed can produce hydrogen and that a microwave SiC bed can produce high methane conversion was not successful. This objective was not met.

3. The double quartz tube reactor and nickel catalyst combined with pre-heating inlet gas provided high CH4 conversion efficiencies and more than 3.8 moles H2 produced per mole of CH4. The microwave WGS reactor required very low power and gave high conversion efficiency. Therefore the goals of this task were met.

4. The CuO-ZnO catalyst absorbed microwave energy and was very effective for microwave WGS reaction and complete removal of H2S to prevent catalyst poisoning. The researchers developed good evidence that microwave based H2 production for pre-combustion NOx control is superior to conventional steam reformers. They substantially met the goals of this task.

5. The researchers estimated the microwave pre-combustion NOx control system had a much lower NOx removal cost ($0.01/kWh) for high NOx inlet concentration than alternative methods such as selective catalytic reduction (SCR) and NOx Tech. Thus they met the goals of this task.

Based on the facts presented, the researchers established the feasibility of microwave based production of hydrogen from dairy biogas for the pre-combustion NOx control of reciprocating engine exhaust.

2.4.6 Recommendations
The Program Administrator recommends that a microwave hydrogen production system for pre-combustion NOx control be demonstrated with a working IC engine fueled by biogas from a working dairy digester, as is already planned by the researchers. The Program Administrator also recommends that a working fuel cell be demonstrated with the hydrogen output of the test system.

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.
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 is reduced environmental impacts of the California electricity supply or transmission or distribution system. Potentially, California dairies could generate nearly 14.6 billion cubic feet of methane each year, which corresponds to 140 megawatts of electrical capacity. If this biomass resource could be converted to methane on-site and combusted in IC engine generators, it would be a significant resource of distributed electrical capacity. At full utilization this corresponds to $1.23 \times 10^9$ kWh per year. Assuming a value of $0.10 /\text{kWh}$, the economic value is $123$ million. There could be several other advantages. It is a distributed source of capacity which could displace new grid infrastructure to more remote locations, as well as displace required new generating capacity. If the issue of sulfur can be eliminated, there is the option of employing hydrogen produced on-site in fuel cells for even greater efficiency. Other sources of biomass, such as landfills and cattle feedlots, could use the same technology.

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 been working with SMUD and C-Microsystems to commercialize this microwave technology in California. They expect C-Microsystems will help to identify potential customers in California.

Engineering/Technical

The researchers plan to conduct the field demonstration of this microwave technology at Tollenaar Holsteins Dairy in Elk Grove, California. They estimate it will take two additional years and about a million dollars to complete engineering and technical work.
Legal/Contractual

The researchers have two patents from previous work. They have not applied for new patents based on this project. Their patent attorney completed a patent search.

Environmental, Safety, Risk Assessments/Quality Plans

These activities must be addressed during the completion of the engineering work.

Production Readiness/Commercialization

The researchers had not developed a business plan for the development of this technology by the end of the project. They plan to complete that plan in the year after the project.

2.5 High Efficiency Thin Film Solar Cells on Nanostructured Substrates

Awardee: nLiten Energy Corporation

Principal Investigator: Alan Chin

2.5.1 Abstract

The goal of this project was to determine the feasibility of using nanostructured substrates to improve significantly the photovoltaic conversion efficiency (target of 20 percent) of low cost tandem micromorph (amorphous silicon on microcrystalline silicon) thin film solar cells. The new substrate topology has the potential to enhance the conversion efficiency of the conformal thin film PV cell through increased light absorption and reduced carrier recombination due to a thinner absorber layer. To produce these nanostructured substrates, the research team developed a self-assembled growth process to deposit nanorod structures onto inexpensive substrates. Working with a solar manufacturer, the team demonstrated over 30 percent relative enhancement in the conversion efficiency of nanostructured tandem micromorph silicon thin film PV solar cells compared to a reference cell deposited on a flat substrate. However the researchers did not demonstrate conversion efficiency greater than that reported in the literature elsewhere. In optimizing the substrate surface morphology, the research team found that a trade-off exists between a surface morphology that maximizes light scattering with high aspect ratio nanostructures and one that facilitates the conformal deposition of thin film devices. The demonstrated relative efficiency enhancement using a nanostructured substrate promises a path toward a significant cost reduction for thin film PV solar modules.

Keywords: Nanostructured substrates, nanorods, conformal, thin film PV, enhanced absorption, light scattering
2.5.2 Introduction

California Assembly Bill AB 32 requires that the total of California greenhouse gas emissions (GHG) from all sources be no greater than its total in 1990.\(^{16}\) This will require a 29 percent reduction over the estimate of business-as-usual forecast. Additionally, California Senate Bill 2 requires that the amount of electricity generated from eligible renewable energy resources per year be at least 33 percent of total retail sales of electricity in California per year by December 31, 2020.\(^{17,18}\) Solar photovoltaic (PV) electricity generation will be an important tool in meeting these goals. In 2011, 14.2 percent of all California electricity (measured in GWh) came from renewable sources, of which solar comprised 0.4 percent.\(^{19}\) In 2012, large utilities achieved 20.6 percent of their generation by renewable sources\(^{20}\) and commercial in-state generation by solar climbed to 1.0 percent.\(^{21}\) To date, larger market penetration by PV has been limited by high system cost due to the high cost of the PV cells that go into the PV modules and the balance of system (BOS) costs. Recently the cost per peak watt of cells, both bulk and thin film, has dropped significantly. The cost per watt of bulk crystalline silicon cells is reported to be significantly less than $1/Wp, but this cost may not be true due to commercial dumping practices.\(^{22}\) The cost per watt of thin film cells has also dropped dramatically to less than $1/Wp. However thin film cell efficiency is still considered to be too low. Even with equal cost per watt at the cell or even module level, PV efficiency is important because it seriously impacts the BOS costs. Lower efficiency requires more or larger modules that increases the cost of real estate, increases the cost of mounting hardware, and increases the cost of labor for installation. It is noteworthy that a promising new higher thin film efficiency layout technique has been proposed of growing nanowires or nanorods with a radial conformal junction around each nanorod.\(^{23}\) For this to succeed commercially, what is needed is a low cost fabrication technique for mass production of nanorod structures.

If a low cost fabrication technology for efficient nanorod-based cells can be demonstrated, the economic benefits to California ratepayers could be large. For example, in 2010 Californians purchased 250,384,248 MWh of electricity.\(^{24}\) The average recent residential price of electricity in

\(^{16}\) http://www.arb.ca.gov/cc/ab32/ab32.htm
\(^{17}\) http://www.leginfo.ca.gov/pub/11-12/bill/sen/sb_0001-0050/sbx1_2_bill_20110412_chaptered.pdf
\(^{18}\) http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=CA25R
\(^{19}\) http://energyalmanac.ca.gov/electricity/total_system_power.html
\(^{21}\) http://energyalmanac.ca.gov/electricity/electricity_generation.html
\(^{24}\) http://energyalmanac.ca.gov/electricity/per_capita_electricity_sales_1990-2010.html
California was 15.2 cents per kWh. At this price, the annual cost of California electricity consumption is estimated to be $38.1 B. At the 2012 solar penetration level of 1.0 percent, the solar component could have an estimated annual value of $381 M. Clearly this is only an approximation, since it uses only the residential rate, and there are a variety of different consumers paying a variety of different rates. But it serves to illustrate the magnitude of potential economic value of solar power to California.

The advancement of science or technology that was proposed in this project was the development of a new manufacturing technique for nanostructured photovoltaic devices. The key innovation was to produce low cost nanostructured substrates on which folded junction photovoltaic devices were conformably grown. The approach utilized seeded self-assembled nanowire growth onto low cost and large area substrates, as shown schematically in Figure 5.

**Figure 5: Schematic Process Flow for Substrate Nanostructuring Utilizing Self Assembly. No Lithography is Utilized in the Nanostructuring Process.**

Following the growth of nanowires on the substrate, the researchers grew thin film photovoltaic junctions conformably onto the nanowires by deposition. A tandem multiple junction was formed, as shown schematically in Figure 6. The researchers described the resultant junction structure as “folded” across the substrate, resulting in a long effective optical path length for light absorption between the rods and short carrier path length across the thin film junctions on the rods. The device produced had inherent anti-reflection properties from the low effective index due to the more open structure. While the preferred orientation of each structure element was perpendicular to the substrate, the folded junction approach was effective as long as the structures were substantially oriented perpendicular to the substrate. The primary consideration was the need for three-dimensional structuring that increased the optical path length into the photovoltaic device. This relaxed requirement on structure orientation significantly reduced the manufacturing cost and enabled the use of non-lithographic structuring processes that were easily scalable to large substrates. In addition, the spacing between individual rods did not have to be regular as long as the average spacing was at the

target spacing for optimized device performance. This project targeted active photovoltaic material with a higher potential efficiency, so-called “micromorph”, i.e., a stacked tandem junction consisting of a top layer of hydrogenated amorphous Si a-Si:H p-i-n cell with band gap 1.7 eV and a bottom layer of microcrystalline hydrogenated Si μc-Si:H with effective band gap 1.0 eV. The researchers set the efficiency target goal of the tandem cell at 20 percent.

Figure 6: Schematic Process Flow for Device Manufacturing

The nanostructured substrates are shown placed with reference flat substrates in the device deposition chamber so that both substrates have the same thin film photovoltaic device deposited to allow direct measurement of the benefit of the folded junction approach.

2.5.3 Objectives

The goal of this project was to determine the feasibility of using nanostructured substrates to significantly improve the photovoltaic conversion efficiency (target of 20 percent) of low cost tandem micromorph (amorphous silicon on microcrystalline silicon) thin film solar cells and thereby enable the production of affordable solar energy. The researchers established the following project objectives:

1. Set up experimental apparatus: electrochemical cell and solar simulator.
2. Scale up nanostructured substrate. Optimize structure size/spacing for amorphous silicon and for microcrystalline silicon. Optimize reproducibility. Demonstrate uniform deposition (no voids >10 μm) of nanostructures (<1 μm features with >1 μm height) on a 15 cm × 15 cm substrate, as confirmed by microscopic analysis.

3. Demonstrate optimized enhanced performance of amorphous silicon photovoltaic
device on nanostructured substrates with >10 percent photovoltaic conversion efficiency
and with >1 cm² single junction amorphous silicon folded junction device.

4. Demonstrate optimized enhanced performance of microcrystalline silicon photovoltaic
device on nanostructured substrate with >15 percent photovoltaic conversion efficiency
and with >1 cm² single junction microcrystalline silicon folded junction device.

5. Demonstrate optimized enhanced performance of tandem micromorph photovoltaic
device on nanostructured substrates with 20 percent photovoltaic conversion efficiency
and with >1 cm² tandem micromorph folded junction device.

2.5.4 Outcomes
1. The researchers did not report the setup of an experimental apparatus containing an
electrochemical cell and a solar simulator. The proposed budget did list $32,100 of major
equipment to be purchased as applicant contributions.

2. The researchers successfully demonstrated deposition on 10 cm x 10 cm substrates, but
they were not able to scale up to 15 cm x 15 cm substrates.

3. In partnership with another solar company, the research team demonstrated 9.64
percent conversion efficiency in single junction a-Si photovoltaic devices of area 0.5 cm²
with nanostructured substrates.

4. The researchers did not report any fabrication or measurements results of
microcrystalline silicon photovoltaic device on nanostructured substrates.

5. The researchers did demonstrate enhanced performance of tandem micromorph
photovoltaic device on nanostructured substrates, but they did not meet the 20 percent
photovoltaic conversion efficiency goal. Instead they reported conversion efficiency of
6.4 percent on a 1.1 cm² folded junction device compared to a conversion efficiency of 3.4
percent on a standard reference device.

2.5.5 Conclusions
1. The researchers did not meet the goal of experimental apparatus development.

2. The researchers did not meet the goal of scale up to 15 cm x 15 cm substrates.

3. The researchers almost met the goal of amorphous silicon photovoltaic device on
nanostructured substrates with 10 percent efficiency and area >1 cm².

4. Evidently the researchers did not attempt the fabrication of a microcrystalline alone
silicon photovoltaic device on nanostructured substrates.

5. The researchers did not demonstrate achievement of the goal of a tandem micromorph
photovoltaic device on nanostructured substrates with 20 percent photovoltaic
conversion efficiency and area >1 cm².
6. The researchers did demonstrate that the nanostructured substrate approach significantly enhances the optical absorption in thin film solar devices. If other device parameters can be controlled, the enhanced optical absorption could lead to higher conversion efficiency.

The research team did not achieve the main goal of this project to demonstrate the feasibility of using nanostructured substrates to improve significantly the photovoltaic conversion efficiency (target of 20 percent) of low cost tandem micromorph thin film solar cells.

2.5.6 Recommendations
The Program Administrator recommends that the researchers carefully review their original proposed project objectives. In particular, they should first fabricate microcrystalline silicon photovoltaic devices on nanostructured substrates to allow for later interpretation of results from tandem micromorph devices. The researchers should also examine the possibility of PV contamination by the growth seeds or the nanorod material itself. Such deleterious contamination, if present, would likely be more acute in the µc junctions.

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 to the ratepayer from this research could be increased affordability of electricity in California. If a low cost fabrication technology for efficient nanorod-based cells could be demonstrated, the economic benefits to California ratepayers could be large. For example, in 2010 Californians purchased 250,384,248 MWh of electricity. The average recent residential price of electricity in California is 15.2 cents per kWh. At this price, the approximate annual cost of California electricity consumption is estimated to be $38.1 B. At the 2012 solar penetration level of 1.0 percent, the solar component would have an estimated annual value of about $381 M. Clearly this is only an approximation since it uses the residential rate, and there are a variety of different consumers paying a variety of different rates. But it serves to illustrate to potential magnitude of the economic value of solar power to California.

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 had not conducted a market analysis by the end of this project, but they had surveyed potential customers for interest.

**Engineering/Technical**

The researchers plan to continue this development effort. They estimate they will need two to three years and several million dollars to complete engineering development and demonstration.

**Legal/Contractual**

The researchers have patents pending in the U.S., Japan, and Europe and have been awarded a patent in the People’s Republic of China.

**Environmental, Safety, Risk Assessments/Quality Plans**

Additional testing or plans in these areas seem premature until feasibility is established.

**Production Readiness/Commercialization**

The researchers are seeking industrial partners to take this technology to market. They have received interest from both thin film solar module manufacturers and substrate manufacturers.

### 2.6 Smart Wind Turbines: A New System for Improved Energy Yield

**Awardee:** University of California, Berkeley

**Principal Investigator:** Fotini K. Chow

#### 2.6.1 Abstract

California is on track to meet its goal of increasing procurement from eligible renewable energy resources to 33 percent of total electricity by 2020. Policymakers are now beginning to discuss adoption of a 50 percent goal by 2030. Wind farms have been a key element to successful adoption of renewable energy in the State. Wind turbines have the potential to generate more power from higher, steady wind speeds. However, the electricity generating potential of wind farms is limited, because wind farm operators typically lock turbine rotors when wind speed gets too high to avoid the risk of damaging turbine equipment.

The goal of this project was to develop a means to enable more productive wind farm operations during high wind speed, turbulent conditions without impacting wind turbine reliability or durability. High speed wind events produce coherent structures which result in varying turbulent flow across the rotor plane of a wind turbine, a situation that can potentially damage it. The researchers set out to better understand how stable atmospheric boundary layer (ABL) conditions trigger large bursts of wind breaking-wave (coherent) structures, and what can be done to harness this energy without risk of damaging the turbine.

The researchers first collected and analyzed data from various instruments for the presence of coherent structures in high speed wind conditions. The team then assessed the capability of state-of-the-art atmospheric models and turbulence closures to simulate coherent structures.
using the wavelet analysis methodology calibrated on real observations. It also performed a sensitivity study that compared modeled versus actual winds observed at two wind farms to determine resolution requirements for intra-farm wind flow characteristics.

The results of this project demonstrated that coherent turbulence can be identified and observed using computer modeling and observational data techniques. The researchers believed that the results of this study could serve as a foundation for further work to develop more effective controls and increase productivity and the financial rate of return of wind farms. Further simulation work is needed to view high frequencies and to provide higher resolution for coherent structures which are relevant to wind turbine fatigue. This would involve the use of additional computing resources and more sophisticated field instrumentation.

**Keywords**: Wind energy, wind turbine, turbulence, turbine fatigue, atmospheric modeling, stable boundary layer, coherent structures

### 2.6.2 Introduction

California is on track to meet its goal of increasing procurement from eligible renewable energy resources to 33 percent of total electricity by 2020. Policymakers are now beginning to discuss adoption of a 50 percent goal by 2030. Wind turbine farms have been a key element to successful adoption of renewable energy in the State. Wind turbines generate more power with higher, steady wind speeds. Power output of a wind turbine increases by a factor of eight as wind speed increases. However wind farm operators typically lock turbine rotors when the wind speed is excessive to avoid the risk of damaging turbine equipment. This limits the amount of electricity generated and impacts the productivity and economic value of wind farms.

The goal of this project was to develop a means that would enable more productive wind farm operations during high wind speed, turbulent conditions without impacting wind turbine reliability or durability. The research team sought to better understand how stable atmospheric boundary layer (ABL) conditions trigger large bursts of wind-breaking wave (coherent) structures, and what can be done to harness this energy by allowing turbines to operate during high wind conditions without the risk of unusual fatigue and/or damage. Improved understanding of ABL conditions and detection of coherent structures could enable wind farm managers to continue operating turbines under strong wind conditions, leading to increased production and lower cost of electricity generated.

The research team determined that high resolution wind data is needed to interpret the three-dimensional (3D) time dependent velocity field and detect the presence of coherent structures which could harm turbine blades. The impact of turbulence and shear on wind turbines is based on theoretical estimates for idealized air flows. However this technique does not capture temporal and spatial variability. As such, researchers decided to collect data using a scanning lidar, single-column lidar, sonic anemometers, and two large eddy simulations (LES) with wavelets. Lidar is a remote sensing technique that can measure velocities in the atmosphere by scattering laser pulses in vertical or horizontal patterns. The use of lidar is gaining in popularity as a means of assessing the wind potential of wind farms, monitoring wind shear at airports,
measuring air pollution, and detecting the presence of contaminant plumes. Two-dimensional (2D) cross sections of radial wind velocity can be obtained at high spatial distribution (approximately 30 meters) and temporal resolution (approximately 1.0 Hertz). Column and volume measurements can also be obtained using different scanning patterns.

Lidar applications are inherently limited by the instantaneous nature of the data. For example, a lidar slice of data may detect a strong wind shear event at one location, but cannot predict which way the winds will shift in the future. Measurements of current conditions have little predictive ability and may come too late for operational purposes. For lidar to be used effectively, it must be integrated with three-dimensional (3D) time dependent numerical simulation results to interpret the observed slices of velocity data. LES appears to be a well-suited numerical technique for modeling atmospheric flow. It allows control of turbulent length scales through spatial filtering to separate large, resolved motions from subfilter-scale, turbulent motions. LES ideally complements the type of data obtainable from lidar to provide 3D time dependent predictions of turbulent motions in the atmosphere at high resolution. See Figures 7 and 8.

LES is currently limited in its ability to capture strong, nighttime stable stratification featuring higher wind speeds but often complicated by low level jets, inertial oscillations, and gravity waves. In the Southern Great Plains region of the United States, for example, low level wind jets occur regularly at night and represent a large untapped wind resource.

Figure 7: Example of Wavelet Analysis Used to Detect High Frequency Coherent Structures Generated in the Stable Atmospheric Boundary Layer

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Each encircled burst represents an energetic eddy that, if it came in contact with a wind turbine blade or tower, could cause damage.

Researchers in this project performed and analyzed LES simulations of idealized and real field conditions to examine mean wind and turbulent variables through a nocturnal period. Any observable turbulence from different types of lidar can be characterized by analyzing two different types of lidar data (2D scanning and volumetric) during turbulent bursting events.

**Figure 8: Sample Range Time Plot of Streamwise Velocity Variance (A Measure of Turbulence)**

Calculated from high resolution Doppler lidar in staring mode at 10 elevation angle for the night of September 9, 2003 from 7:29 a.m. to 7:39 a.m. (Coordinated Universal Time). Coherent structures are evident. Bottom strip: corresponding tower measured coherent turbulent kinetic energy.

Research-grade scanning lidar data can detect microscale atmospheric phenomena, such as the presence of Kelvin-Helmholtz (KH) waves. Upon breaking, these KH waves can cause strong coherent turbulent kinetic energy (CTKE) events at frequencies that could damage wind turbines. When placed in staring mode, these lidars can detect turbulent kinetic energy (TKE), a likely indicator of potentially dangerous coherent structures, providing adequate time for a wind turbine to react and avoid potential damage.

The research team also deployed the use of the Advanced Regional Prediction System (ARPS) atmospheric model to simulate idealized and real terrain atmospheric states in which intermittent turbulence was found. The team selected a Leosphere Windcube, which is a volumetric lidar that collects data in a vertical column and measures a 3D wind field in a single column of the atmosphere. The researchers found the 1.0 Hz sampling rate inadequate for measuring high frequency CTKE. However, commercially available scanning lidars such as the Halo-Photonics Galeon scanning unit could be used to detect TKE. A network of sonic anemometers and scanning lidars, combined with 3D numerical modeling, could provide the
necessary information to quantify the full range of relevant TKE and CTKE values at a wind farm.

ARPS successfully modeled a Kelvin-Helmholtz (KH) billow observed by lidar to within one meter/second on average over a three hour period at 25 meter horizontal resolution. That simulation used the Dynamic Reconstruction Model (DRM) turbulence closure and generated wind shear as much as 25 percent more intense and 30 meters higher than conventional turbulence closures. The DRM also agreed better with observations. ARPS simulations could not generate the higher frequency structures that could affect wind turbines due to limited spatial resolution of the model. Spatial resolution is currently limited by computational constraints, but expected technological advances in computing power will eventually ease those constraints.

The researchers performed idealized simulations of the stable boundary layer with ARPS to demonstrate the impact of higher resolution. These ideal simulations generated the high frequency coherent structures that could fatigue wind turbines, although the intensity was reduced for these ideal conditions. The DRM closure developed by the research team sustained turbulence under stable conditions better than conventional turbulent kinetic energy (TKE) closures. Ideal ARPS simulation with DRM showed excellent agreement with similarity theory over a wide range of atmospheric stability and grid resolution, a requirement to simulate turbulence accurately in the ABL at the height of a wind turbine under most stability conditions. Horizontal resolution would need to be increased much beyond 3.125 meters to resolve the highest range of relevant frequencies (approximately 30 Hz), but it is not clear if this is yet necessary for creating a coherent structure detection system for wind farms.

High resolution simulation of the ABL is computationally expensive, with the cost increasing by a factor of about 16 when the resolution is refined by a factor of two in each of three dimensions and the time step is halved for stability constraints. The research team studied the optimal model resolution at which atmospheric models can accurately predict the wind speed in a wind farm using nested simulations of the Weather Research and Forecasting Model (WRF). Using various terrain and synoptic weather conditions to initialize the model, WRF wind fields were validated against sodar measurements at a wind farm on the west coast of the United States. The researchers found horizontal resolution made little difference in improving the accuracy of modeled wind fields in simple terrain. However, it improved the root mean square error (RMSE) for complex terrain by 34 percent, from 8100 to 9000 meters in horizontal resolution. Under stronger, synoptically forced conditions, the wind speed prediction error did not improve substantially over either terrain type, likely due to errors in the synoptic forcing. These results may lead to computational savings for future experiments involving various real terrain and ABL forcing configurations.

This project took the first steps of combining LES and lidar to evaluate smart strategies for turbine design and operation to optimize energy extraction and minimize turbine damage. The results of ARPS modeling demonstrated that coherent turbulence can be identified and observed using computer modeling and observational data techniques. The research team believed that the results of this study could serve as a foundation for further work to develop
more effective controls and increase productivity and the financial rate of return of wind farms. The research team recommended continued development of the dynamic reconstruction model (DRM) turbulence closure based on the superior performance in comparison to conventional closures. Significantly increasing the horizontal resolution of ARPS or LES simulations with DRM could improve the ability for these models to simulate coherent structures. Additionally, obtaining more computer time to run idealized ARPS/LES simulations at submeter resolution would be useful to determine if even higher resolution and increased temporal sampling can improve the generation of CTKE.

Networks of strategically located sonic anemometers and lidars have the potential of detecting the presence of harmful CTKE in a wind farm better than a single instrument solution. Additional experiments using high resolution LES to determine the spatial extent of high CTKE events could aid in designing such an observational network and could be used in conjunction with the observations in a data assimilation approach. Further exploration of existing co-located lidar and anemometer data, such as the CWEX data set, could also provide insight.

A partnership with a wind farm operator is needed to validate the concerns of potential turbine damage during high wind conditions and the projected economic benefits of installing a forward-looking scanning lidar and/or sonic anemometers. Analysis of wind farm operation logs could help identify times when ABL conditions could have caused damage to wind turbines and lay the groundwork for new cases of ABL conditions/terrain configurations to simulate. Temporary instrumentation of a wind farm suspected of high CTKE events would also provide a new dataset to validate LES simulations and investigate the benefits of increased instrumentation.

2.6.3 Objectives
The goal of this project was to develop a means to enable smarter and more productive wind farm operations during high wind speed, turbulent conditions without impacting wind turbine reliability or durability. The researchers established the following project objectives:

1. Investigate whether LES can reproduce turbulence structures similar to those seen with lidar at wind farms. Verify that mean winds are within three meters per second (m/s) of observed winds on average. Demonstrate that fine-scale turbulent structures can be reproduced with a nesting procedure down to very fine resolution of less than five meters.

2. Test sensitivity of turbulence structures to help choose a turbulence closure model. Demonstrate that choice of closure model changes predictions of shear relevant to wind turbines by more than 20 percent. Show that test simulations provide equivalent or superior agreement with similarity theory, at least 50 percent better than standard closures such as the traditional Smagorinsky model.
3. Simulate a diurnal cycle to see if timing of strong shear and coherent structures in LES agrees with distribution in observations. Demonstrate that the occurrence of shear events in the model shows a similar spectral distribution to observations over a 24-hour period.

4. Investigate resolution requirements for different topographic and synoptic conditions (site locations and prevailing weather conditions). Demonstrate that resolution requirements depend on a number of factors including topography details at a particular site, prevailing wind direction, and time of day. Resolution requirements can vary by at least a factor of two, leading to potential computational savings.

2.6.4 Outcomes

1. The results of Advanced Regional Prediction System (ARPS) modeling indicated that LES can reproduce turbulence structures similar to those seen with lidar at wind farms. Mean winds were within one meter per second (m/s) of observed winds on average. The research team was able to resolve turbulent structures using a dynamic reconstruction model (DRM) at 25 meter resolution but was not able to complete five meter resolution simulations for the real domain due to computational resource constraints. Nonetheless, fine-scale turbulent structures could be reproduced with a nesting procedure down to very fine resolution of 3.125 meters under ideal ARPS simulations.

2. The DRM turbulence closure outperformed the traditional Smagorinsky turbulence closure model by at least 50 percent and generated wind shear by up to 25 percent more intense than the Smagorinsky model.

3. The researchers captured two significant bursting events with surprising temporal accuracy using ARPS and the DRM but not the standard turbulent kinetic energy (TKE) closure. Wavelet analysis revealed that ARPS was not able to resolve the relevant high frequencies for turbine fatigue due to computational limitations. Simulations under ideal conditions showed high frequencies when using higher grid resolution, illustrating the ability to capture turbulent structures that can cause wind turbine fatigue.

4. A resolution of 2700 meters at the complex terrain site and 8100 meters at the simple terrain site were required to achieve a mean absolute error (MAE) rate of 2.3 meters per second or better. Resolution requirements differed depending on different days. For example, a MAE of 2.3 meters per second could be achieved with 2700 meter spacing under local conditions but 3.5 meters per second under synoptic conditions.

2.6.5 Conclusions

1. ARPS modeling indicated that LES can reproduce turbulence structures similar to those seen with lidar at wind farms. Co-locating sonic anemometers alongside the lidar would have determined whether coherent structures that have potential to affect wind turbines adversely were present at higher frequencies. This data was unfortunately not available, but provides an opportunity for future research.
2. The DRM turbulence closure matched or nearly matched similarity theory and outperformed the standard Smagorinsky turbulence closure model by at least 50 percent.

3. ARPS did a good job generating turbulent bursting events with surprising temporal accuracy. Although ideal ARPS simulation does not characterize a real atmospheric state, it does represent very stable nighttime stratification with intermittent turbulence at high resolution. The model was able to capture relevant frequencies when the spatial resolution was high.

4. It is possible that strong synoptic forcing diminishes the significance of capturing more complex terrain at higher resolution. Resolution requirements are dependent on both terrain details and synoptic weather conditions. The research team expects similar performance when comparing other simple and complex terrain locations. This may lead to computational savings when simulating cases with simpler terrain. It is not surprising that the simple terrain case does not show any improvement with increased resolution since this was true under the more sensitive local forcing conditions. The MAE error for the complex terrain site of around 3.5 meters per second is likely due to a forcing problem (initial/boundary conditions) because the different resolutions give very similar results for significantly complex terrain.

This project examined coherent turbulent structures and their potential negative effects on wind power and turbine fatigue to enable smarter wind farm operations. Researchers compared detailed wind field data from multiple lidar and numerical models to determine the extent to which these coherent structures can be observed and simulated in the ABL. The improved understanding developed here could lead to improved energy yields at existing and new wind farm sites.

ARPS simulations could not generate the higher frequency structures that could affect wind turbines due to computational constraints. Ideal ARPS simulations generated the high frequency coherent structures that could fatigue wind turbines, although the intensity was reduced for these ideal conditions. The DRM closure developed by the research team sustained turbulence under stable conditions better than conventional turbulent kinetic energy (TKE) closures. Ideal ARPS simulation with DRM showed excellent agreement with similarity theory over a wide range of atmospheric stability and grid resolution. Horizontal resolution would need to be increased much beyond 3.125 meters to resolve the highest range of relevant frequencies (approximately 30 Hz), but it is not clear if this is yet necessary for creating a coherent structure detection system for wind farms.

Researchers found horizontal resolution made little difference in improving the accuracy of modeled wind fields in simple terrain. However, it improved the RMSE for complex terrain by 34 percent, from 8100 to 9000 meters in horizontal resolution. Under stronger, synoptically forced conditions, the wind speed prediction error did not improve substantially over either terrain type. This was likely due to errors in the synoptic forcing. These results may lead to
computational savings for future experiments involving various real terrain and ABL forcing configurations.

2.6.6 Recommendations
The Program Administrator recommends the following actions to complete the development of this project:

- Continue development of the dynamic reconstruction model (DRM) turbulence closure based on its performance in comparison to conventional closures.
- Increase the horizontal resolution of ARPS or LES simulations with DRM to improve the ability for these models to simulate coherent structures.
- Obtain more computer time to run idealized ARPS/LES simulations at submeter resolution to determine if even higher resolution and increased temporal sampling can improve the generation of CTKE.
- Develop experiments using high resolution LES to determine the spatial extent of high CTKE events. This could aid in designing an observational network and could be used in conjunction with the observations in a data assimilation approach.
- Develop a partnership with a wind farm operator to validate the concerns of potential turbine damage during high wind conditions
- Validate the projected economic benefits of installing a forward-looking scanning lidar and/or sonic anemometers with the partner.
- Analyze wind farm operation logs to identify times when ABL conditions could have caused damage to wind turbines. This could lay the groundwork for new simulation cases of ABL conditions/terrain configurations.
- Instrument a wind farm suspected of high CTKE events to provide a new data set to validate LES simulations, and investigate the benefits of increased instrumentation.
- Improve computing resources to simulate higher resolution coherent structures relevant to wind turbine fatigue
- Improve field instrumentation to quantify a larger range of scales.

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 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 benefits to the ratepayer from this research are reduced environmental impacts of the California electricity supply or transmission or distribution system.

Newer, smarter wind turbine systems which can extract power from more intermittent winds or winds with higher shear can help expand the footprint of wind in the energy market, even without requiring new wind farms. Lidar systems and numerical simulations are not prohibitively expensive. Therefore, it is possible for wind farms to operate lidars in the field, as is the case at some airports. Lidar systems working together with LES could provide unprecedented data that could be used for effective and more efficient smart turbine control. A recent demonstration project in Denmark found that the use of lidar mounted on a wind turbine to see larger flow features such as wind direction shifts and gusts of oncoming flow could increase energy production by 5 percent.\(^{29}\)

The average performance of U.S. wind farms is up to 10 percent below project design estimates. Atmospheric turbulence is believed to play a role in the divergence of expected and actual operating conditions. Larger, more flexible turbines being installed today are subject to larger shear stresses and torques than expected. Turbulence creates dynamic loads on rotor blades that excite vibrational frequencies in the blades, leading to blade fatigue and damage. Over time the repetitive stresses on the mechanical components of the turbine lead to component failure. Errors in power estimates could also be due to the common practice of using power laws with fixed shear exponents and ignoring speed variations across the span of the turbine blades.\(^{30}\)

The research team estimated that for one wind farm a 0.5 meter/second difference in annual wind speed was equivalent to $30 million per year in profit or loss. Thus seemingly small differences in wind speed could lead to very large revenue implications.

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*

The researchers have not performed market assessment or surveyed any customers. They made a technical presentation at the fall meeting of the American Geophysical Union in December of 2012.

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Engineering/Technical

The researchers do not intend to continue the development started in this project.

Legal/Contractual

The research team does not intend to file for patent protection. All work is considered public domain.

Environmental, Safety, Risk Assessments/ Quality Plans

There are no obvious environmental or risk issues at this time. The research team will be able to better assess safety and environmental risk after commercial models are fully developed and ready for demonstration in conjunction with a wind farm operator.

Production Readiness/Commercialization

The concept is not yet sufficiently developed for commercialization. Additional development work is needed to optimize the modeling technique and validate performance. Partnership with a wind farm operator is required to commercialize this modeling technique.

2.7 Passively Stable Shroud for Airborne Wind Turbine

Awardee:   Altaeros Energies, Inc.

Principal Investigator:  Ben Glass

2.7.1 Abstract

This project was an attempt to verify the possibility of developing an airborne wind turbine (AWT) that utilized a helium-filled tethered balloon to access higher level winds than are reachable with current fixed tower technology. The concept included a shroud to concentrate wind at the wind turbine. The researchers developed a dynamic computer model of the AWT system to aid in the analysis of design and enable improvements. The researchers flew a small-scale functional prototype AWT to evaluate the feasibility of the concept. They determined a number of important limiting features, including passive operation through all flight modes, alignment in sustained winds up to 5 m/s (11.2 mph), and increased power production due to the shroud effect and higher wind speed aloft. The researchers observed flight instability at wind speeds higher than 5 m/s. Higher wind speeds, together with wind gustiness, pose significant challenges for the design’s concept.

Keywords: Wind, airborne wind, turbine, aerostat, offshore wind, high altitude wind, renewable

2.7.2 Introduction

Expanded development of renewable energy remains a high priority focus of California’s energy and environmental policy. Wind-generated electricity is the dominant form of renewable energy being developed and will likely continue to be so. Reducing the cost and improving on the intermittency of wind generation are important related goals that must be
addressed if California is to achieve the 33 percent renewable portfolio standard at lowest possible cost and grid reliability impacts.

One approach to improving cost and intermittency is to elevate wind turbines to heights where winds are stronger and less turbulent. Current wind technology relies on placing turbines and associated equipment on tall towers over 300 feet high, while winds are more suited to energy conversion at levels exceeding 1000 feet. California’s coast has water too deep for existing bottom anchored systems. Other research groups have developed airborne wind energy prototypes that rely on kite, wing, and auto gyro-like designs.

The central innovation of the AWT is the helium-filled inflatable shell. The shell is intended to provide four functions:

- Provide buoyant lift for raising the turbine when there is little to no wind to provide aerodynamic lift.
- Provide aerodynamic lift to counter drag when winds are strong.
- Align the rotor passively into the changing winds.
- Augment turbine power, allowing a more compact design.

The researchers also envisioned floating platform base stations to allow for offshore installation. Figure 9 illustrates the concept.

*Figure 9: Overview of Altaeros AWT Buoyant Inflated Shell Technology*
2.7.3 Objectives

The goal of this project was to determine the feasibility of using a helium-filled shroud with no active control surfaces to align and stabilize an airborne wind turbine with changing wind direction. The researchers established the following objectives:

1. Perform dynamic assessment of candidate shroud designs. Confirm through simulation on a high fidelity 3D model that the candidate shroud design exhibits over-damped passive alignment into the wind in response to wind direction changes (lateral behavior) and over-damped altitude and pitch response to gusts (longitudinal behavior). Confirm through simulation that dynamic tether loading does not exceed material limitations at maximum wind speed.

2. Design and fabricate prototype. Confirm that prototype provides sufficient buoyancy to lift measurement instrumentation to a height of 100 m. Demonstrate attainable pitch angles from zero degrees to six degrees in varied wind conditions.

3. Calibrate measurement instrumentation. Confirm test setup is capable of measuring hub height wind speed within an error of 1.0 m/s. Confirm test setup is capable of measuring shroud linear and angular velocity within greater of 5 percent or 0.1 m/s. Confirm test setup is capable of measuring tether tensions within 100 Newtons (N). Confirm that the test setup is capable of measuring atmospheric pressure within 50 Pascals (Pa). Confirm that test setup is capable of measuring shroud position and altitude within an error of ±2 m.

4. Conduct prototype testing without turbine installed. Demonstrate that shroud exhibits over-damped dynamic performance as in Objective 1 in real-world wind conditions. Confirm that tether tension does not exceed material limitations in real-world wind conditions.

5. Conduct prototype testing with functional turbine. Demonstrate that the shroud exhibits the over-damped dynamic performance of Objective 1 in real-world wind conditions with gyroscopic coupling of turbine. Confirm that tether tension does not exceed material limitations in real-world wind conditions.

6. Analyze cost of offshore scale-up. Use validated cost model of megawatt scale AWT to demonstrate potential for levelized cost of energy of $0.09 or less, a 60 percent reduction compared to the California Energy Commission 2018 offshore wind forecast that averages $0.21/kWh for a private installation.31

2.7.4 Outcomes

1. The researchers developed a computer model to simulate the flight characteristics and stability of various designs, including the inflatable shell, tethers, and docking station. The researchers included variables for degrees of freedom that influence airborne wind

31 http://energyalmanac.ca.gov/electricity/levelizedcosts.htm1
turbine stability when aloft, including center-of-gravity and center-of-buoyancy location, which affect down-wind and cross-wind performance. The researchers’ simulated data showed attainable pitch angles up to 16 degrees. Calculated pitch angles were very sensitive to design and buoyancy. The researchers modeled several different designs for the airborne wind turbine and determined that the most stable design included a vertical stabilizer (tail) and multiple and distributed attachment points for the tethers. The researchers also calculated the tension on the four tethers under a simulated turbulent air flow to be approximately 15000 N under a simulated turbulent wind with 30 m/s wind speed. The tether tension approached zero during this simulation, exhibiting a rapid decline from the approximate 15,000 N.

2. The researchers designed and fabricated a prototype airborne wind turbine. Using the same model as in Objective 1, the project team simulated the performance under simulated turbulence with base wind speeds varying from 3 m/s to 30 m/s and changing wind direction. The researchers showed that altitude and pitch angle were maintained throughout the course of the varying simulation. The researchers also showed tether tensions remained below their structural limits of 20 kN forward attachment and 11 kN aft attachment points. The research team tested the buoyancy under in-hanger and in-field with low wind conditions to a height of 104 meters and showed the airborne wind turbine had sufficient buoyancy to maintain pitch angle.

3. The researchers compared test equipment specifications as purchased from equipment manufacturers with equipment specifications as noted in the project statement of work. They did not calibrate the test equipment independently, relying on manufacturers’ specifications which were well within the required accuracy and precision.

4. The researchers completed indoor and outdoor flight tests without the functional wind turbine. In sustained winds up to 5 m/s, the performance of the AWT was stable, with adequate wind heading tracking. Above 5 m/s the airborne wind turbine began to exhibit unstable flight.

5. The researchers completed indoor and outdoor flight tests with the functional wind turbine in operational mode. In low speed winds up to 5 m/s, the performance of the AWT was stable, with adequate wind heading tracking. Above 5 m/s, the airborne wind turbine began to exhibit unstable flight. The tethers did not fail.

6. The research team calculated that a multi-megawatt system could achieve a $0.08/kWh levelized cost of energy.

2.7.5 Conclusions

1. The shroud designed under computer modeling exhibited stable flight under simulated wind up to 30 m/s. However in physical flight tests, researchers observed unstable flight, especially near-oscillating yaw, at wind speeds greater than 5 meters per second. This indicated that the 3D model was inadequate for design verification. The researchers completed this objective, but did not meet the metric of accuracy of the model.
2. The prototype design showed adequate pitch control and buoyancy under the conditions tested. The researchers completed this objective. The results are not directly transferable to the larger-scale airborne wind turbines representative of sizes expected for commercial use. Size effects are likely to be important.

3. The researchers did install instruments on buoyant airborne wind turbines. However they did not meet this objective, because they did not calibrate the instruments independently.

4. The current airborne wind turbine design was unstable with no turbine installed above 5 meters per second wind speed, close to the cut in speed of typical power curves of the turbines considered, as shown in Figure 10. Note that Figure 10 measures miles per hour; 5 m/s is approximately 11.2 mph. The researchers completed the objective of flight testing the design, but did not meet the objective’s metric of stable flight in real-world wind conditions. Tether strength was adequate to hold, deploy, and retrieve the airborne wind turbine.

5. The current airborne wind turbine design was unstable with turbine installed above 5 meters per second wind speed, close to the cut in speed of typical power curves of the turbines considered. The researchers completed the objective of testing the airborne wind turbine in flight, but did not meet the objective’s metric of stable flight in real world wind conditions. Tether strength was adequate to hold, deploy, and retrieve the airborne wind turbine.

6. The researchers completed an assessment of the cost of electricity from the design concept in stand-alone construction and operation. Important cost elements (e.g., network of transmission lines to collect produced electricity, underwater cables to

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32 http://www.westwindenergy.net/2_5kw_winturbine.html
transmit power to land, etc.) The calculated $0.08/kWh levelized cost of electricity was not directly comparable to published EIA estimates for wind electricity in on-shore or off-shore applications.

The researchers have not yet demonstrated feasibility of the concept.

2.7.6 Recommendations
The Program Administrator recommends that the researchers:

1. Improve modeling capabilities so that model results match in-flight results. The improved model should account for size effects as well as local wind phenomenon such as downdrafts and laminar shear, in addition to the potential effects of platform movement currently assumed fixed. This would be important in offshore applications that would experience waves and currents. This should include consideration of airborne wind turbine spacing to avoid entanglements or collisions when individual airborne wind turbines differentially move in relation to changes in wind direction.

2. Investigate potential maritime and aviation conflicts under a scenario of flotillas of airborne wind turbines. Also investigate their effect on aviation and radar. The researchers should investigate the anchoring requirements for offshore installations, considering the deep water off California’s coast.

3. Develop a contingency plan for potential breakaway that may include self-destruct mechanisms.

4. Investigate behavior of tether material encrusted with salt for offshore applications and determine if abrasion or stiffening of tethers is an issue. Abrasion would reduce lifetime, and stiffening would reduce control capability on deploy and retrieval.

5. Evaluate the need for helium replacement from bleed-off, and include such in operating and maintenance protocols and cost estimates.

6. Evaluate the potential installation of two counter-rotating turbines, fore and aft, to offset roll inducing torque.

7. Improve the design so stable flight could be achieved in turbulent and gusty winds that have speeds that match the power curve of wind turbines.

8. Develop and refine engineering and technical requirements.

9. Address potential conflicts with aviation and maritime traffic and with defense radar.

10. Continue working with California Fish and Wildlife Service to avoid issues associated with avian mortality, and develop mitigation techniques if such issues are identified.
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 from this research is increased reliability of the California electricity system. Because the researchers have not yet proven the feasibility of the concept, any quantification of benefits is speculative. However, by raising the height of wind energy conversion and accessing higher level more consistent winds, intermittency and volatility of wind energy could be reduced. Current wind energy technology imposes reliability risks on the grid and requires balancing services. These services are most often from fossil fired and hydroelectric facilities generally operating in less efficient modes than normal, termed ramping penalty. As the amount of wind generation increases, the capacity value of each megawatt decreases. Because of the increasing amounts of intermittent and volatile generation from wind, driven by the renewable portfolio standard, the California ISO is signing capacity contracts in increasing numbers. Senior Advisor to the California grid operator, Clyde Loutan, has stated that additional capacity is needed to accommodate 33 percent renewables (RPS). “To meet the 33 percent RPS, technical studies show ramp rates may triple, which is not possible for the ISO’s conventional generation as configured today.” The airborne wind turbine could assist in maintaining wind generation’s capacity value, thus reducing the need for additional capacity resources needed to maintain reliability.

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 research team has received multiple letters of interest or intent to purchase from potential customers. Additional marketing is premature until the concept is more fully developed.

Engineering/Technical

The researchers estimate they will need two to three years of additional engineering in real-world conditions to increase stability, reliability, and flight autonomy. They have estimated, but have not revealed, funding needs for this additional engineering effort. The researchers have

33 http://integrating-renewables.org/grid-impacts/
received SBIR grants from the U.S. Department of Agriculture and from the National Science Foundation to further the development of this concept.

The researchers have applied for and received U.S. patent approval number 12/579839.

Environmental, Safety, Risk Assessments/Quality Plans

The researchers are working with FAA on airspace permitting to allow deployment of AWT at heights more than 500 feet. They are also working with California Fish and Wildlife Service to ensure reduced avian impacts relative to conventional tower-mounted wind turbines.

Production Readiness/Commercialization

The concept is not ready for production or commercialization.

2.8 Hybrid Solar System for Stationary Electric Power Generation

Awardee: Duke University
Principal Investigator: Nico Hotz

2.8.1 Abstract

This report describes research of a hybrid solar fuel cell system generating electric power for stationary applications such as residential buildings. The system is fed by methanol and combines methanol steam reforming and proton exchange membrane (PEM) fuel cells with solar collectors to generate the required process heat for the steam reforming. The combination of these technologies leads to a higher efficiency system with significantly larger power densities compared to conventional solar systems. The report gives experimental results from a bench test unit that generated 10 W of electric power, and it presents a feasibility study for a 1 kW single family household system based on these results. It is shown that the methanol-to-electricity efficiency of the entire system would be above 50 percent.

An important result of this study was that a novel nano-scale catalyst for methanol steam reforming reduced the required reaction temperature to below 250°C, achieving at least 90 percent methanol conversion and reducing the fraction of CO in the gas stream. Another result was the use of nano-layered selective absorber coatings and high vacuum to develop high temperature solar collectors with a collector stagnation temperature of 252°C, making them compatible with the steam reformer. The researchers synthesized an inverse catalyst which provided for the effective preferential oxidation of CO in the presence of large amounts of water and CO2, producing reformate gas mixture for direct use in a PEM fuel cell. The fuel cell achieved more than 50 percent hydrogen-to-electricity conversion efficiency.

Keywords: PEM fuel cell, hydrogen production, methanol steam reforming, solar collector, hybrid system, CO preferential oxidation

2.8.2 Introduction

Renewable energy sources are needed to replace burning of carbon in fossil fuel powered generation of electricity. Both solar and wind power can replace fossil fuel in stationary
systems, but their widespread implementation has been hampered by the twin problems of intermittency, especially in the case of wind, and the lack of dispatchability in the case of solar and wind. For example, solar energy is not available for use at night. For these reasons there is a need for inexpensive reliable energy storage to solve the problems of intermittency and dispatchability. A variety of energy storage schemes have been studied to meet this need, including batteries, compressed air, pumped hydro, and fuel cells. Stored hydrogen powered fuel cells, in particular, are considered to be attractive for their efficiency and dispatchability. However the long term storage of hydrogen gas at the point of use is a problem due to its low volumetric energy density, even when compressed. Long term storage of high density hydrogen is available, however, in the form of liquid methanol (CH₃OH). Here the methanol could be manufactured off-site and stored on-site in a much smaller tank than with gas storage. Industrial liquid methanol is inexpensive, and if it is produced from biomass, the overall reaction is carbon neutral. The methanol can be used directly in the so-called direct methanol fuel cell (DMFC), but it is hampered by low energy efficiency. The indirect methanol fuel cell (IMFC) is more efficient. In the IMFC liquid methanol fuel and water are reacted by pressurizing and heating to 250°C in the presence of a catalyst that liberates hydrogen and some carbon dioxide.

\[
\text{CH}_3\text{OH} + \text{H}_2\text{O} \rightarrow 3\text{H}_2 + \text{CO}_2
\]

This reforming reaction is endothermic, requiring a heat input of 49.2 kJ per mole methanol. Additionally, the methanol and water reactants must be vaporized and heated to 250°C, requiring 147.5 kJ of heat per mole methanol to be provided to the reformer. The elevated temperature is required to drive the reaction to near completion. Traditionally, heating is achieved by burning an approximate 25 percent fraction of the methanol to supply the heat, significantly lowering the overall methanol-to-electricity conversion efficiency. In addition,

34 http://www.methanol.org/getdoc/300af053-04bd-4b2a-8dce-f6a3e4cd4ce/MI-Renewable-Methanol-Pathways-White-Paper_final.aspx. It is not a carbon negative sink but it is carbon neutral.


37 http://en.wikipedia.org/wiki/Methanol_reformer


parasitic losses of heat to the environment and the energy needed to compress hydrogen gas for short term storage for nighttime use require burning as much as another 25 percent of the methanol to make up for these losses. These fuel losses for process heat make this storage approach only marginally economic. If a means could be found to supply this process heat by a renewable source such as solar thermal energy, it could approximately double the overall efficiency of the indirect methanol fuel cell and make it very attractive as a source of electricity.

In particular, if the methanol component of the energy input were provided by carbon neutral biomass-derived feedstock, it could displace the GHG emissions of fossil fueled electrical generation. For a targeted residential-sized system of 1 kW operating 24 hours daily, the annual output could be 8,760 kWh. At the 2011 average California residential electricity rate of $0.152/kWh, this corresponds to an economic annual value of $1,331 per residence per year. For an assumed market penetration of 10,000 residences this corresponds to a value of $13,310,000. Assuming a carbon neutral source of methanol, it could offset GHG emissions from coal-fired generation of California purchased power or natural gas fired in state generation. For coal the average CO\textsubscript{2} emission rate is 2.1 lbs/kWh, and for natural gas it is 1.22 lbs/kWh. Thus a 1 kW residential system could avoid 18,396 lbs of CO\textsubscript{2} emissions over coal-derived generation or 10,687 lbs CO\textsubscript{2} for natural gas generation per residence.

The advancement of science proposed in this project was to develop a very high temperature solar thermal collector with integrated catalyst for reforming methanol. A complete system is shown schematically in Figure 11. Water and liquid methanol from a long term storage tank are supplied to the evaporator. This new solar collector supplies the heat of evaporation and preheating to the evaporator. The reactant gases are passed to the reformer where the collector supplies the endothermic heat of reaction as shown. The resultant gas stream (hydrogen gas, carbon dioxide, and inevitable carbon monoxide impurity) is passed to the preferential oxidation (PROX) reactor. The CO poisons the proton exchange membrane (PEM) fuel cell and must be removed. The PROX emits purified hydrogen and CO\textsubscript{2} gas stream, part of which is used during the day and a majority of which is pressurized to 100 bar for short term storage. This hydrogen-rich gas stream is delivered to the PEM fuel cell for electric power generation. While the liquid methanol is slowly reformed to a hydrogen-rich gas stream, the compressed gas is rapidly deployable to the fuel cell, providing dispatchable electricity for use at any time.


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

57
2.8.3 Objectives

The goal of this project was to determine the feasibility of a hybrid solar system for stationary electric power generation in buildings by conducting an experimental test. The researchers established the following project objectives:

1. Build and test experimental framework. Demonstrate that a gas chromatograph (GC) is able to detect molar fractions with absolute accuracy of 0.1 percent for all relevant gases except carbon monoxide (CO). It should also demonstrate a CO detection limit below 100 ppm. Demonstrate that flow meters are able to measure and control flow rates with ≤ 5 percent relative error. Temperature sensors need to measure temperatures with ≤ 2 K absolute error.

2. Design, fabricate, and test a solar collector with integrated catalyst. Test and operate this hybrid reformer. The solar collector with integrated catalyst needs to be ready for bench tests. Demonstrate that the methanol conversion of the hybrid reformer is ≥ 85 percent and that it achieves a hydrogen yield of ≥ 85 percent of theoretical maximum.

3. Combine the hybrid reformer with a preferential oxidation (PROX) reactor for CO removal. Demonstrate that the optimized hybrid reformer combined with PROX reactor converts ≥ 90 percent of the inlet methanol and achieves a hydrogen yield of ≥ 90 percent of theoretical with ≤ 100 ppm CO.

4. Build and test the gas storage component and the fuel cell. Demonstrate that the gas storage tank and the fuel cell are ready for bench tests. The fuel cell is to achieve efficiency (hydrogen to electric power) of ≥ 50 percent and a power density of ≥ 20 mW/cm² if operated independently from the entire system.

5. Test and operate the entire system. Demonstrate that the overall system efficiency (methanol to electric power) is ≥ 50 percent and the operating (fuel) cost is ≤ $0.10/kWh.

2.8.4 Outcomes

1. The researchers built and tested an experimental setup including a gas chromatograph (GC), flow meters, and temperature sensors. The GC had absolute accuracy of 0.1 percent for all relevant gases except carbon monoxide (CO). The GC detection limit for
CO was below 10 ppm. Flow meter accuracies were ≤ 5 percent, and temperature sensors were accurate to within ≤ 2 K absolute error.

2. The researchers designed, fabricated, and tested a solar collector with integrated catalyst (hybrid reformer). The hybrid reformer demonstrated a collector temperature of 252°C (stagnation temperature), a methanol conversion of ≥ 90 percent, a hydrogen yield of ≥ 90 percent, and CO mole fractions significantly < 1 percent.

3. The researchers demonstrated that the hybrid reformer converted ≥ 90 percent of the inlet methanol and the PROX reactor oxidized ≥ 99.85 percent of CO, leading to ≤ 15 ppm CO for fuel cell feed gas.

4. The researchers built and tested a gas storage component and associated fuel cell. They successfully stored reformate gas mixture produced by the reformer and cleaned by the PROX reactor in the gas storage tank, and they subsequently fed it to a PEM fuel cell. The researchers demonstrated a fuel efficiency (hydrogen-to-electric power) of ≥ 50 percent and a power density of ≥ 40 mW/cm² at room temperature and ≥ 50 mW/cm² at 80°C.

5. The researchers demonstrated the entire system (methanol reformer, PROX reactor, gas tank, fuel cell) operated at an overall system efficiency (methanol-to-electric power) of between 50 percent and 51 percent. They projected the operating fuel cost to be $.126/kWh at an assumed methanol fuel price of $1.05/gal.

2.8.5 Conclusions

1. The researchers achieved the goals for flow meter accuracy and CO detection limit for the experimental apparatus. Therefore they met the objectives of this task.

2. The researchers exceeded operational methanol conversion and hydrogen yield goals for the hybrid reformer (solar collector with integrated catalyst). Thus they met this objective.

3. The researchers combined the hybrid reformer with the PROX reactor for CO removal. They met the goals of converting ≥ 90 percent of the inlet methanol and achieving hydrogen yield of ≥ 90 percent with ≤ 100 ppm CO.

4. The researchers successfully compressed the reformate gas, stored it in a gas storage component, and then fed it to a PEM fuel cell. The fuel cell achieved hydrogen-to-electric power efficiency and power density goals when operated independently from the entire system. Thus the researchers met this objective.

5. The researchers demonstrated the complete system had an overall efficiency (methanol-to-electric power) of 50—51 percent, meeting this efficiency goal. The researchers estimated operating fuel cost to be $0.126/kWh at a methanol fuel price of $1.05/gal. Thus they did not meet the operating fuel cost goal of ≤ $0.10/kWh.
The goal of this project was to determine the feasibility of a hybrid solar system for stationary electric power generation in buildings. Overall technical feasibility was established. Economic feasibility remains to be established.

2.8.6 Recommendations
The Program Administrator (PA) recommends that typical municipal codes be examined for existing legal barriers to or requirements for pressurizing and storing hydrogen-rich gas on residential sites. The PA also recommends that the researchers survey the market for dispatchable electricity generation for larger sites that might have fewer legal obstacles, such as landfill gas producers, dairy waste gas producers, and light industrial parks.

The researchers should evaluate the cost of delivering relatively small quantities of methanol to residential locations. This project used a cost of methanol of $1.05/gal. While this cost may be available to large industrial users, it is definitely not the cost that a small user could obtain. Electricity cost projections for the proposed system should be based on methanol costs available to the small buyer.

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.

2.8.7 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 is reduced environmental impacts of the California electricity supply or transmission or distribution system through the use of a methanol fueled IMFC generator. In particular, if the methanol component of the energy input were provided by carbon neutral biomass-derived feedstock, it could displace the GHG emissions of natural gas fueled electricity generation.

For a targeted residential system of 1 kW operating 24 hours daily, the annual output could be as high as 8,760 kWh. At the 2011 average California residential electricity rate of $0.152/kWh,
this corresponds to an economic annual value of $1,331 per residence per year. At a methanol cost of $1.05/gal, fuel cost would be $1,104 per year for a net savings of $227. Capital amortization and maintenance costs would be deducted from that savings. If methanol cost more than $1.05/gal to the residential buyer, there may be no net savings.

Assuming a carbon neutral source of methanol, the proposed device could offset GHG emissions from natural gas fired generation. For natural gas the average CO₂ emission rate is 1.22 lbs/kWh.⁹ Thus, a 1kW residential system could avoid 10,687 lbs CO₂ per residence.

At this time the production cost of bio-methanol is estimated between 1.5—4.0 times higher than the cost of natural gas based methanol. Thus, these environmental benefits may not occur because of the resulting high cost of the produced electricity.

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 been in contact with potential customers, but they had not performed a complete market survey or analysis by the end of this project.

Engineering/Technical

The researchers have a development plan that requires about three years and half a million dollars to complete. This effort would produce a larger scale demonstrator.

Legal/Contractual

Duke University’s Office of Licensing and Ventures performed patent searches. It found no product or patent infringement. The researchers have filed one Provisional Patent Application, and others were being prepared at the end of the project.

Environmental, Safety, Risk Assessments/ Quality Plans

No essential additional testing or plans in these areas are apparent at this time.

Production Readiness/Commercialization

The researchers intend to prepare a commercialization plan after they have developed a larger scale demonstration unit.
2.9 Energy Harvesting from Ocean Currents Using Piezoelectric Elements

Awardee: The University Corporation, California State University Northridge
Principal Investigator: Hamid Johari, Mohab Shalaby

2.9.1 Abstract

Ocean currents along the California coast contain huge amount of kinetic energy. If harvested, these currents could meet a significant portion of California’s energy demand while contributing to achieving AB 32 greenhouse gas emission reductions and renewable portfolio standards. The main goal of this project was to examine the feasibility of extracting electrical energy from ocean currents or river flows using an in-flow device consisting of a large, thin piezoelectric element attached to a cylinder. Water flow around the cylinder causes the piezoelectric element to bend back and forth, much like a flag waving in the breeze. The resulting tension and compression on opposite sides of the element produce a variable electrical charge that can be harvested for storage or transmission.

The researchers documented parameters associated with current flows necessary for the proposed design. They assessed ocean currents near California’s coastline and designed conceptual devices. The researchers used finite element analysis to find the natural frequencies of the various piezoelectric concepts. Using computer simulations, they calculated that deflections of only a few micrometers resulted in power generation in the order of $10^{-10}$ watts (a pico-watt) from a single harvester. The researchers concluded that the proposed energy harvester design would not be a viable approach for expected ocean current velocities.

Keywords: Piezoelectric energy harvester, FSI analysis of harvester, energy from ocean current

2.9.2 Introduction

Development of renewable energy remains a high priority of California’s energy and environmental policy. One significant untapped renewable resource available to California is ocean currents. Ocean currents are much more consistent, predictable, and reliable than other renewable energy sources such as wind or solar. Due to their predictability and nearly constant availability, ocean currents could provide base load power. This characteristic may make this resource particularly favorable to a future energy system otherwise reliant on intermittent renewable resources. However the low velocity of these currents makes the use of currently available turbines challenging.

Various ocean energy extraction technologies are currently being developed, including those from ocean thermal energy, wave and tidal energy, and ocean currents. Of all these technologies, energy extraction from ocean currents is still at the earliest stage of development, with only a few prototypes and demonstration units having been tested. There is a need to study the potential of this resource and to develop new technologies for capturing ocean current...
energy. Significant work is needed to determine the viability of this resource for large-scale power generation to supplement other renewable energy resources.

The researchers proposed a piezoelectric based energy harvester for use in ocean (or river) currents. Piezoelectric elements generate electric charges when they are exposed to mechanical loads such as strain. The researchers proposed a simple system comprised of thin piezoelectric elements, or strips, directly attached to a moored cylinder. The cylinder acts as a bluff body and housing for the associated electrical power extraction and storage systems. Operating in the wake of the cylinder, the piezoelectric elements wave, or flap, due to the turbulent flow downstream of the cylinder. The resulting strain energy is converted to electrical energy by the piezoelectric effect. The built-up charge can be stored or transmitted via hardware placed within the cylinder. The concept is illustrated in Figure 12.

Figure 12: Schematic of the Harvester and the Geometric Parameters of the Design

2.9.3 Objectives

The goal of this project was to determine the feasibility of using a new piezoelectric energy harvesting system to economically and efficiently generate power from ocean currents near the coast of California. The researchers established the following objectives:

1. Identify key parameters that cover 90 percent of operating conditions for California ocean currents. Identify 2 or 3 most probable piezoelectric harvesting system configurations.

2. Perform finite element modeling and analysis of piezoelectric system. Demonstrate that the model can capture the coupled effects of fluid structure interactions. Demonstrate that the model represents the available experimental data to within a margin of error of ± 20 percent.

3. Demonstrate that the system is capable of generating a minimum power density of five watts per cubic meter (W/m³).

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43 Piezoelectricity is the electric charge that accumulates in certain solid materials (such as crystals, certain ceramics, and some biological matter) in response to applied mechanical stress.
4. Demonstrate that the cost of harvested energy per kWh is comparable to other renewable energy generation methods (0.05 – 0.1 $/kWh).

2.9.4 Outcomes
1. The researchers completed a literature review on the three major ocean currents off the California coast and summarized the physical properties (including density, viscosity, and velocity) in which the piezoelectric harvesters could operate. The ocean current velocities ranged from 0.05 to 0.5 meters per second. Other properties are shown in Table 2. The researchers chose dimensions for the cylinder and piezoelectric element to maintain laminar flow around the cylinder.

Table 2: California Ocean Current Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min. Value</th>
<th>Max. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>current velocity ( V ) (m/s)</td>
<td>0.05</td>
<td>0.5</td>
</tr>
<tr>
<td>density ( \rho ) (kg/m(^3))</td>
<td>1012</td>
<td>1032</td>
</tr>
<tr>
<td>kinematic viscosity ( \nu ) (m(^2)/s)</td>
<td>1.05×10(^{-6})</td>
<td>1.83×10(^{-6})</td>
</tr>
<tr>
<td>viscosity ( \mu ) (Pa s)</td>
<td>1.08×10(^{-3})</td>
<td>1.88×10(^{-3})</td>
</tr>
</tbody>
</table>

2. The researchers established design parameters and completed analysis of potential piezoelectric designs and assessed the potential of power generation for each design. The researchers calculated the natural frequency and bending moments using a finite element-based model and the vortex shedding characteristics of the cylinder using computational fluid dynamics (CFD). They found that the stand-alone CFD and structural simulations resulted in solutions that were within the required ± 20 percent margin. The design parameters chosen are shown in Table 3.

Table 3: Design Parameters for Energy Harvester

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min. Value</th>
<th>Max. Value</th>
<th>Most Probable Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cylinder diameter ( D ) (m)</td>
<td>0.001</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>cylinder span ( H ) (m)</td>
<td>0.025</td>
<td>0.3</td>
<td>0.03</td>
</tr>
<tr>
<td>element width ( W ) (m)</td>
<td>0.025</td>
<td>0.25</td>
<td>0.025 or 0.05</td>
</tr>
<tr>
<td>element length ( L ) (m)</td>
<td>0.05</td>
<td>0.5</td>
<td>0.05 or 0.25</td>
</tr>
<tr>
<td>element thickness ( T ) (m)</td>
<td>0.0001</td>
<td>0.005</td>
<td>0.001</td>
</tr>
</tbody>
</table>
3. The researchers computed the power density of the proposed energy harvester, using various configurations from Table 3, by dividing the power generated by the volume occupied. They found a maximum power density of 0.15 micro-watts per cubic meter ($\mu$W/m$^3$).

4. The researchers did not estimate the cost of energy harvested using this concept but did conclude that the proposed design would not be able to compete with other techniques, given the extremely small power generated by individual harvesters.

2.9.5 Conclusions

1. The researchers characterized physical parameters of California ocean currents, but did not estimate the technical potential energy of California currents. They completed this objective.

2. The researchers demonstrated that the finite element analysis and computational fluid dynamic modeling are capable of ±20 percent accuracy. They completed this objective.

3. The calculated power density of the proposed energy harvester designs was six orders of magnitude below the stated performance metric of 5 watts per cubic meter. The researchers completed this objective, but they did not demonstrate performance necessary for technical feasibility.

4. The researchers determined that the proposed design did not perform as expected and was not a viable ocean current energy harvester. They did not estimate generation costs. The researchers completed this objective, but they did not demonstrate performance necessary for technical feasibility.

The researchers did not demonstrate technical feasibility of the proposed concept.

2.9.6 Recommendations

The Program Administrator recommends the following actions:

1. The researchers should consider fundamentally different and non-cylindrical design concepts that may increase vortex size, vortex shedding, and increase piezoelectric element bending motion.

2. The researchers should evaluate different piezoelectric materials that are resistant to stress cracking from continuous flexing.

3. The researchers should consider adding surface elements to the bluff element and increase surface roughness to increase vortex shedding and non-cylindrical bluff elements to improve laminar flow.
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 of this research, if successful, would be reduced environmental impacts of the California electricity supply system. In addition, it could provide baseload renewable capacity. This could lead to increased reliability of the California electricity system. Quantifying those benefits before achievement of technical feasibility would be highly speculative. However, by accessing the energy in more consistent natural energy flows such as ocean currents, problems associated with intermittency and volatility of other renewables such as wind could be reduced. Current wind energy technology imposes reliability risks on the grid and requires balancing services, most often from fossil fired and hydroelectric facilities operating in less efficient modes than normal. As the amount of intermittent generation increases, the capacity value of each megawatt decreases. As a result, due largely to the increasing amounts of intermittent and volatile generation from wind, the California ISO is signing capacity contracts in increasing numbers. The need for flexible conventional generation to ensure grid reliability going forward would be reduced a significant, but unquantified, amount if some of the renewable generation were from baseload and consistent sources, as in the concept described here.

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 will need to develop an entirely new design and demonstrate technical feasibility before attempting to establish market connections either with potential development partners or with potential customers.

Engineering/Technical
The researchers will need to develop an entirely new design and demonstrate technical feasibility before attempting to establish and refine engineering and technical requirements.
Legal/Contractual

Establishing legal and or contractual agreements is premature until the concept is shown to be technically feasible.

Environmental, Safety, Risk Assessments/ Quality Plans

Conflicts with maritime traffic will need to be addressed. Oceanic leaching of piezoelectric device constituents (such as rare earth elements) will need to be evaluated for environmental and durability purposes. Stress cracking of crystalline piezoelectric elements under constant flexing will need to be considered in durability assessment and quality plans.

Production Readiness/Commercialization

The concept is not ready for production or commercialization.

2.10 Tar Removal by Catalyzing Gasification Bed Materials for Power Generation

Awardee: University of California, San Diego
Principal Investigator: Dr. Kenneth S. Vecchio

2.10.1 Abstract

Researchers in this project demonstrated tar removal capabilities of iron and nickel catalysts for use in biomass gasification. The researchers activated commercial ceramic bed material used in the gasification process by the addition of nickel and iron using wet impregnation. They measured the performance in reducing tars in simulated producer gas to reduce the cost of biomass power generation.

The catalyzed bed material with three highest Ni concentrations (100 percent, 75 percent, and 50 percent) provided catalytic activity with stabilized conversion efficiencies greater than 28 percent for the tar surrogate toluene through 48 hours of operation. Catalyst stability in tar reforming was demonstrated over a period longer than 72 hours with a half nickel/half iron catalyst providing the best stability.

The elimination of a separate tar-reforming unit by using the catalyzed bed material demonstrated in this project could lower the capital cost of a biomass gasification plant by approximately $1,200 per installed kilowatt and reduce the electricity generation cost by an estimated $0.031/kWh.

Keywords: Biomass, gasification, tars, reforming, catalyst

2.10.2 Introduction

Expanded development of renewable energy remains a high priority focus of California’s energy and environmental policy. Until 1993, California’s biomass power generation was at its highest (more than 800 MW of installed capacity), but growth stalled and capacity declined after that. In 1996 energy production from biomass dwindled to about 590 MW. Currently there
There are about 30 direct combustion biomass facilities in operation with a capacity of 640 MW. Biomass power conversion is currently not cost competitive with other renewable energy sources like wind. Biomass resources have received growing attention in recent years as a major renewable energy source to fulfill future energy and capacity needs, but biomass power generation will require innovative cost reduction approaches to become cost competitive and take a larger role in meeting California’s renewable goals.

Gasification of biomass results in a producer gas containing hydrogen (H₂) and carbon monoxide (CO) that can be used for the production of power or converted to fuels or commercial chemicals. The raw producer gas commonly includes tars, ammonia (NH₃), and hydrogen sulfide (H₂S). Tars contain a mixture of complex aromatic hydrocarbons that are liquid at room temperature. Tars present numerous challenges for the downstream applications of producer gas, particularly for power generation. They need to be removed before entering the downstream processes, as they can cause plugging and corrosion. Catalytic tar removal using separate equipment is one of the common ways to eliminate the tars and improve the H₂ and CO content in the producer gas. Because downstream cleaning steps are relatively expensive, the removal of tars by the use of catalyzed gasifier bed material could reduce these costs and enhance biomass cost competitiveness.

This project investigated the use of catalytically active gasification bed material to reduce the production of tars in the gasifier. Commercial ceramic bed material used in the gasification process was catalytically activated by the addition of nickel and iron. Nickel and iron are relatively inexpensive elements and wet impregnation is an easy and cost effective method for catalytically activating materials. Figure 13 illustrates the experimental setup.

**Figure 13: Schematic Representation of the Fixed-Bed Reactor System for Experiments**
2.10.3 Objectives

The goal of this research project was to determine the feasibility of tar removal in producer gas from biomass gasification by catalyzing gasifier bed material. The researchers established the following objectives:

1. Demonstrate the successful preparation of iron and nickel catalytically activated gasification bed material for use in demonstrating tar reforming in producer gas to concentrations less than 0.1 g/Nm³ dry.
2. Achieve catalyst loading of approximately 1.0 percent by weight of nickel and iron on the CARBO Ceramics bed materials for the reduction of tar content to 0.1 g/Nm³ dry in the producer gas.
3. Demonstrate the durability (less than 33 percent reduction in efficiency) of the gasification bed material for the reduction of tar content to 0.1 g/Nm³ dry in the producer gas for longer than 48 hours.
4. Determine the stability, less than 33 percent reduction in active metal sites, of the gasification bed materials after 48 hours of tar removal operation.
5. Demonstrate that the achieved tar reduction performance can reduce the cost of biomass power generation by at least $0.033 per kWh.

2.10.4 Outcomes

1. The researchers used a wet impregnation method with nickel hexahydrate (Ni(NO₃)₂·6H₂O) and iron nitrate nonahydrate (Fe(NO₃)₃·9H₂O) in solution to activate CARBO HSP ceramic bed material.
2. The researchers calcined the material at a temperature of 900° C and produced five Ni/Fe catalyzed samples with composition from 100 percent nickel to 100 percent iron with steps in 25 percent increments and with a total metal loading of 1.0 percent by weight. They measured the removal efficiency under fixed flow and catalyst loading and estimated the residence time and catalyst loading necessary to achieve an output stream content of 0.1 g/Nm³ dry, corresponding to a 97.5 percent removal of the initial tar loading. The researchers showed that the catalyst had a different tar removal efficiency for each of the simulated tar constituents, as shown in Figure 14.
3. The researchers measured the conversion efficiency before and after catalyst regeneration to determine durability. They measured the efficiency for the 100 percent nickel catalyst at 28 percent at 48 hours and at 29 percent after regeneration. Other percentage nickel v. iron results are shown in Table 4. The researchers did not further test 75 percent and 100 percent iron for catalytic activity.

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>Efficiency Before Regeneration</th>
<th>Efficiency After Regeneration</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 Ni</td>
<td>28%</td>
<td>29%</td>
</tr>
<tr>
<td>75 Ni/25 Fe</td>
<td>31%</td>
<td>32%</td>
</tr>
<tr>
<td>50 Ni/50 Fe</td>
<td>40%</td>
<td>40%</td>
</tr>
</tbody>
</table>

4. The researchers characterized the stability of the active metal sites after 48 hours of tar removal operation using X-ray diffraction (XRD), Temperature Programmed Reduction (TPR), and Temperature Programmed Oxidation (TPO). They found no loss of active metal sites. The researchers concluded that the iron prevents sintering of nickel and the loss of catalytic activity.

5. The researchers calculated the capital cost impact of the use of the 50 percent Ni/Fe and 50 percent catalyst compared to using a separate tar removal unit. They calculated a reduction of $0.031/kWh for a commercial-size power plant.

2.10.5 Conclusions

1. Iron and nickel can be homogenously deposited on commercial gasification bed material and can exhibit catalytic activity in reducing simulated tar constituents. Multiple passes and/or long residence times may be required to reduce tar constituents from actual
gasifiers to levels low enough for ultimate use in power generation equipment without further treatment. Catalyst with 50 percent iron is more efficient than 100 percent nickel in reducing the simulated tars. The chemicals the researchers used to simulate gasification tars may not be representative of the complex and higher hydrocarbons present in gasified biomass materials. The researchers partially and indirectly completed this objective.

2. Iron and nickel can be deposited on commercial gasification bed material at levels of approximately 1.0 percent by weight. The researchers completed this objective.

3. The iron and nickel composite catalyst did not exhibit significant efficiency degradation upon one regeneration cycle after 48 hours of activity. The researchers completed this objective.

4. The iron and nickel composite catalysts are physically and chemically stable at the temperature conditions (up to 900° C) tested by the researchers and showed no loss of active metal sites. Iron levels up to approximately 50 percent of the catalyst load stabilized the catalyst loading on the bed material. The researchers completed this objective.

5. The removal of a separate tar-reforming unit by using the catalyzed bed material demonstrated in this project could lower the capital cost of a biomass gasification plant potentially to a level that would allow cost competitiveness. The reduction of capital costs estimated by the researchers appears plausible, but other cost factors (e.g., operations and maintenance) need to be determined to compare overall costs. The researchers partly achieved this objective.

The researchers demonstrated the technical possibility of catalytic removal of tars in gasified biomass but did not demonstrate the technical feasibility or practicality, both of which will require demonstration using actual biomass gasifier output.

2.10.6 Recommendations
The Program Administrator recommends the following actions:

1. The researchers should determine the performance of the catalyst on actual producer gas from a gasifier. The output stream from an actual gasifier may contain organic and inorganic constituents (such as chlorides) that may impede or deactivate the catalyst.

2. In addition to testing overall tar reduction efficiency on actual producer gas, the researchers should determine speciate reduction efficiency under various temperature profiles and conditions within the gasification bed.

3. The researchers should test longer term tar reforming efficiency, including multiple catalyst regeneration cycles, to evaluate long term catalyst durability. This should include testing of a variety of biomass, as gasification output streams can vary depending upon the biomass gasified.
4. The researchers should evaluate the full estimated cost of power, including operating and maintenance and related costs, for comparison to other alternatives.

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 of this research is increased affordability of electricity in California.

If all of the 32 million bone dry tons (BDT) per year of biomass available in California were used in power generation, it could provide about 4,650 MW of electricity and 9,050 MW of thermal energy. The catalytic bed material technology for tar removal in the gasifier could reduce the capital cost of such power generation by perhaps 30 percent, which corresponds to $0.033—$0.039 per kWh if no significant other costs occur. This could lead to a potential annual cost saving of $1.2 billion to $1.4 billion. Alternatively, just returning to the historic peak level of 7,362 GWh per year (restoring the lost 1,787 GWh of biomass power) would lead to an annual cost of savings of $59 million to $70 million.

Quantifying the likely cost savings is premature until the net cost savings are estimated and demonstration using real-world biomass gas is complete.

Secondary benefits would likely include reduced environmental impacts from the electrical supply system by reducing emissions of greenhouse gasses from increased offset of fossil fired generation for both capacity and energy. Further, expanded development of biomass to energy that is enabled by cost reductions could reduce wildfire risk and severity through the harvesting of biomass and reduction of fuel loads in California forests.
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 established a research partnership with West Biofuels, a commercial private sector biomass development firm. They are continuing research and development activities leading to commercialization of the process.

Engineering/Technical

The researchers plan to conduct laboratory-scale testing at UC Davis and pilot-scale demonstration at the Woodland Biomass Research Center. To complete the development and demonstration the researchers estimated a need for two to three years and up to one million dollars.

Legal/Contractual

The researchers have entered into a development partnership with West Biofuels LLC. At the end of this project they had not applied for nor received any patents.

Environmental, Safety, Risk Assessments/Quality Plans

There are no known environmental, safety, or other risks unique to this process.

Production Readiness/Commercialization

The process is not ready for commercialization until further large scale testing on actual biomass gasses is complete.

2.11 High Performance Battery Exploiting Scaled Manufacturing Technology

Awardee: Jasper Ridge LLC dba Gridtential Energy
Principal Investigator: Dr. Peter Borden

2.11.1 Abstract

This project provided proof of concept for new lead acid battery architectures that reduced weight and improved performance. Semiconductor wafers replaced heavy lead plates as the battery electrodes’ substrates. Second, electrochemical processes deposited thin layers of high porosity materials to improve deep discharge rates. Third, the researchers implemented bipolar architecture to reduce the battery footprint and simplify connecting multiple cells into a battery stack by coating opposite sides of the semiconductor electrode. The researchers’ modeling suggested that the new design could lead to performance enhancements and cost advantages compared to current lead acid batteries. In addition, the technology and design innovations could integrate seamlessly into low cost and high volume manufacturing techniques. The
researchers preliminary testing provided proof of concept, but longer term more rigorous testing and design and manufacturing process refinement are necessary to demonstrate technical feasibility and market potential.

**Keywords:** Lead acid battery, bipolar battery architecture, lead electrodeposition

### 2.11.2 Introduction

Increasing renewable energy generated electricity and advanced transportation vehicles requires significant improvements in energy storage technology, including batteries. To balance intermittent electrical generation technologies, batteries need to be capable of increased energy storage density and lifetime charge/discharge cycles. For transportation applications, storage devices like batteries also need high energy storage density combined with low weight. While different battery chemistries, like lithium ion, are receiving research attention and early commercial application, the lead acid battery remains the technology of choice because of its low cost, simplicity, and user experience. The lead acid battery has been improved incrementally since its invention in both ease of use (e.g., maintenance free) and performance (e.g., deep discharge), but it faces significant challenges as diverse applications require broader performance.

Lead acid batteries are heavy due to the lead and lead oxide plates and the heavy duty casings needed to provide mechanical support and to contain the strong acid electrolyte. Lead acid batteries’ energy density is low relative to other battery types. Deep discharge (full use of capacity) for lead acid batteries can only be achieved at low currents, rendering them of limited use in grid balancing or transportation. Finally, the plate material expands and contracts mechanically under charge/discharge cycles, leading to short battery life.

In this project researchers tested several innovations to change fundamentally the lead acid battery. Changes included the electrode substrate, the active materials, the overall battery design, and the manufacturing approach. The innovations were intended to increase energy density, simplify design, and lead to a low cost, low weight lead acid battery design competitive for renewable energy applications. The researchers proposed to replace the heavy lead grid structure with semiconductor wafers. For the electro-active materials, the researchers tried several fabrication techniques to deposit thinner layers of more porous active materials to enable higher current density in deep discharge applications. The researchers also tested a novel electrical connection architecture that simplified design and manufacture for multiple cell battery stacks. The overall concept is shown in Figure 15.
2.11.3 Objectives

The goal of this project was to determine the feasibility of a new battery design based on the well-known lead acid electrochemistry. The research team defined the following objectives in technology, design and manufacturing, and marketing areas:

1. Demonstrate long term corrosion stability of silicon electrodes in sulfuric acid electrolyte. Demonstrate active mass deposition onto silicon substrates with thickness >0.2 mm. Develop a process to deposit active material with porosity >30 percent estimated by SEM. For single cells, demonstrate >1.65 V discharge voltage with >80 percent discharge depth at C5 discharge rate. Deposit positive and negative active materials on opposite sides of a bipolar plate. For multi-cells, demonstrate >1.65 V discharge voltage per cell with >80 percent discharge depth at C5 discharge rate. The number of cells needs to be ≥5. Achieve cycle life of ≥20 cycles with <5 percent degradation at 80 percent discharge depth.

2. Complete a bipolar battery design with ≥3 cells/cm with at least 25 cm² plate area. Design associated assembly tooling and test fixtures for building battery stacks, acquire parts to build test batteries, and assemble a bipolar battery stack with ≥5 cells for testing.

3. Complete market and product requirements and identify markets and applications for the technology. Identify key product requirements to meet market needs and speed adoption. Estimate energy density based on preliminary design. Demonstrate potential advantages of the new battery. Perform cost analysis and show viability of <$200/kWh.
2.11.4 Outcomes

1. The researchers evaluated the corrosion resistance of the silicon electrodes to sulfuric acid electrolyte (six molar) and demonstrated that the substrate material and the contact adhesion layer were stable after three months of immersion. They used scanning electron microscopy to show that the contact material remained attached to the substrate.

The research team investigated several electroplating bath chemistries and process parameters to determine the variables which control mass, thickness, and porosity of the deposited active material. They achieved plate thicknesses of 0.16 mm under certain combinations of substrate pre-treatment and plating bath chemistry and plating current. Using trace hydrochloric acid and high plating current, the researchers obtained a porosity of 50 percent, as estimated by comparing plated thickness and density of plating material. The researchers sequentially plated negative and positive electro-active materials on opposite sides of a bipolar plate. The negative Pb material was deposited first, followed by deposition of the PbO₂ positive material.

The researchers tested a single cell battery by repeating the charge/discharge cycle and measuring the cell voltage and current. The cycling test was performed with a discharge voltage threshold of 1.5V, which is equivalent to 80 percent depth of discharge. The researchers measured the discharge voltage at ~ 2.1V for all the cycles, with the each cycle’s discharge time close to three hours.

The researchers built two cell and five cell battery stacks and performed cycling tests on the stacks. They measured the discharge voltage of the two cell battery at 4.2V and the five cell battery at 10.5V. The researchers measured the decay in capacity with multiple charge/discharge cycles. They determined the energy storage capacity of the two cell stack (left hand panel) and of the five cell stack (right hand panel) remained relatively constant up to 50 cycles and decayed slowly after that, as shown in Figure 16.

Figure 16: Plot of Discharge Capacity with Number of Cycles for a Double Cell (left) and a Multi-Cell (right)

2. The research team designed and built a battery stack with linear density of 4.37 cells per centimeter. A five cell stack would have a total area of 26 cm² with the edges not...
counted. The team procured the cell casings with the help of a machine shop. The team also developed a procedure to assemble battery stacks and assembled five cell battery stacks.

3. The researchers assessed different applications of the battery stack, including electric grid balancing and motive power, to determine initial market focus and potential commercial introduction. They identified light motive application (e.g., golf carts) and renewable energy firming as high priority focus.

The researchers estimated the energy density of a preliminary design of the battery module with an energy storage target of 5 kWh comprised of 24 cells (~48 volts) and equipped with electrical connections, mechanical support, casing structures, and heat exchangers. They then used a mathematical model to calculate the energy and power densities of the battery module. The model estimated that the battery would have gravimetric and volumetric energy densities of 65 to 90 watt hours per kilogram and 75 to 130 watt hours per liter, respectively.

The research team analyzed the manufacturing processes and materials for the proposed technology design and estimated the total cost to manufacture the batteries to be approximately $150/kWh.

2.1.1.5 Conclusions

1. The researchers demonstrated that the silicon electrodes are stable for at least three months in six molar sulfuric acid. In addition, active material of Pb and PbO can be deposited onto the silicon electrodes at thicknesses of nearly 0.2 millimeters with porosity up to 50 percent. Battery cells having voltages of approximately 2.1 volts can be constructed, comparable to traditional lead acid batteries. The researchers showed that positive-active and negative-active materials can be sequentially plated onto opposite sides of the electrodes to form bipolar devices. They stacked multiple cells to provide higher voltages, and showed the higher voltages can maintain charge/discharge performance for at least 50 cycles with less than 5 percent degradation. The researchers completed this objective.

2. The researchers demonstrated that functional design(s) of multiple cell batteries can be built with more than three cells stacked to increase battery voltage and watt-hour storage and can be assembled using straightforward techniques. The researchers completed this objective.

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44 Renewable energy firming refers to the required ability of electrical grids to accommodate volatile and intermittent output of certain renewable energy forms, such as wind energy, on a fifteen minutes or shorter basis. It is different, in time scale, from energy storage which usually refers to daily or longer renewable energy output.
3. There are several potential market applications of the technology concept, some more likely than others. Energy density on both a gravimetric and a volumetric basis are favorable to many applications. Manufacturing costs appear to be attractive, with costs under $200 per kilowatt hour. The researchers completed this objective.

The researchers successfully demonstrated the technical feasibility of their battery concept design, although considerable work is required for commercial practicality.

### 2.11.6 Recommendations

The Program Administrator recommends the following actions:

1. The researchers should determine the life expectancy of the battery under normal operating regimes typical of the several applications envisioned. This should include sensitivity to mechanical stresses such as vibration, especially for motive power use.

2. The researchers should investigate the battery’s susceptibility to memory effects under partial charge/discharge cycling.

3. The researchers should determine the battery’s capability in rapid cycling for use in grid balancing of renewables, where the cycling time may be less than 15 minutes, more rapid than diurnal energy storage.

4. The researchers should use a third party to verify manufacturing cost estimates.

5. The researchers should begin to develop battery maintenance protocols and battery recycling/recovery methods.

6. The researchers should develop a better contact adhesion layer, active materials, and alternative methods of material deposition. Automated and consistent manufacturing methods need to be developed.

7. The researchers need to scale up cell size for commercial introduction.

8. The researchers need to improve techniques for small particle size plating with high porosity.

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 is from increased affordability of electricity in California. The estimated value depends on the applications that actually shift from traditional battery technology and the extent of that shift. Some applications have long payback periods because of infrequent use, such as electric service reliability and power quality. Others require low cost per kWh, including time of use energy management, intermittent renewables capacity firming, and storage. Actual dollar values are too speculative to estimate but could be in the tens of billions of dollars over 10 years.

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 are working with partners in the renewable energy field and battery distributors. They will need to work with motive power users and manufacturers to penetrate the motive power markets.

Engineering/Technical
The researchers project a requirement of several million dollars and two to three years to complete engineering and development work. They plan to continue this work as funding becomes available.

Legal/Contractual
The researchers have applied for an international patent. The application, number PCT/US2012/037598, is pending.

Environmental, Safety, Risk Assessments/Quality Plans
There are no unique environmental risks associated with the battery technology beyond those associated with conventional lead acid batteries. Given the high energy density, safety issues must be addressed.
Production Readiness/Commercialization

The product is not ready for production or commercialization.

2.12 Autonomous Flexible Wings for High Altitude Wind Energy Generation

Awardee: University of California, Santa Barbara
Principal Investigator: Lorenzo Fagiano

2.12.1 Abstract

California is on track to meet its goal of increasing procurement from eligible renewable energy resources to 33 percent of total electricity by 2020, and policymakers are now beginning to discuss adoption of a 50 percent goal by 2030. Wind energy has been a key element to successful adoption of renewable energy in the State. Virtually all of existing wind energy resources are considered to be low altitude in that they are located at or near ground level. However, high altitude wind is a vast, untapped renewable source of energy that has received increased attention from both industry and academia over the past several years under the broad category of airborne wind energy (AWE) systems. Many airborne wind energy generator concepts were published in various patents and publications in the 1970s. More recently, an increasing number of research groups and companies have been trying to develop operating prototypes of devices which are designed to harness high altitude winds blowing up to 1,000 meters from the ground and to convert this energy into electricity.

The purpose of this project was to investigate the feasibility of using an automatic control system for an airborne wind energy generator with a flexible wing tethered to the ground with three lines. If successful, the concept would enable a new class of renewable energy systems that are capable of capturing energy and generating electricity from high altitude winds during flight. Autonomous operation of the system is crucial as the wing must be controlled to enable carefully designed figure eight flight paths perpendicular to the wind flow while coping with turbulence and keeping a safe distance from the ground. The control system is particularly challenging because flexible wings are subjected to fast changing, nonlinear, uncertain and unstable dynamics, constraints, and external disturbances.

The research team developed mathematical models, sensor fusion algorithms, and controls that it used for the design and fabrication of a small-scale prototype. The team then conducted a series of tests at a beach in Oxnard, California. Data collected in the experiments support theoretical and numerical analyses that have been conducted recently on high altitude wind energy. The results demonstrated the plausibility of a carefully designed automatic control system that is able to meet all operating requirements of an airborne wind energy device with a flexible tethered wing. Once fully developed, airborne wind energy systems have the potential to generate wind energy anywhere in the world in large quantities and at potentially lower costs than fossil fuels, without the need for incentives.
Keywords: Wind energy, airborne wind energy, high altitude wind energy, kite power, crosswind kite power, automatic control, sensor fusion

2.12.2 Introduction

California is on track to meet its goal of increasing procurement from eligible renewable energy resources to 33 percent of total electricity by 2020, and policymakers are now beginning to discuss adoption of a 50 percent goal by 2030. Wind energy has been one key element to the State’s successful adoption of renewable energy. The technical potential of wind power itself can supply global energy needs several times over. California has excellent wind power potential at an altitude where current wind turbines operate and even greater potential at high altitude. This power could be harvested by airborne wind generators once products are ready for commercialization.

Virtually all existing wind energy resources are considered to be low altitude type in that they are located at or near ground level. High altitude wind, otherwise known as airborne wind energy (AWE), is a vast untapped renewable source of energy that has received increased attention from both industry and academia over the past decade. AWE generators, once fully embraced by the market, could potentially produce electricity at a lower levelized cost than fossil fuels, hence making wind power competitive with traditional coal and natural gas thermal power plants anywhere in the world without incentives.

A significant amount of research was conducted on AWE generator concepts in the early 1970s, resulting in several patents and publications. In general, AWE devices exploit the motion of wings flying fast in crosswind conditions (e.g., roughly perpendicular to the wind flow) and linked to the ground by flexible lines. The aerodynamic forces generated by the wings are then converted into electricity with tether lines and various kite configurations.

Over the past 10 years, various research groups and companies resumed development work on AWE concepts, including fabrication and testing of prototypes, in an effort to convert the energy of high altitude wind blowing up to 1,000 meters from the ground into electricity. This work led to the establishment of well-assessed common fundamental concepts and various

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potential design approaches regarding the type of wing deployed (rigid or flexible), the position of the generators (onboard or at ground level), and the number of tethers linking the wing to the ground. Despite recent development work, AWE energy generators are not yet commercially available, mostly due to key cost and technology hurdles.

The purpose of this project was to investigate the feasibility of using an automatic control system for an airborne wind energy generator with a flexible wing tethered to the ground with three lines. All actuators and ground-level generators (GLG) were installed on a ground unit (GU), and control of the wing was carried out by differentially pulling two of the three steering lines. This configuration provided the best potential for low cost, high safety, and versatility.

Unlike onboard generators, GLGs use tether lines which do not conduct current or transfer electricity generated from the kite to the ground and as such can be constructed using a light, high-tech material with 10 times the loading capacity compared to steel of the same weight. The aerodynamic efficiency of rigid wings is, in general, higher than flexible wings, and the control requirements are less complex thanks to the possible use of rigid onboard control surfaces. However the cost and safety issues of rigid wings are excessive for practical consideration. Flexible wings are much less expensive to build and easier to deploy. Also, in case of critical failure, they are much less likely to cause damage to ground structures since they have much lower weight distributed over a larger surface area. Power kites used in this project had ten to twenty square meters (m²) of area and weighed less than three kilograms (kg). In addition, flexible wings offer greater possibilities for future improvement, since their shape and size can be adapted to the wind conditions and different generator (traction and passive) phases, which can maximize the production of energy. Finally, use of a three-line tether inherently features a higher safety margin compared to reliance on a single line.

The research team discovered that an effective and practical control strategy for AWE systems using flexible wings had yet to be developed. Control algorithms for this type of configuration are challenging because the concept involves fast, nonlinear, unstable time-varying dynamics that are subjected to hard operational constraints and external disturbances. Airborne wind generators with flexible wings have different operating phases with corresponding control objectives. For instance, in the traction phase the wing flies along figure eight paths in crosswind conditions, which yields the highest traction forces on the lines, hence maximizing power/electricity production. Previous work produced several theoretical and numerical studies on control strategies for wings with one tether line and onboard actuator. Researchers have yet to publish a practical solution for controlling AWE systems using flexible wings and three lines, a key technical hurdle in preparing a market-ready product.

Control of a single line tether is achieved with actuators hung below the wing.\textsuperscript{53} Actuators on AWE systems using two or three tethered lines can be located on the ground unit (GU), which offers the advantage of reducing the weight of the wing. In the most common configuration, the lines are rolled around drums, installed on the GU, and connected to electric generators. See Figure 17, left. Energy is produced by continuously repeating a two-phase yoyo (or pumping generator) cycle. In the traction phase the wing is controlled to fly fast in crosswind conditions and the lines are unrolled under high pulling forces, thus rotating the drums and the generators to produce electricity. The passive phase begins when maximum line length has been reached, after which the wing is controlled along a path that minimizes pulling forces, while the lines are rolled back by spending about 10 percent of the energy generated in the previous traction phase. See Figure 17, right.

The Ground Unit Contains All the Mechanical and Electrical Components Needed to Control a Single Wing. Right. Sketch Demonstrating a Yoyo Cycle with Traction (Solid) and Passive (Dashed) Phases.

\textbf{Figure 17: Left. Sketch Depicting a Ground Level Generator with Two Lines.}

![Diagram](image)

The drawback of using flexible wings and actuators on the ground is that there is greater difficulty in designing a reliable automatic control system. Control of flexible wings is not possible with rigid onboard surfaces. Control action from a three-line tether is obtained by suitably changing the difference of length of the outer lines, named steering lines, which has a steering effect on the wing, and eventually by changing the length of the center line, which can be used to depower the wing. The research team attempted to develop and demonstrate the feasibility of an automatic control system that enables a three-lined flexible wing to fly consistently along figure eight paths in crosswind conditions, as required in the traction phase.

of the described generating cycle, hence advancing the research and development of airborne wind energy.

The conceptual scheme adopted for the prototype is shown in Figure 18. The prototype can be described according to three main elements: the wings; the control hardware, ground sensors, power electronics, and electric motors; and the mechanical frame and linear motion system.

**Figure 18: Conceptual Layout of the Prototype**

The use of flexible wings is an ideal compromise of low cost, aerodynamic efficiency, weight, and structural stiffness that allows the use of onboard sensors, thanks to the inflated leading edge and perpendicular struts. The researchers modified each kite tested to allow the installation and easy removal of an Inertial Measurement Unit (IMU) and a radio, together with a lithium-polymers battery. The battery could supply energy to the IMU and radio for at least eight continuous hours. The onboard sensors, radio, and battery were packed in an ad-hoc designed package, secured with Velcro straps, and attached to the kite. Figure 19 shows one of the power kite prototypes with on-board sensors attached to the main inflated wing strut.
Researchers used a real-time machine manufactured by SpeedGoat® and customized software to log measurements and send commands for reference currents to the drivers according to the actual and desired position of the prototype’s electric motors and to control the wing. The real-time machine interfaced with the sensors and radio located on the ground, which received the signals sent by the IMU placed on board the kite. Ground sensors included an anemometer and wind vane to measure wind speed and direction, three load cells to measure line forces, a Global Positioning System (GPS) used to acquire the position of the GU, an incremental encoder to measure the position of the motor, and a line angle measurement apparatus. The researchers accomplished line angle measurement by linking a rod to the wing’s center line and connecting it to two encoders, measuring its lateral and vertical inclinations with respect to the frame of the GU. Encoder signals were transmitted to the real-time machine for data acquisition and control of the wing.

Motor drivers used in this project, manufactured by Copley Controls®, were powered by a 115 volt alternating current (AC) electric supply and a 24 volt direct current (DC) logic supply. The motor drivers were used to modulate DC voltage, actuate two 0.44 horsepower (HP) electric motors that controlled the difference of length of the steering lines, and drive a 0.38 HP gear motor to control the length of the center line. The power kite was operated and controlled by an individual with the help of a laptop, Matlab® software, and a two-axis joystick. The system operator could issue start and stop commands from the joystick and press a button to either activate or deactivate the logic input to the drivers. The position of the joystick lever along the first axis corresponded to a desired difference of length of the steering lines that was used to
steer the kite during manual control. The second axis corresponded to a desired length of the center line. Power supply for all equipment was provided by a pack of sixteen, 12-volt direct current (DC) batteries with a total energy storage of 320 amp-hours linked to a 1.5 kilowatt (kW) inverter that converted 12 volt DC to 115 volt alternating current (AC). Figure 20 illustrates the real-time machine, inverter, batteries, joystick, and line angle sensor.

**Figure 20: Joystick, Real-Time Machine, Batteries and Inverter (left) and Line Angle Sensor (right)**

The ground system aluminum frame, built by Numatic Engineering®, met strength design criteria, was lighter than steel, and was corrosion resistant. The frame was shaped to offer a range of possibilities in the mounting of components like the motor, load cells, pulleys, and linear motion system. The latter was a lead screw actuator that converted the rotational motion of the motor into translational motion of a slide. The slide carried two pulleys that directed the kite’s two steering lines to suitable attachment points on the frame. Each attachment point had a load cell to measure the line force. Other pulleys were used in different parts of the frame to redirect the lines to the kite. The last pulleys before the kite, named exit pulleys, were able to swivel to follow the kite movement correctly.

Figure 21 shows a conceptual scheme of the linear motion system and pulleys. Figure 22 shows a rendering of the frame including a second motor to change the length of the kite’s center line. Figure 23 is a photo of the actual frame constructed, the linear motion system, and all electrical and mechanical parts, which were conveniently installed on a four foot by eight foot trailer for easy transport to the test zone.
Figure 21: Conceptual Scheme of the Prototype’s Linear Motion System and Pulleys

- Moving slide
- Linear actuation system
- Load cell
- Electric motor
- To kite
- "Exit" pulleys
- Kite line
- Fixed pulley

Figure 22: 3D Rendering of the Designed Prototype

- Actuator for power/depower line
- Linear motion system for steering lines
- Supports for load cells to measure forces on steering lines
- Swaying pulleys to the kite
- Moving plate with pulleys to measure force on power/depower
The research team selected a beach location in Oxnard, California, to test kite performance after evaluating several candidate locations (see Figure 24). A line length of 30 meters was chosen for test purposes. The use of a fixed line length was not a limitation, since the problem of crosswind path control could be decoupled from the problem of controlling reeling of the lines. The researchers achieved optimal operation of the ground-based airborne wind energy generator with a constant line speed approximately equal to one-third of the wind speed.\textsuperscript{54} The use of such short lines made the control problem especially challenging since the flying paths needed to be contained in a small area to avoid contact with the ground and/or an aerodynamic stall occurring at the border of the wind window (e.g., quarter-sphere defined by the intersection of the span of the lines, the ground, and a plane perpendicular to the wind flow).

The red semi-circle has a 30 meter radius, representing the area where the wings usually flew. The arrows represent typical directions of the wind flow (W).

The researchers conducted several manual tests with the constructed prototype, trying various take-off maneuvers, starting either downwind in crosswind conditions or in a lateral position with respect to the wind flow. The researchers also experimented with different ways of carrying out figure eight paths such as up-loops, where the wing gains altitude on the sides of the figure eight and moves towards the ground in the middle, or with down-loops, where the wind gains height in the middle of the figure eight and approaches the ground on the sides. The team determined that the use of up-loops for figure eight paths was the best type of crosswind trajectory due to the apparent need for less complex controls, in contrast with down-loops which required much larger control inputs. The adopted control scheme is shown in Figure 25.
The researchers successfully developed and demonstrated the feasibility of using an automatic control system to operate airborne wind energy systems with flexible wings, ground-based generators, and three lines. All project objectives were either met or exceeded. Measured forces on the lines show a very good congruity with the theoretical equations, hence giving confidence in the validity of modeling projections for power and energy that can be achieved with airborne wind energy. According to such models, a large-scale, 2.0 MW rated power airborne wind energy system, based on the concept considered in this project, would have a power curve similar to an industry standard 2.0 MW wind turbine. Further development of the concept using industrial sensors, actuators, and wings could improve the performance and reliability of the system.

The next logical step is to build a larger 20 kW model aimed at demonstrating full operation of the concept including complete generation cycles and automatic takeoff and landing. This work would require a budget of approximately $1.0 million and two years for completion. Such a project would use off-the-shelf components and could be developed completely in the context of public research. The length of the kite lines is expected to be in the range 30 to 200 meters, using a kite with 12 to 20 square meter (m²) wings. If successful, kite performance (in terms of power curve) would match the results of previous numerical studies, providing confidence to move forward with final product design and scale-up.

The final development phase would be the construction and testing of a system that could deliver approximately 2.5 MW of mechanical power during the traction phase, all within the range of current wind turbine products. Significant improvement (up to 50 percent) in wing efficiency could be expected using larger, industrial equipment. Actual generated electricity depends on the installed power electronics and on the efficiency of the generating cycle. The research team envisioned global commercialization of products in the range of 2.0 to 5.0 MW rated power for both inland and offshore applications. The concept could also benefit from ongoing research in fields like aerodynamics, materials, sensors, actuators, power electronics, and storage with features tailored for airborne wind energy systems.

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Conventional wind turbines can achieve a capacity factor of up to 35 percent in certain locations. An airborne wind energy system taking advantage of stronger high altitude winds can achieve up to 70 percent capacity factor, essentially halving the cost of energy, assuming the same construction and installation costs. Airborne wind energy generators can also be arranged in wind farms with 22 MW rated power per square kilometer of occupied land, more than twice the density of actual wind farms, due to exploitation of the greater flexibility of tethered wings. Overall, these two effects (stronger high altitude winds and higher power density) could lower the cost of producing electricity from wind energy farms to 50—80 percent of the cost of electricity generated by existing coal and natural gas power plants. The potential of generating electricity from airborne wind is quite attractive, with no greenhouse gas emissions. Product commercialization could be achieved in four to ten years depending on funding availability to complete development work, the success in solving technical challenges not yet identified, and investors willing to drive the technology to market.

2.12.3 Objectives
The goal of this project was to investigate the feasibility of using an automatic control system for an airborne wind energy generator with a flexible wing tethered to the ground with three lines. The researchers established the following project objectives:

1. Design and build a mechanical system able to support at least 400 pounds of total load on the lines.
2. Demonstrate the ability to actuate at least one meter of difference in the length of the steering lines, with less than one centimeter (cm) error.
3. Provide energy to all the electric and electronic components for at least six hours.
4. Stabilize and control the wing for at least 10 consecutive minutes with different wind conditions, using a human operator.
5. Acquire at least one hour of required data with varying wind conditions and wing sizes.
6. Achieve at least four hours of continuous automatic wing control, making the wing follow figure eight paths.

2.12.4 Outcomes
1. The prototype was able to sustain peak forces of about 670 pounds, well above the target of 400 pounds.
2. The mechanical system exceeded the target of actuating up to 1.2 meters of difference in the length of the steering lines, with only a few millimeters of error.
3. The prototype supplied energy to all electric and electronic equipment for more than six hours.
4. Extensive experimental testing enabled manual control of the wing for more than 30 consecutive minutes.
5. Nine days of testing with manual control of the wing enabled acquisition of more than five hours of data.

6. The research team successfully executed a test using automatic controls of more than four hours of autonomous flight. The wing safely landed on the ground upon completion of the test.

2.12.5 Conclusions

1. The prototype easily exceeded the targeted design force generated by a twelve square meter kite with about five meters per second wind speed.

2. The designed inner control loop met required specifications.

3. The installed battery capacity within the prototype was more than adequate to meet the energy needs of electric and electronic equipment.

4. Manual control of the wing enabled more than 30 consecutive minutes in each test, exceeding the target by a factor of three.

5. The research team collected five times more aggregate data than targeted, enabling it to derive control-oriented models and design the automatic control algorithm.

6. Due to initial success with testing, the researchers conducted additional tests, for a total of eight testing days and about 20 hours of autonomous flight, about five times greater than target.

Researchers successfully developed and demonstrated the feasibility of using an automatic control system to operate airborne wind energy systems with flexible wings, ground-based generators, and three tether lines. A wind range of two to six meters per second experienced during the test flights, using various wing sizes, demonstrated sufficient robustness of the designed control approach.

The force exerted by each steering line on the actuator in the current design of the real-time machine was equal to twice the force on the line, causing minor discrepancies in tracking performance. The research team was confident that the position controller could be further tuned to achieve better tracking performance. Measured line forces reflected very good congruity with theoretical equations, providing greater confidence in projections of power and energy from airborne wind energy systems. According to such models, a large-scale 2.0 MW power airborne wind energy system based on the concept considered in this project could have a power curve similar to current wind turbine products in this size class. Further development of the concept using industrial sensors, actuators, and wings could improve the performance and reliability of the system.
2.12.6 Recommendations
The Program Administrator recommends the following steps:

1. Build a larger 20 kW model to demonstrate full operation of the concept, including complete generation cycles and automatic takeoff and landing.
2. Construct and test a scaled-up system that can deliver approximately 2.5 MW of mechanical power during the traction phase.
3. Demonstrate AWE systems using flexible wings in a wind farm configuration.

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

California is on track to meet its goal of increasing procurement from eligible renewable energy resources to 33 percent of total electricity by 2020, and policymakers are now beginning to discuss adoption of a 50 percent goal by 2030. Wind energy has been a key element in the State’s successful adoption of renewable energy. The technical potential of wind power itself can supply global energy needs several times over. California already has excellent wind power potential at an altitude where current wind turbines operate and even greater potential at high altitude. This could be harvested by airborne wind generators once products are ready for commercialization.

Conventional wind turbines can achieve a capacity factor of up to 35 percent in certain locations. An airborne wind energy system, taking advantage of stronger high altitude winds,
can achieve up to 70 percent capacity factor which equates to half the cost conventional wind turbines, assuming similar construction and installation costs. Airborne wind energy generators can also be arranged in wind farms with 22 MW rated power per km² of occupied land, which is more than twice the density of the conventional wind farms due to the greater flexibility of tethered wings.

Overall, stronger high altitude winds and higher power density could help lower the cost of producing electricity from wind energy by up to 80 percent of the cost of electricity generated by existing coal and natural gas power plants. The research team projected the levelized cost of airborne wind energy to be approximately $20 per megawatt-hour ($/MWh), compared to costs of $34—$47/MWh for fossil-fueled power plants. Once fully developed, airborne wind energy systems have the potential to generate wind energy potentially anywhere in the world in large quantities, at potentially lower costs than fossil fuels, and without the need for incentives.

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

The researchers did not report contact with any potential customers. They did claim to have performed a preliminary market analysis. They recognize the potential problem with lack of regulation for this type of wind generator. At the conclusion of this project they had not realized a partnership with a company that would help take this concept to commercialization.

Engineering/Technical

The researchers stated that they could produce a small-scale demonstrator in about two years with an investment of $1.0 M to $1.5 M. They believe a large-scale demonstrator could be developed and built in three to five years.

Legal/Contractual

The research team performed a patent search and discovered that the main concepts of airborne wind energy systems are now considered public domain since most of the patent work occurred in the late 1970s. Individual companies who pursue incremental investment in the technology will likely file for patent protection or develop trade secrets along the path towards commercialization.

Environmental, Safety, Risk Assessments/Quality Plans

New codes, standards, and regulations are anticipated as this emerging breed of wind energy generators moves closer to market.
The concept is not yet sufficiently developed for commercialization. To bring this device to market, the researchers stated that they will need to partner with a large company working in electricity generation.

### 2.13 Development and Testing of a New Solar Irradiance Forecast Methodology

**Awardee:** Aerisun LLC  
**Principal Investigator:** Vincent E. Larson

#### 2.13.1 Abstract

This research demonstrated an improvement in forecasts of day ahead irradiance by combining outputs from two currently available models: the North American Mesoscale (NAM) and Global Forecast System (GFS) models. Using model data for the Atmospheric Radiation Measurement (ARM) site in the Southern Great Plains (SGP) and seven SURFace RADiation (SURFRAD) sites, researchers post-processed several weeks of outputs from the two models using proprietary techniques to yield a combined accuracy improvement of 14—16 percent over either single model. The insights gained, including greater understanding of relationships between irradiance forecasts and cloud related fields, suggest a path to further improvements in accuracy using these techniques.

**Keywords:** Solar irradiance, solar power forecasts, Atmospheric Radiation Measurement (ARM), SURFace RADiation (SURFRAD), numerical weather prediction, Independent System Operator, electric dispatch models

#### 2.13.2 Introduction

The increasing amounts of solar generated power serving California represent an important, but variable, source of clean energy. Dealing with differences between expected and actual output from solar plants creates operational risks and can increase cost as backup non-solar or storage units are required to balance loads and resources. While there are rich sources of meteorological data and several available day ahead forecasting models, the resulting day ahead forecasts of solar potential represent a source of considerable uncertainty in developing unit commitment plans to meet California’s anticipated needs.

More accurate forecasts of day ahead solar potential are required to help plant and system operators maximize solar production and minimize required reliability expenditures. This would yield reduced environmental impacts, reduce costs, and encourage solar plant expansion.

The researchers in this project utilized an ensemble approach to improve day ahead irradiance forecasts. They showed that outputs from two well-known models yielded better accuracy when combined in a simple average. Furthermore, significant further improvements are possible from proprietary post-processing of initial model outputs.
2.13.3 Objectives
The goal of this project was to determine the feasibility of improving integration of solar power in the electric grid through improved forecasting of solar output potential using a new multi-model ensemble solar forecast system to reduce root mean square (rms) errors of day ahead ground level solar irradiance by 10 percent.

The researchers established the following project objectives:

1. Confirm that errors of at least 10 percent exist in irradiances and cloud profiles hindcasted by the North American Mesoscale (NAM) and Global Forecast System (GFS) models at the Atmospheric Radiation Measurement (ARM) site in the Southern Great Plains (SGP).

2. Create a multi-model ensemble forecast system\(^\text{56}\) based on NAM and GFS NWP forecasts.

3. Demonstrate that rms errors in surface irradiance by ensemble forecasts are 10 percent smaller than those in either NAM or GFS forecasts alone at ARM-SGP.

4. Demonstrate that rms errors in surface irradiance by ensemble forecasts are 10 percent smaller than those in either NAM or GFS alone at SURFRAD sites.

2.13.4 Outcomes

1. Hindcasted global irradiance errors for the ARM-SGP site were very large for both models. The NAM and GFS models averaged 45.1 percent and 42.0 percent errors, respectively. Both models also showed poor ability to characterize cloud formation, averaging more than 400 percent error in liquid water path (LWP)\(^\text{57}\) forecasts.

2. The researchers determined that averaging of outputs from the two models had the potential to improve overall accuracy. They further determined that proprietary detailed statistical post-processing of model outputs using insights gained from study of comprehensive related site data could further improve results.

3. The researchers’ forecast methodology improved results by 14 percent over the better of NAM or GPS at ARM-SGP.

4. Similar comparisons for the seven SURFRAD sites studied showed an average improvement of 16 percent.

\(^\text{56}\) Results from both NAM and GFS NWP models to be used as inputs

\(^\text{57}\) A measure related to presence of liquid cloud cover and irradiance
2.13.5 Conclusions

The researchers met their goals, confirming that a simple averaging of two models’ outputs over a somewhat short study period\(^{58}\) provided some improvement in accuracy and that additional post-processing of individual results could yield further improvements when combined for further analysis. However these conclusions are necessarily tentative pending further development and testing using data from a much longer time period.

1. The large percentage errors found suggest that while even imperfect forecasts can be useful, far better day ahead irradiance forecasts are needed to facilitate full integration of solar energy into the grid.

2. The researchers confirmed that even simple averaging of two models’ outputs could improve results for some sites. This improvement appeared to be more pronounced at the ARM-SGP site than the SURFRAD sites. The most important learning at this stage was identification of likely influences on accuracy that could be addressed in post-processing.

3. Model results exceeded the goal of a 10 percent improvement in forecast results. Inclusion of post-processing in the researchers’ forecast methodology represents the most significant innovation in this project. Using data from the ARM-SGP site in Oklahoma as the foundation for analysis and model development, followed by validation at seven SURFRAD sites, was an appropriate use of available information. There are no comparable sites in California, leaving results from the Desert Rock, Nevada, SURFRAD site as the nearest proxy. It appears likely that benefits found for the tested ARM-SGP and SURFRAD sites would generalize to California locations.

4. Similar comparisons for the seven SURFRAD sites studied showed an average improvement of 16 percent, again exceeding the 10 percent improvement goal.

2.13.6 Recommendations

This early work suggests an approach to further improvement in day ahead irradiance forecasting. The most significant logical next step is to apply this work to a time series taken over a much longer time period. This would likely provide additional insights for model refinements and the ability to test statistical significance of conclusions.

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.

\(^{58}\) Researchers used data selected from an eight week period in 2012.
2.13.7 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 could be reduced environmental impacts of the California electricity supply. Assuming subsequent development and testing over longer periods confirm the improvements seen in this research, its use to provide better day ahead forecasts could improve dispatch of existing solar generation, thereby decreasing reliance on fossil fuels. Since the economics of building solar plants depends on their expected utilization, it is also possible that the prospect for improved dispatch would help stimulate new solar plant construction.

2.13.8 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
This product would address a specialized, but important, market consisting primarily of electric system operators (such as the California Independent System Operator), electric utilities, and other power generation owner/operators.

Engineering/Technical
The researchers envision further improvements in accuracy with continued development, including longer time series forecasts and statistical validation. They estimate additional funding required would be roughly $300,000 over three years.

Legal/Contractual
No patents are presently contemplated.

Environmental, Safety, Risk Assessments/ Quality Plans
Further testing over longer forecast time periods as described by the researchers and in the recommendations section above is the most important next step.
Aerisun presently provides NAM and GFS forecasts, as well as an ensemble of the two, on its web site. This positions it well to offer an enhanced commercial-scale product based on further research.

2.14 Converting Waste Carbon Dioxide to Methane and Energy

Awardee: AOS Solar Inc
Principal Investigator: Anikara Rangappan

2.14.1 Abstract
The researchers in this project reported on a technique for low temperature conversion of carbon dioxide into methane. Inputs to the reaction were pure water and carbon dioxide from sources such as power plant effluent. The technique used a new proprietary bimetallic catalyst on a single carrier which allowed the reaction to take place at the low temperature of 250° C. The energy input to drive the reaction was the relatively low temperature waste heat from the exhaust stream. In the bimetallic catalyst, one metal oxide had an affinity for carbon and a second had an affinity for oxygen. The second catalyst split water molecules, liberating free hydrogen that reacted with free carbon to form methane, as in the well-known Sabatier reaction. Water splitting was enhanced by external excitation of water molecules with 100 W of 13.6 MHz RF power. It appeared, however, that hydrogen ions were created in the water splitting reaction. These ions recombined with oxygen, thus limiting the amount of free hydrogen available for methane production. Accordingly, the researchers added a third metal oxide on its own carrier to regulate hydrogen ion concentration. The resultant tri-metallic catalyst mixture delivered superior results. The best CO₂ conversion efficiency was 39.1 percent at 2 psi and 250° C. However, the researchers observed this conversion rate to be stable only over 30 minute intervals before the process went into oscillation. Investigation showed that the methane formation rate oscillated between 16.0 percent and 39.1 percent. In some cases the methane burned inside the reactor, and the output was considerably reduced. Further research on process control is needed.

Keywords: CO₂ reformation, methane production, metal oxide catalysts, waste heat, low temperature

2.14.2 Introduction
California Assembly Bill AB 32 mandates that by 2020 the total of the State’s greenhouse gas (GHG) from all sources be no greater than its total in 1990.59 A comprehensive list by the California Air Resources Board gives a total gross GHG production of 448.11 million metric tonnes of CO₂ equivalent (MMTe) in 2011.60 Of particular note is that natural gas (NG)

59 http://www.arb.ca.gov/cc/ab32/ab32.htm
60 http://www.arb.ca.gov/cc/inventory/data/tables/ghg_inventory_scopingplan_00-11_2013-08-01.pdf
combustion provided 53.4 percent of California’s in-state electricity generation in 2010.\textsuperscript{61} The main GHG effluent from NG combustion is CO\textsubscript{2}. Converting CO\textsubscript{2} back to methane (CH\textsubscript{4}), the main component of NG, has attracted attention for decades, in particular by the use of Sabatier’s reaction:\textsuperscript{62}

\[ \text{CO}_2 + 4 \text{H}_2 \leftrightarrow \text{CH}_4 + 2 \text{H}_2\text{O} \]

One can describe this reaction as the hydrogenation of carbon dioxide to methane and water. The problem with this approach has been that producing and transporting the hydrogen off-site produces more atmospheric carbon than is saved by the reaction. This has led to the search for methods of on-site production of hydrogen without requiring combustion of additional carbon.\textsuperscript{63} Candidate methods for the production of this hydrogen include electrolysis of water, photochemical splitting of water using solar energy, and thermochemical water splitting using heat from power plant exhaust and a catalyst to speed up the reaction. The last method, thermochemical water splitting with a catalyst, is particularly attractive because it requires a minimum of additional hardware and uses only heat energy already present in the exhaust. The problem, however, is the identification of a suitable catalyst to speed up the reaction and make it practical.

If such a catalyst could be identified, the payoff to the California ratepayer in terms of lower fuel costs and avoided cost for GHG remediation could be substantial. In particular, the conversion of carbon dioxide from the exhaust stream into methane, which could then be reused for fuel, would partially displace the cost of purchased natural gas fuel. Similarly, converting exhaust carbon dioxide into new fuel would lower net emissions. In 2011, emissions from California in-state electricity generation produced 39.71 MMTe of CO\textsubscript{2} of which NG contributed 34.53 MMTe. Since NG electrical generation sources are point sources and they are a significant fraction of total GHG emissions (7.7 percent), they are an attractive category for California GHG reduction measures. Thus the production of on-site hydrogen is a candidate for reduced power plant fuel cost and lower GHG generation.

The advancement of science or technology that was proposed in this project was to scale up the researchers’ earlier work on a single stage bi-catalyst that directly converts CO\textsubscript{2} to methane and oxygen in the presence of water. The researchers had produced the catalyst in 100 gram quantities. In this project they proposed to scale up the production of the catalyst to kilogram quantities and to build a correspondingly larger CO\textsubscript{2} to methane reactor. The multi-step bi-catalysis reaction can be simplified and stated as

\[ \text{CO}_2 + 2\text{H}_2\text{O} \leftrightarrow \text{CH}_4 + 2\text{O}_2 \]

\textsuperscript{61} http://energyalmanac.ca.gov/overview/energy_sources.html

\textsuperscript{62} For example see http://www.enea.it/it/produzione-scientifica/EAI/anno-2011/n.-6-2011-novembre-dicembre-2011/alternative-use-of-co2

\textsuperscript{63} http://www.pennenergy.com/articles/pennenergy/2010/03/the-sabatier-reaction.html
The equation shows the water molecule and CO₂ being split to form methane and oxygen, as shown schematically in Figure 26. In the reactor, gas flows from one side to the other, and methane is continuously formed as long as there are carbon dioxide and water vapor present and the system is kept between 150° C and 250° C. These are the reaction ingredients typical of the waste heat and pressure of power plant flue gases. A goal of the project was to achieve a carbon dioxide to methane single pass conversion efficiency of 40 percent and eventually 70 percent single pass conversion efficiency. This emissions control technique would take part of the carbon-rich flue gas before it entered the power plant stack. The regenerated methane and oxygen byproducts would be siphoned off and re-injected into the plant’s burners or used for additional combined cycle output. In either case, the plant’s overall efficiency would increase since less feedstock would be required for a given power output or power output was increased for a fixed fuel input.

This process can be described as a bottoming cycle. Heat recovery steam generators and combined cooling heating and power (CCHP) are other ways to extract and use energy remaining in the exhaust gases of a combustion engine.

![Two Stage Methane Reformer Process with Bi-Metallic Catalyst in Reactor](image)

**Figure 26: Two Stage Methane Reformer Process with Bi-Metallic Catalyst in Reactor**

### 2.14.3 Objectives

The goal of this project was to determine the feasibility of using a bi-catalytic encapsulated membrane to reduce emitted carbon compounds from stationary sources below statutory levels and convert them into reusable gaseous methane and oxygen. The researchers established the following project objectives:

1. Scale up bi-catalyst production volume. Increase batch size from 100 grams to 1 kilogram.

2. Build a prototype next generation reactor. Develop a fully encapsulated reactor that can handle 10 standard liters per minute (SLPM) of CO₂ production.

3. Design and fabricate a larger next generation reactor chamber. Enclose a bi-catalytic membrane having a surface area of 100,000 cm².
4. Calibrate the reactor and data capture technique. Monitor input gas flows and calibrate reaction byproducts for accurate volume. Measure flow rate accurate to +/- 1.0 percent.

5. Determine the optimal flow rates and volume of the reaction chamber under continuous reactor operation. Optimize the ratio between catalyst surface area and CO₂/water vapor flow rate (currently at 5 SLPH to 10 SLPM) for prototype and production-sized operations.

6. Increase the catalytic membrane’s useful life before regeneration is required. Increase the 80 percent useful life before regeneration from the current 148 hours to 168 hours (one week).

7. Build full gas analysis capability into the system to determine conversion percentage. Perform analytical study of catalyst and report on reaction kinetics.

8. Perform a life cycle cost analysis. Confirm the preliminary findings that the installed cost would be $4400 per MW and up to $4.50 per MWh.

2.14.4 Outcomes

1. The researchers increased the batch preparation of the initial bimetallic catalyst to 1.0 kilogram. One oxygen scavenging and one carbon scavenging metallic oxide catalyst were manually combined and vapor deposited in a 1.0 micron thick layer over a porous alumina substrate. The researchers added a separate third catalyst compound on its own substrate.

2. The researchers developed a fully encapsulated reactor that could handle 10 standard liters per minute (SLPM) of CO₂ production.

3. The prototype reactor vessel used 500 grams of the catalytic compound on an aluminum oxide carrier having a catalytic surface area of approximately 15,000,000 cm², much greater than the objective of 100,000 cm². The relationship between the carrier and the proposed membrane was not clear. In fact, the researchers gave no description of an actual membrane.

4. The researchers calibrated the reactor and data capture technique and monitored input gas flows and reaction byproducts to an accuracy of +/- 1.0 percent.

5. The researchers measured methane conversion rate of 39.1 percent per pass at 2 psi and 250° C. However the conversion rate was stable for only 30 minute intervals. They found methane output was enhanced by increasing hydrogen density at the catalytic surface and by RF energizing the incoming water vapor. Significantly, a hydrogen ion-scavenging third catalyst improved methane output.

6. Determination of the useful life of the catalytic compound was only partially accomplished since the prototypes’ steady state conversion rate did not remain constant for more than 30 minutes. In part, the researchers thought this was due to the RF
matching network conditions not being stable. However this was not conclusively demonstrated.

7. The researchers conducted an experimental study of the reaction kinetics. They found that the bimetallic catalyst alone could not produce sufficient methane due to low hydrogen density at the catalytic surface. They added a third catalyst to the bimetallic composite, which improved the reaction kinetics.

8. The researchers performed a life cycle cost analysis showing a coal power plant owner would bear a capital cost of between $4,400 and $6,900 per MW. They would incur a levelized cost of ownership between $0.005 per MWh savings and $0.120 per MWh cost, depending on flue gas CO₂ concentration and conversion efficiency.

2.14.5 Conclusions

1. The researchers successfully scaled up bi-catalyst production volume to one kilogram. They met this objective.

2. The researchers successfully developed a scaled-up prototype reactor that could handle 10 standard liters per minute (SLPM) of CO₂ production, meeting this objective.

3. The researchers developed a 12 inch prototype reactor vessel that utilized 500 grams of the catalytic compound. Due to the porous nature of the alumina substrate, the catalytic surface area was approximately 15,000,000 cm², greater that the objective of 100,000 cm². Thus they met this goal.

4. The researchers successfully calibrated and measured reactor flow rates to an accuracy of +/- 1.0 percent. They met this objective.

5. The researchers concluded that preventing liquid water formation and methane combustion at the catalytic surface requires additional engineering to regulate oxygen density. They also concluded that reaching an eventual commercial goal of a 70 percent conversion rate per pass requires greater control over the catalytic process. They partially met this objective.

6. It was not possible to determine the useful life of the catalytic compound because the prototypes steady state conversion rate did not remain constant for more than 30 minutes. Therefore the researchers did not meet this objective.

7. The researchers built full gas analysis capability into the system to determine conversion percentage, conducted an analytical study of catalysts, and reported reaction kinetics. They carried out this objective.

8. The researchers carried out a life cycle cost analysis. The preliminary findings indicated that the installed cost was in the range of $4,400 to $6,900 per MW, but cost per MWh was only loosely determined.
The researchers made incomplete progress in determining the feasibility of using a bi-catalytic encapsulated membrane to convert emitted carbon compounds from stationary sources into reusable gaseous methane and oxygen. They made encouraging progress, however, in \textit{in situ} production of hydrogen in the prototype reactor.

2.14.6 Recommendations

The Program Administrator recommends that the researchers:

- Clarify the relationship of the work carried out in this project to the proposed membrane approach.
- Investigate the effects of diluent concentrations to suppress conversion rate oscillations and to control the burning of methane in the reactor.
- Form a partnership(s) with natural gas fueled engine manufacturers. Those manufacturers could give guidance on how to incorporate the proposed device into natural gas fueled engines.
- Determine the maximum conversion possible with the energy available in the exhaust gases.
- Conduct a technical and economic evaluation of competitive bottoming cycles. Engine manufacturers could provide valuable information in this area.

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.

2.14.7 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. If a long-lived and stable catalyst could be identified, the payoff to the California ratepayer could be substantial in terms
of lower fuel costs and avoided cost for GHG remediation. The conversion of carbon dioxide from a power plant exhaust stream into methane, which could then be re-used for fuel, would partially displace the cost of purchased natural gas fuel. Similarly, converting exhaust carbon dioxide into fuel would lower net emissions. In 2011, emissions from California in-state electricity generation produced 39.71 MMTe CO₂ of which natural gas (NG) contributed 34.53 MMTe. Since NG electrical generation sources are point sources and are a significant fraction of total GHG emissions, they are an attractive category for reduction and amenable to this approach.

These benefits must be compared with the benefits of using conventional bottoming cycles for large natural gas fueled engines. Most, if not all, engines of this type are equipped with bottoming cycles. These cycles provide the same benefits as the proposed technology. Thus the new technology must show benefits in excess of those provided by installed bottoming cycles. In addition, this new cycle cannot be added to an engine already equipped with a bottoming cycle, since most bottoming cycles reduce the exhaust temperature to near or below the 150°C minimum temperature required for the proposed cycle. The proposed cycle may be useful on medium-size combustion engines where traditional bottoming cycles may not be economical.

2.14.8 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

While the researchers have not conducted a market study, they have talked to two utilities. Both Detroit Edison and Duke Energy have indicated interest in this concept.

Engineering/Technical

The researchers suggested that a prototype system could be completed in two years with funding of about one million dollars.

Legal/Contractual

The researchers have conducted a self-directed patent search. They had not applied for any patents at the end of this project.

Environmental, Safety, Risk Assessments/ Quality Plans

At the present stage of the research, development of these plans appears to be premature. However the researchers should be paying close attention to safety and risk areas. Their device/process could handle large quantities of reactive methane, hydrogen, and oxygen gases.

Production Readiness/Commercialization

The researchers have completed a commercialization plan. At the completion of the project they did not yet have a comprehensive business plan.
2.15 G Development of Energy Efficient Dehulling and Drying Methods for Walnuts

Awardee: Regents of the University of California Davis
Principal Investigator: Griffiths G. Atungulu and Zhongli Pan

2.15.1G Abstract
Researchers in this project evaluated the feasibility of using dry hull removal, near infrared (NIR) spectroscopic sorting, and infrared (IR) pre-drying of walnuts to reduce energy use and improve processing efficiency and product quality. The researchers found that walnuts with and without hulls can be separated based on axial dimensions which could facilitate easy classification for in-field hull removal. They observed that walnuts with whole and partially attached hulls could have hulls removed using an existing dehuller that was not optimal to achieve over 90 percent clean nuts in less than a minute. The project results further indicated that IR pre-drying of walnuts before low temperature air drying can improve overall drying efficiency. During IR pre-drying of high moisture nuts, the nut center temperature remained considerably below 43° C in the first 150 seconds, which drove out significant amounts of moisture while not affecting nut quality. The researchers found no significant difference in the quality of walnuts after both high and low moisture walnuts were processed by conventional and sequential IR pre-drying for 180 seconds followed by conventional drying methods. The new approach shows promise to improve processing efficiency, but significant development work remains.

Keywords: Walnuts, dry dehulling, infrared pre-drying, near infrared spectroscopy, energy efficiency

2.15.2G Introduction
California’s food processing industry generates over $50 billion in gross annual revenues and is the third largest industrial energy user in the State. The California walnut sector represents one of the large energy consumers in the industry, with the walnut drying process the most energy intensive step. The industry consists of 5,300 walnut growers and 55 walnut processors, and it produces nearly 400 thousand tons of walnuts. Reducing energy use and improving processing efficiency have been identified as research priorities by the California walnut industry.

During harvest, walnuts with and without hulls are collected with harvesters and then transported in bulk to a facility for hull removal and drying. In conventional walnut processing, after hull removal the walnuts are placed into a batch air dryer for drying using natural gas or propane at about 43° C (110° F) air temperature. The drying time can be up to 24 hours for the wettest nuts to achieve the safe storage moisture of ~8 percent. Even though the processors have attempted different approaches to reduce energy consumption, the average energy consumption for walnut drying is still high, with 12.16 therms of natural gas or propane and 23.6 kWh of electricity per ton of walnuts.64 This amounts to annual consumption of nearly 5  

million therms and over 9.5 million kWh. Because walnuts treated in this fashion include wetter and dryer walnuts, processing involves over-drying the initially dryer walnuts to ensure that the wetter walnuts are sufficiently dry. This over-drying results in a significant waste in energy and prolonged drying time. Walnut sorting based on moisture content could reduce gas and electricity use by minimizing the over-drying of walnuts. Removing the hulls in the orchard would further reduce energy consumption used in transporting walnuts to the processor.

In this project, researchers developed and evaluated new walnut treatment approaches aimed at improving energy use by the walnut industry and growers. The new approaches involved in-field dry hull removal, viability of near infrared (NIR) spectroscopic sorting of walnuts based on moisture content, and sequential infrared pre-drying and low temperature air drying. The research could ultimately reduce energy use and production cost. Figure 27 illustrates the dry de-huller used in tests, one component of the multiple step process. Other steps in the process include infrared sorting and pre-drying.

**Figure 27: A Batch-Type Conventional Vegetable Dehuller/Peeler for Testing Feasibility of Dry Hull Removal of Walnuts**

2.15.3G Objectives

The goal of this project was to determine the feasibility of dry hull removal of walnuts and new drying methods to reduce energy use and improve processing efficiency, as well as product quality. The researchers established the following objectives:

1. Determine the physical characteristics of walnuts with and without hulls for in-field sorting. This was to demonstrate that differences in size (length, intermediate and minor diameters) of nuts with and without hulls can be used for in-field sorting and for in-field dehulling to avoid energy and cost associated with transporting walnuts with hulls.

2. Develop dry dehulling technology for in-field dehulling to demonstrate that dry dehulling can be achieved with acceptable dehulling capacity, time, and cleanness of hull removal.
3. Develop a new near infrared (NIR) spectroscopic sorting method based on moisture content (MC) of individual walnuts. This was to demonstrate that the correlation between walnut shell MC and near infrared (NIR) spectral characteristics (absorbance) can be used to predict the MC of whole nuts for sorting to achieve optimized drying performance and energy saving.

4. Study the drying efficiency and product quality with use of infrared heating (IR) for partial drying. This was to demonstrate that IR heating can be used for initial and partial drying of walnuts to result in reduced drying time while maintaining shelf life in terms of color and peroxide value.

5. Estimate the total energy saving and benefits of the new processing methods. This was to demonstrate the potential total saving of a significant amount of dollars for the California walnut industry each year as result of the new sorting, drying, and in-field dry dehulling methods.

2.15.4G Outcomes

1. The researchers selected freshly harvested walnut samples of the Chandler variety. They included walnuts treated with Ethephon with and without hulls. The walnut samples with hulls were further categorized into two groups as whole and partially attached (>50 percent cover). The researchers measured the dimensions of selected nuts with and without hull. The results showed that there was a wide range of the size distributions for nuts with and without hull, but had slight overlaps in size distribution. The researchers were able to classify walnuts with and without hulls based on three axis dimensions. The researchers achieved this objective.

2. Using a vegetable de-huller, the researchers measured the time required to remove hulls and the percentage of walnuts completely dehulled (0 percent hull cover), partially dehulled (>0 percent but < 50 percent and >50 percent but <100 percent hull cover). The researchers showed that greater than 90 percent of walnuts had hulls removed in less than sixty seconds for both treated and untreated walnuts. The researchers achieved this objective.

3. The researchers demonstrated that using NIR spectroscopy and multivariate partial least square regression (PLS-R) techniques could predict the moisture content of walnut shell with R² of 0.9783 and could be used to sort walnuts based on moisture content. The researchers achieved this objective.

4. The researchers evaluated the impact of IR pre-drying using selected walnuts with different initial MCs. The researchers placed the walnuts in a single layer between two catalytic IR emitters which were spaced 25 cm apart and at surface temperatures of 326°

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65 Ethephon is the common name of 2-Chloroethylphosphonic acid, widely used in agriculture to promote pre-harvest ripening in a wide variety of crops.
C. The walnuts were then heated for 120, 180, and 240 seconds followed by hot air
drying at 43° C for up to 24 hrs. The researchers measured the drying characteristics,
product quality, and shelf life of the IR pre-dried in shell walnuts. The researchers
achieved this objective.

5. The researchers estimated the new method could achieve at least a 40 percent energy
saving by reducing over-drying, resulting in potential saving to the nut processors using
both natural gas (50 percent) and propane (50 percent) of $2.9 million per year. In
addition, they estimated savings in electricity from shorter drying time, assuming a 20
percent electricity savings will have an economic value of $283,000. They did not
estimate the cost of the equipment or the cost/benefit of the new approach. The
researchers partially met this objective.

2.15.5G Conclusions

1. Walnuts with hulls have sufficiently different size than walnuts without hulls, and this
can be used to sort walnuts with respect to hull attachment.

2. Equipment basically similar to vegetable de-hullers can be used to quickly remove hulls
from walnuts while maintaining walnut quality.

3. NIR spectroscopy can adequately determine the moisture content of individual walnuts
and can be used to separate wetter walnuts from dryer walnuts.

4. Infrared pre-drying of walnuts can speed the drying process. The energy use of pre-
drying should be less than the longer dry times of conventional drying methods.

5. The potential energy savings from the process could be significant, but the cost for
achieving those savings has not been determined.

The researchers demonstrated the technical possibility of in field hulling, sorting, and pre-
drying to reduce energy consumption in the walnut industry. The researchers have not yet
demonstrated the commercial feasibility of the concept.

2.15.6G Recommendations

The Program Administrator recommends the following actions:

1. The researchers should evaluate the sorting capabilities of nuts with and without hulls
using different walnut cultivars (beyond Chandler) and other nut types and determine
applicability to other nuts grown in California.

2. The researchers should evaluate operational and orchard health (soil condition, disease
encouragement, soil fertility, etc.) due to disposal of large quantity of hulls in the
orchard.

3. The researchers should design a prototype unit and estimate the capital and operational
costs for production units. Using this information, the researchers should estimate net
savings/cost of the new process compared to current nut processing methods.
4. The researchers should design a prototype device for continuous in-field dry dehulling of walnuts, optimize dehulling capacity and operating conditions of the dry dehuller, and provide processing parameters to achieve dehulling of walnuts with different hull attachment.

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 would be increased affordability of energy in California. If fully developed and commercialized, the new approach could provide significant saving of natural gas and propane in the walnut industry and transportation fuel for walnut hauling. The process may be useful in other tree nut industries in California. The proposed methods could save substantial, but unquantified, electricity and fuel. The researchers estimated that commercialization of in-field hull removal and disposal alone could save the California walnut industry some 160,000 gallons of transportation fuel per year ($480K) by reducing the unnecessary transport of hull tonnage.

The researchers estimated the new method could achieve at least a 40 percent energy saving by reducing over-drying, resulting in potential saving to the nut processors using both natural gas (50 percent) and propane (50 percent) of $2.9 million per year. In addition, they estimated savings in electricity from shorter drying time assuming a 20 percent electricity savings will have an economic value of $283,000.

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 surveyed potential users of the process and generally found enthusiastic interest. Growers and processors have a significant need to reduce energy use and cost and would likely accept a change in process provided net cost savings and operability are demonstrated. The researchers plan to work with the California Walnut Board to facilitate information transfer to the growers.

Engineering/Technical

The researchers estimate three years and about $400,000 are needed to complete the technical work on all parts of the system. A prototype in-field hull removal and pre-drying system must be designed and proven. In addition, the system must be optimized for proper drying.

Legal/Contractual

The researchers have completed a self-search of patents and have not found any potential infringements. They have not yet applied for patents.

Environmental, Safety, Risk Assessments/ Quality Plans

There are no known safety or environmental risks associated with the technology. The overall health impacts to orchards disposing of large quantities of hulls in the orchard need to be evaluated.

Production Readiness/Commercialization

The process is not yet ready for production or commercialization.

2.16G Prototype and Demonstration of Membrane Processes for Natural Gas Dehydration

Awardee: Membrane Technology and Research, Inc.

Principal Investigator: Haiqing Lin

2.16.1G Abstract

Natural gas extracted from wells must be dried prior to injection into the national pipeline distribution system. Current industry practice is to use glycol dehydrators for the drying process. However, glycol dehydrators extract hazardous volatile organic compounds (VOCs) from the raw natural gas stream and are typically vented to the atmosphere. In California VOC emissions from dehydrators are estimated to be 5,000 tons per year, half of which are benzene, toluene, ethylbenzene, and xylene (BTEX). Prolonged exposure to BTEX can cause skin and sensory irritation plus problems with the central nervous system (tiredness, dizziness, headache, loss of coordination) and respiratory system (eye and nose irritation).

The purpose of this project was to determine the feasibility of using membrane processes for natural gas dehydration. Membrane processes have the potential of reducing equipment costs
and curtailing or eliminating VOC emissions. The research team first constructed various membrane stamps and performed a parametric study on each to determine water/methane and water/VOC separation performance. Test results of the membrane stamps were highly promising in that they were highly permeable to water vapor with high water/methane selectivity and sufficient water/VOC selectivity, resulting in sufficient separation of water vapor from methane and VOCs.

The team then fabricated two membrane prototype modules using commercial-scale coating machines. Testing of the membrane prototypes indicated that water/methane separation properties were much lower than those of the membrane stamps, suggesting issues with the module design and/or fabrication process. Additional work is needed to optimize the design of the module configuration, enhance the fabrication process, and validate performance, reliability, and durability by demonstrating the membrane process at a natural gas processing facility.

This project successfully demonstrated the potential of using a simple membrane structure to dehydrate natural gas at relatively low cost and in an environmentally friendly manner. Several natural gas industry stakeholders have already expressed interest in this emerging concept. The research team plans to pursue efforts to complete development of the technology and prepare it for commercialization.

**KeyWords:** Natural gas, dehydration, polymeric membrane, water/methane selectivity, process design, VOC emissions

### 2.16.2G Introduction

All raw natural gas is fully saturated with water vapor when produced from an underground reservoir. It must be dried prior to injection into the natural gas pipeline distribution system to control corrosion and prevent formation of solid hydrocarbons and water hydrates. Current industry practice is to use glycol dehydrators for the drying process. According to the United States Environmental Protection Agency (USEPA), there are approximately 36,000 dehydration units in the United States which remove water from gas in production, gathering, and boosting applications. Researchers estimate that 10 percent of the nation’s dehydration units are located in California.

The bulk of gas dehydration systems use glycol which can absorb water from natural gas production wells. Desorption is accomplished using a distillation method. Although methane losses can be as low as one percent (including the use of methane as a fuel for the water vapor capture process),

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desorption process), there are several drawbacks which may restrict their future use for natural gas dehydration.

- Glycol dehydrators are ill-suited for use on offshore platforms, an increasingly common source of natural gas, due to the open flame in the desorption column and associated safety concerns.
- System operation is complex and requires solvent storage, replacement, and disposal.
- Glycols also absorb volatile organic compounds (VOCs), especially benzene, toluene, ethylbenzene, and xylene (BTEX), from the raw natural gas streams. The vent streams from dehydrators have become a major source of emissions of VOCs.

Prolonged exposure to BTEX can cause skin/sensory irritation and problems with the central nervous system (tiredness, dizziness, headache, loss of coordination) and respiratory system (eye and nose irritation). A typical glycol-based system dehydrating a five million standard cubic feet per day (MMscfd) natural gas stream discharges more than four tons per year of various organic pollutants, about half of which are BTEX. Natural gas consumption in California totaled 23,323 million therms (or approximately 2.3 trillion standard cubic feet) in 2012. In California alone, VOC emissions from dehydrators are estimated to be 5,000 tons per year, half of which are (BTEX) variety. Controlling such emissions to meet the clean air regulations imposed by USEPA is becoming one of the largest environmental challenges facing the natural gas industry.

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The purpose of this project was to determine the feasibility of using membrane processes for natural gas dehydration. Membrane processes have the potential of reducing equipment costs and curtailing or eliminating VOC emissions. Membrane systems offer an attractive alternative to glycol for natural gas dehydration as they are more compact with a relatively small footprint, have no moving parts, are very reliable, and do not require constant attention when operating in remote locations. Optimal membrane system design has the potential to significantly reduce or eliminate VOC emissions. Membrane systems for natural gas dehydration have been explored previously by other researchers but have only been found to be useful for niche applications. Successful deployment of membrane technology would benefit California and the nation.

Figure 28 illustrates schematically how a membrane process can be used to dehydrate natural gas.

![Figure 28: Schematic Membrane Process to Dehydrate Natural Gas with Essentially no VOC Emissions](image)

Raw natural gas passes over a membrane that selectively permeates water vapor and rejects methane and VOCs. The permeate stream, containing water vapor and a small amount of methane, can be used as fuel for on-site generators or other process equipment. The dry natural gas residue stream containing more than 99 percent of the VOC compounds is delivered for injection into the pipeline. The VOC content of pipeline-quality gas, a standard defined in federally regulated tariffs, is relatively low and therefore not considered to be hazardous to the environment or consumers. Dehydration, therefore, can be achieved with essentially no VOC emissions.

Industrial membranes for gas separation are often characterized by their permeance and selectivity. Permeance is the degree to which a material admits a flow of matter. Selectivity is choosing something as the best or most suitable material. Both solubility selectivity and diffusivity selectivity strongly favor the permeation of water vapor over methane (CH₄), the main component of natural gas. Water vapor molecules are smaller than methane and thus have much higher diffusivity. Researchers selected a membrane that is highly permeable to water vapor, minimizing membrane area requirements so as to reduce capital cost. The membrane is also highly selective for water compared with VOCs. If successfully developed, the proposed membrane process could be cost competitive compared with glycol dehydration and would
offer the natural gas industry a way to produce dry pipeline quality gas without VOC emissions occurring.

Polymeric materials with intrinsic water/methane selectivities of greater than 500 can be easily obtained. However, when these polymer materials are fabricated into conventional membrane structures, water/methane selectivity is much lower than the polymeric material. The supporting layers which provide the mechanical strength required for operation at high pressures result in significant transport resistance to water, but not to methane. This substantially reduces water permeance and water/methane selectivity, thus increasing the capital cost of membrane systems. A new membrane configuration, specifically optimized to minimize the influence of support layers on water transport, is required for membrane processes to be economically competitive with glycol units.

Researchers attempted to develop customized configurations of membrane composites and demonstrate how they can be used successfully in high pressure natural gas dehydration applications. The research team chose a membrane with a much thinner microporous support layer (40—60 micrometers, or μm), rather than conventional composite membranes for gas separation (150—250 μm), in an attempt to minimize transport resistance to water vapor. Every component in the membrane, including the selective layer and support, was optimized to improve water permeance plus water/methane and water/BTEX selectivity.

Figure 29 shows a schematic of an industrial thin-film composite membrane that can be used for natural gas dehydration.74

![Figure 29: Schematic illustration of the industrial Thin-Film Composite Membranes](image)

The microporous support structure has surface porosity of less than five percent and fine pores with an average pore diameter of less than 100 nanometers (nm). The proprietary gutter layer (optional) and selective layer are formed by a dip coating process using an industrial-scale coater.75 The smooth surface of the gutter layer allows for deposit of a very thin, dense


selective layer with high water/methane separation performance. The microporous support and gutter layer contribute minimal resistance to gas and vapor flow. Therefore the resistance to gas transport in the thin film composite membranes lies mainly in the selective layer. In this manner the gas selectivity is determined primarily by the selective layer. Gas permeance is inversely proportional to the selective layer thickness, so the selective layer is often made as thin as possible, typically in the range of 500–1,000 angstroms (Å).

Figure 30 illustrates the apparatus used to deposit the gutter layer and selective layer.

**Figure 30: Schematic Diagram of a Thin-Film Coating Machine to Prepare Industrial Membranes**

The microporous support membrane passes from the feed roll to the coating station where a layer of polymer coating solution is deposited. After evaporation of the solvent, a defect-free polymer film remains on the support membrane. The thickness of the selective layer is determined by comparing the methane flux of the composite membrane with that of a known thickness of the isotropic film of the polymer.

Figure 31 shows an exploded view of a conventional cross-flow spiral-wound module for gas separation with three ports (feed, residue, and permeate).

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Two flat sheets with permeate spacers between them are glued along three sides to form an envelope with an open end facing the permeate pipe. Many of these envelopes are wound around a perforated central collection pipe, with a feed spacer between each set of envelopes. Feed gas passes down the module, parallel to the permeate pipe in the channel created by the feed spacer. A portion of the feed gas permeates the membrane, enters the permeate channel, and exits through the collection pipe. Figure 32 shows a general procedure used to form membrane modules.

The membrane is cut to size and folded around the feed-spacer material and the product distribution pipe. The membrane envelope is then moved to the wind-up machine. The product collection pipe is placed in the jaws of a motor clutch and the membrane envelope is glued in place while being wound around the product pipe. In a final operation, reinforcing tapes are used to keep the membrane envelope in place. When the number of modules required for a given test or application have been formed, the modules are housed in a steel pressure vessel.

The research team modified an existing high pressure test loop for the module evaluation. A schematic flow diagram of the modified system is shown in Figure 33.
The original system had one 7.5 horsepower (HP) two-stage diaphragm compressor. The modified system used a new booster 10.0 HP compressor on the residue stream to increase the flow rate available in the system. The system was designed to operate in a complete recycle mode so that continuous experiments lasting several hours, or even days, could be carried out with a limited supply of feed gas.

The research team worked to simplify membrane system designs for natural gas dehydration. For example, it explored a combined design of a membrane module vessel design with a coalescence filter. The research team also contacted several producers of vacuum pumps to understand what is available in the market, especially pumps fueled by natural gas. Figure 34 shows photos of the module housing incorporating 3.0 inch or 4.0 inch diameter membrane modules, the new booster compressor to increase feed flow rate, and the small module housing incorporating 2.5 inch diameter membrane modules.
Figure 34: Photos of (a) Module Housing (b) New Compressor to improve the Feed Flow Rate in the Modified System (c) Small Module Housing incorporating 2.5 Inch Diameter Membrane Module

(a) Module Housing

(b) New Booster to Increase Feed Flow Rate

(c) Fabricated Module Housing Incorporating 2.5-inch Diameter Membrane Module
Figure 35 shows a schematic membrane process (with supporting table) proposed for natural gas dehydration.

**Figure 35: Process Simulation of the Proposed Membrane Process to Dehydrate Natural Gas without BTEX Emissions**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Wet Natural Gas</th>
<th>Dry Natural Gas</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>99.84</td>
<td>96.93</td>
<td>83.2</td>
</tr>
<tr>
<td>Propane</td>
<td>3</td>
<td>2.97</td>
<td>7.6</td>
</tr>
<tr>
<td>Toluene</td>
<td>1,000 ppm</td>
<td>900 ppm</td>
<td>1.6</td>
</tr>
<tr>
<td>Water</td>
<td>600 ppm</td>
<td>100 ppm</td>
<td>7.6</td>
</tr>
<tr>
<td>Flow rate (MMscfd)</td>
<td>10</td>
<td>9.934</td>
<td>0.066</td>
</tr>
<tr>
<td>Pressure (psig)</td>
<td>800</td>
<td>800</td>
<td>50</td>
</tr>
</tbody>
</table>

The wet natural gas containing 600 parts per million (ppm) water passes over a membrane that selectively permeates water vapor and rejects methane, propane, and BTEX. A pump is used to create a vacuum on the permeate side to increase the driving force for water vapor transport across the membrane. The permeate stream, containing water vapor and a small amount of methane, can be used as fuel for on-site generators or other process equipment such as the vacuum pump. The dry natural gas residue stream contains more than 99 percent of the BTEX compounds and other VOCs and is sent directly to the pipeline. The total hydrocarbon loss in the permeate stream is about 0.6 percent, which is lower than the loss rate for conventional glycol dehydrators. Using the membrane process dehydration is achieved with virtually no VOC emissions.

This project enabled researchers to demonstrate the viability of membrane technology for natural gas dehydration. Membrane stamps tested showed very high water/methane separation properties which meet performance and cost targets. However, when the membranes were
fabricated into prototype modules, the water/methane separation properties were much lower than those of the membrane stamps. The research team determined that further effort is needed to optimize module design and fabrication technique. The ideal module would demonstrate separation performance similar to that of membrane stamps.

The research team plans to demonstrate the membrane concept at a natural gas processing facility to provide long term operating performance data in a real-world operating environment. Such a test would help validate performance, reliability, and durability. Although the technology needs further work, several companies in the natural gas industry have already expressed interest. The research team will continue to explore the opportunities to complete development of the technology and prepare it for commercialization.

Researchers estimate the total market potential for the new membrane systems is about $380 million if all glycol dehydrators in California were replaced over time. Full adoption of the technology in California could reduce VOC emissions from dehydrators by 5,000 tons per year.

2.16.3G Objectives
The primary goal for this work was to determine the feasibility of using membrane processes for natural gas dehydration which offer the advantage of curtailing VOC emissions. The researchers established the following project objectives:

1. Build a membrane test skid housing an industrial 4.0 inch module that runs at feed pressures up to 1,000 pounds per square inch gauge (psig).
2. Develop membranes with water permeance of 2,000 gas permeation units\(^77\) (gpu), water/methane selectivity of 1,000, and water/BTEX selectivity of 50.
3. Make industrial-scale modules with no defects.
4. Obtain a database of membrane separation performance to guide the process design.
5. Demonstrate at least 100 hour system operation without failure.
6. Confirm that the membrane system can dehydrate natural gas to pipeline quality with less than 1.0 percent methane loss and zero emissions of VOCs.
7. Confirm that the membrane system developed for dehydrating 10 MMscfd natural gas would cost less than $100,000 and be cost competitive with conventional glycol dehydrators.

2.16.4G Outcomes
1. The researchers modified an existing membrane testing skid for the demonstration of natural gas dehydration per design requirements.
2. Membrane stamps demonstrated water permeance as high as 3,000 gpu, water/methane

\(^{77}\) 1 gpu = \(10^{-6}\) cm\(^3\) (STP)/cm\(^2\)-s-cmHg
selectivity up to 1,000, and water/hexane selectivity of up to 120.

3. The research team successfully scaled up the production of the novel composite membranes using commercial-scale coating machines.

4. The prototype modules showed water/methane selectivity of only 200 at feed pressure of 500 psig, compared with up to 3,500 for low pressure membrane tests. Consequently, it was not possible to develop a performance database.

5. The researchers ran the modules in the skid for more than 100 hours and performance remained consistent over the entire test period.

6. The research team analyzed the costs of natural gas dehydration using test data for membrane stamp performance. The resulting membrane system design was capable of dehydrating natural gas with less than 1.0 percent methane loss and almost zero emissions of VOCs.

7. The cost analysis completed in Outcome 6 above indicated that the membrane systems, as designed, could be cost competitive with conventional glycol dehydrators. The membrane process could be more attractive if a financial credit for reduction of VOC emissions were considered.

2.16.5G Conclusions

1. The researchers performed simple modifications to the existing membrane testing skid, enabling successful demonstration of natural gas dehydration.

2. Design and testing of various membrane stamp designs was a practical step to demonstrate the potential for promising results of membrane systems. Researchers prepared novel two layer composite membranes with high water permeance, water/methane selectivity, and good mechanical properties, meeting membrane performance targets.

3. Researchers successfully fabricated two prototype spiral-wound modules of the composite membrane using commercial-scale coating machines.

4. The discrepancy in performance between membrane stamps and modules suggested problems in the module design and fabrication.

5. The modules demonstrated performance stability at high feed pressures for an extended period of time.

6. The membrane design appeared to be capable of low methane loss and zero VOC emissions, but it was not possible to prove this in the laboratory due to membrane design/fabrication issues.

7. The research team demonstrated that the membrane system design can be cost competitive with conventional glycol dehydrators if membrane design and fabrication issues are resolved in a satisfactory manner.
The results of this project demonstrated the potential viability of membrane technology for natural gas dehydration. The research team fabricated novel, two layer composite membranes which demonstrated high water permeance, water/methane selectivity, and good mechanical properties. The membrane stamps and dehydration module design have the potential to be cost competitive compared with glycol dehydrators. However, when the membranes were made into prototype modules, the water/methane separation properties were much lower than those of the membrane stamps. The research team determined that significant effort is needed to optimize the module design and fabrication. Nevertheless, the results from this project are promising enough that several companies in the natural gas industry have expressed interest in the technology. The research team will continue to explore pathways to complete development and commercialization of the technology.

2.16.6G Recommendations

The feasibility of the proposed technology has been successfully evaluated and tested. Further work is needed to take this technology into the marketplace. The Program Administrator recommends that the researchers:

- Verify that the water separation performance (from methane and VOCs) of the membrane module is similar to that of membrane stamps.

- Optimize the design and fabrication of the module configuration and demonstrate its performance, reliability, and durability at a natural gas processing facility.

- Conduct a long term operating test of the field demonstration system to provide critical operating performance data of fabricated membrane modules in a real-world operating environment and to help optimize computer simulation models. This work will ensure that any remaining membrane permeance, selectivity, and reliability issues are resolved before a full-scale system is built and provide the researchers with the confidence necessary to complete development and commercialization. Any unexpected problems that may occur because of trace components in the feed gas can also be detected and fixed. Several natural gas industry stakeholders, including Chevron and Saudi Aramco, have expressed interest in this technology and could be potential candidates to host the demonstration site.

- Resolve membrane module design/fabrication issues and perform a complete field demonstration for natural gas dehydration to validate performance and ensure durability and reliability in the field.

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.
2.16.7G 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 reduced environmental impacts of the California energy supply and distribution system.

The successful development of commercial membrane systems could potentially benefit California natural gas producers and consumers in at least four ways:

1. VOC Emission Reductions. Current VOC (BTEX) emission from glycol dehydrators in California is approximately 5,000 tons per year. The new membrane systems provide a cleaner, safer means of dehydrating natural gas with essentially zero VOC (BTEX) emissions at the dehydration site.

2. Capital Cost Savings. Capital replacement costs for all glycol dehydrators in California are estimated at about $500 million (3,600 dehydrators at an estimated cost of $140,000 each, assuming an average dehydrator treats about 10 MM scfd of gas). The same number of membrane systems at the same average size would cost about $380 million (3,600 membrane systems at an estimated cost of $105,000 each), resulting in an overall savings of $120 million. This represents almost 25 percent savings in capital cost compared with replacement of existing glycol dehydration equipment.

3. Operating Cost Savings. Membrane systems can typically lower operating costs by 20 percent to 40 percent compared with conventional wet chemistry separations. Membrane systems are inherently more compact, less complex, more reliable, need less operator attention, and use no consumption of chemicals.

4. Local Economy. The research team plans to engineer, design, and fabricate the commercial membrane systems/modules in California, enhancing employment in the general manufacturing industry.

2.16.8G 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 market potential of replacing all existing glycol dehydration units in California is $380 million. The key to commercialization is to find a natural gas producer who can host the field
demonstration of a complete membrane system for natural gas dehydration. Membrane Technology and Research, Inc. (MTR) has been providing products to the natural gas industry for several years. Several companies in the natural gas industry, including Chevron and Saudi Aramco, have expressed interest in this technology and can be considered as potential candidates for hosting a demonstration site.

**Engineering/Technical**

The researchers plan to continue the development of the membranes.

**Legal/Contractual**

The research team has not filed any patents. The production method for this membrane is a trade secret at MTR. The research team has conducted a patent search and has concluded that the proposed concept does not infringe any other active or expired patent.

**Environmental, Safety, Risk Assessments/Quality Plans**

If additional research is pursued, the integrity of the system will need to be thoroughly tested to ensure that it meets standard industry safety and permitting requirements.

**Production Readiness/Commercialization**

The concept needs further refinement and optimization of the membrane module design and fabrication process prior to commercialization.

**2.17G Automatic Combustion Ratio Control for Modulating Natural Gas-Fired Systems**

*Awardee:* Lumec Control Products, Inc.

*Principal Investigator:* Paul Luebbers

**2.17.1G Abstract**

Energy efficiency is emphasized as the highest priority in the California Energy Loading Order related to energy resource planning. California investment-owned utilities spend collectively about $1 billion per year in support of energy efficiency and related demand response programs and incentives.

The purpose of this project was to prove the feasibility of an air-to-fuel ratio control system suitable for natural gas-fired boilers that also enables significant fuel savings and is affordable for a broad range of boiler sizes. Existing parallel positioning control systems have proven to be cost effective for larger (greater than 150 horsepower) natural gas-fired boiler systems. The addition of traditional oxygen trim systems is also cost effective for boilers larger than 300 horsepower (hp).

The research team developed a unique air-fuel ratio control system utilizing flue gas oxygen analysis (FGA) that is cost effective for smaller boiler applications. The proposed concept provides fuel-air ratio control within plus or minus (±) 0.25 percent oxygen (O2) over a control range from zero percent O2 to ambient air conditions. The concept uses a linear control valve and automotive oxygen sensor to form a closed loop, stand alone control system. The new system provides full oxygen trim capabilities, increases boiler efficiency, lowers fuel costs, and offers a potential simple payback of one year for a 30 hp boiler.

The research team estimated that full adoption of the proposed system could save California ratepayers nearly $30 million annually and reduce carbon dioxide emissions by seven million pounds per year. Follow-up development work is needed to reduce the excess oxygen content at low fire, which in turn results in reduced fuel usage and formation of carbon monoxide.

**Keywords:** Combustion efficiency, oxygen trim, gas-fired boilers, ratio control, natural gas combustion

2.17.2G Introduction

From 2007 through 2011 the United States spent approximately $200 billion annually on natural gas, $60 billion of which was burned to produce heat for commercial and industrial processes. Energy efficiency is prominently emphasized as the highest priority in the California Energy Loading Order related to energy resource planning. California investment-owned utilities spend collectively about $1 billion per year in support of energy efficiency and related demand response programs and incentives. Natural gas is the primary fuel source for industrial furnaces and ovens, as well as most commercial-scale steam generating boilers. Natural gas is a relatively clean burning fuel. However many existing modulating combustion systems do not have adequate control resolution necessary to minimize unwanted emissions and maximize heat output. The use of traditional butterfly valves and simple positioning control methods cannot properly control air and gas flows, resulting in poor performance. Furthermore, legacy control systems with on/off or high fire/low fire combustion management schemes perform even more poorly than modulating systems. Many larger boilers can be upgraded with modern combustion systems in a cost effective manner. However, retrofit of smaller boiler systems with modern combustion control systems is generally not cost effective. There is a distinct need for a combustion ratio control system that is affordable, easy to install, easy to maintain, and universally applicable to large and small boilers.

The purpose of this project was to determine the feasibility of a new automated system to control the air-to-fuel combustion ratio of modulating natural gas-fired commercial and industrial steam generating boilers, increasing combustion efficiency by 10 percent at a payback of less than one year. The results of this work demonstrated that the use of a low cost oxygen sensor, coupled with a precise control valve, could provide continuous and precise air-fuel ratio control that results in reduced excess air and fuel usage. This system is notably cost effective for smaller boilers which otherwise could not take advantage of existing modern combustion

79 Energy Information Administration, [www.eia.gov/naturalgas/annual/](http://www.eia.gov/naturalgas/annual/); data table 15/Figure 20.
controls due to high initial cost. The proposed closed-loop, stand-alone system enables a wide range of oxygen control set points, providing flexibility across a broad range of boiler applications. Retrofits are relatively compatible for existing natural gas-fired boilers regardless of the type of combustion controls and do not affect built-in safety systems.

Although the combustion of natural gas is a mature process, current technologies fail to perform this task as efficiently as possible. Generally, one part of natural gas or methane (CH₄) by weight combines exothermically with 9.53 parts of air to produce carbon dioxide (CO₂), nitrogen (N₂), water (H₂O), and the release of thermal energy:

$$CH₄ + 7.53N₂ + 2O₂ → CO₂ + 2H₂O + 7.53N₂ + heat$$

Equation 1

Equation 1 uses generally industry accepted approximations for the chemical composition of natural gas, even though natural gas is composed of varying amounts of several hydrocarbons. This stoichiometric combination of gas and air releases the maximum thermal energy available in the reaction. However, the mechanical methods through which gas and air are mixed prior to combustion have limitations and are incapable of thoroughly and completely mixing the gases. The result is a heterogeneous mix and, upon combustion, some of the gas molecules do not completely oxidize. The gas molecule dissociates (Equation 2) and a partial oxidation leads to the formation of carbon monoxide (CO) as illustrated in Equation 3.

$$CH₄ → C + 2H₂$$

Equation 2

$$2C + O₂ → 2CO + heat$$

Equation 3

CO can then oxidize, releasing heat and forming CO₂ as shown in Equation 4. This only occurs if there is sufficient oxygen available for combustion. Due to the poor mixing of the gases there is typically a release of CO during the combustion process.

$$2CO + O₂ → 2CO₂ + heat$$

Equation 4

Above 2,900 degrees Fahrenheit (°F) nitrogen molecules readily combine with oxygen to form nitric oxide (NO) and nitrogen dioxide (NO₂), generally referred to as NOₓ compounds. The release of NOₓ is very undesirable and subject to strict regulatory controls, especially in California. The inability to achieve ideal, stoichiometric combustion leads operators to run equipment with a significant amount of excess air. This extra air provides more oxygen, which provides a better chance for the oxygen and fuel molecules to interact, allowing for more complete combustion of the fuel. However, the extra oxygen also absorbs a large amount of the
thermal energy released by the combustion reaction, thus reducing the heat available for the process (such as heating water) and reducing boiler efficiency.

One way to reduce formation of NOx at high temperatures is to decrease the concentration of oxygen in the combustion process. The boiler industry has developed many new burner designs in an attempt to solve this problem. However the combustion process is highly dynamic. Fuel and airflows change during modulation of the firing process. The velocities of the molecules also change, resulting in variable mixing. Typical burner designs, especially on smaller boilers, are not capable of making real-time adjustments necessary to compensate for variable conditions and maintain optimal combustion. Control valves used to manipulate fuel and airflows directly impact the volume and mass of fuel and air available for combustion. Standard control schemes used on boilers utilize butterfly valves along with closed-loop controls for temperature or steam production. However these same systems use open-loop controls for products of combustion. The combustion process is not optimized to respond continually to changes in boiler temperature or steam production settings.

Modern combustion systems that use closed-loop controls for the combustion process are very expensive. Very large combustion systems utilize continuous emissions monitoring systems (CEMS), which analyze the products of combustion and cause changes to the combustion control valves for maximized combustion efficiency. CEMS systems have high installed costs and can only be cost justified for very large boilers. Parallel positioning systems are another option to increase combustion efficiency through better air-to-fuel ratio control. Fuel and air control valves are used with very precise motors typically joined to butterfly valves. Expensive oxygen (trim) monitoring can be added to provide closed-loop control combustion control capabilities. Similar to CEMS, parallel positioning systems are relatively expensive and thus not cost effective for smaller boilers.

The proposed system utilizes the patented IRISvalve technology instead of a traditional butterfly valve and its inherent non-linear characteristics. IRISvalve uses an iris diaphragm as the primary control element, along with an actuator and microprocessor, which can provide orifice-size adjustments as small as 0.010". The physical behavior of the IRISvalve closely emulates that of a static orifice plate that is the standard measurement device for low pressure gas flows.

The research team selected a 30 hp boiler for testing with a very basic on/off firing control scheme. The test measured performance data across varying conditions prevalent in larger boilers and complex firing schemes. Figure 36 shows the installation of the IRISvalve on the test boiler. Figure 37 illustrates an intelligent, mass-produced automotive style oxygen sensor located in the flue exhaust that uses the IRISvalve as the enabling control system.
The research team also developed a ratio control algorithm for the embedded microprocessor of the gas valve to control the excess oxygen to less than 2.1 percent. The final control algorithm is shown in Figure 38.
The sensor technology utilizes a dedicated microprocessor to monitor and interpret the sensor data. The IRISvalve utilizes an embedded microprocessor to control valve movement and adjust sensor temperature using a built-in 2.0 megahertz (MHz) data link. This speed provides the opportunity to examine large amounts of data and make subsequent valve adjustments to maintain optimum combustion control. The algorithm used to provide control of the sensor and gas valve is robust and proven, demonstrating the capability to maintain excess oxygen to within plus or minus (±) 0.25 percent of the set point.

The researchers used baseline and steady state tests (Tests A and B, respectively) to determine the fuel savings derived from the increase in combustion efficiency. Baseline test results indicated combustion efficiency below 80 percent with excess oxygen content of 10 to 11 percent. Test data also measured significant traces of CO that likely will need to be addressed in a future effort. Boiler operation was limited to 5.5 percent excess oxygen except for very short duration tests because of the large amounts of CO produced at low excess oxygen concentrations.

Test C provided insight into how the system would respond to random variances by rapid changes of the oxygen set point. This simulates conditions that may occur due to changes in the physical properties of the combustion air, as well as changes in the chemical and physical properties of the fuel. The control system demonstrated the capability to respond to variances within one or two seconds while maintaining the oxygen set point within ± 0.25 percent.
Test D showed the ability of the system to maintain the oxygen set point while repeatedly adjusting between two distinct set points. This type of behavior was expected in low fire/high fire and modulating boilers where different oxygen contents are desirable, depending on the combustion output. At lower outputs, these boilers will typically need to have more excess air present to maintain a well-established flame while at high output. The oxygen content can be minimized to maximize the combustion efficiency. This technology can be integrated with any burner without alteration of the built-in boiler safety system.

The proposed concept adapted sensor technology from the automotive industry to monitor and adjust excess oxygen in the exhaust gas of the boiler based on real-time dynamic operating conditions. The use of variable orifice valve (IRISvalve) technology demonstrated the advantages of using a relatively low cost control device capable of making very fast, precise movements on a wide range of boiler sizes and combustion control systems. The IRISvalve significantly outperformed the standard butterfly valve with its near unity control gain and linear behavior. Integrating the IRISvalve and the oxygen sensor created a stand-alone, closed loop oxygen feedback system that was very simple to operate, easy to install, and cost effective.

The proposed control system, once commercialized, could potentially provide a simple payback of approximately one year, depending on the application and operational profile. The control system could be easily installed on existing boilers with a broad range of combustion control technologies. Lumec introduced this technology at the 2013 Air Conditioning, Heating, and Refrigeration trade show in Dallas, Texas, in January 2013. The response from potential customers was overwhelmingly positive. Lumec plans to complete product development and commercialize the new product, Automated Oxygen Control System (AOCS), beginning with pilot customer projects.

The research team estimated that full adoption of the proposed system could save California ratepayers nearly $30 million annually and reduce carbon dioxide emissions by seven million pounds per year. Follow-on development work should focus on the ability to reduce the excess oxygen content at low fire, which results in reduced fuel usage and formation of carbon monoxide. The formation or reduction in NOx compounds was beyond the scope of this project. The probability for NOx formation is reduced through the reduction of excess oxygen. A follow-on study examining this in detail may provide valuable insight into future development needs.

2.17.3G Objectives

The primary goal of this work was to determine the feasibility of using a relatively inexpensive automated system to control the air-to-fuel combustion ratio of modulating natural gas-fired commercial and industrial steam generating boilers and similar equipment that increases combustion efficiency by 10 percent and produces a payback of less than one year. The researchers established the following project objectives:

1. Demonstrate that both valves achieve a control gain between 0.85 and 1.15 and a flow rate turndown of greater than 35 to 1.0 over the operating range. Demonstration of the turndown capability of a control valve provides an indication of the valve’s ability to
provide flow control over a large range of adjustment. A larger turndown is associated with a greater ability to regulate flow rates.

2. Confirm through functional testing that the gas valve will track the position of the air valve within 0.5 percent of full scale. Confirmation of the valve’s ability to track movement within a narrow band of another valve is necessary for uniform air-to-fuel ratio control during modulation.

3. Demonstrate that the gas valve will respond to the oxygen sensor signal and simultaneously track the air valve position to maintain an optimum combustion ratio with less than 10 percent excess air (2.1 percent oxygen) in the flue gas. Demonstration of the valve’s response to the oxygen sensor signal is required for the valve to make automatic adjustments in response to the signal. Adjustments capable of limiting the excess air to less than 2.1 percent are desirable to maximize combustion efficiency.

4. Determine that the test plan will account for the full operational spectrum of the test boiler from a low fire gas flow rate of 500 cubic feet per hour (cfh) to a high fire gas flow rate of 1700 cfh. Measure the exhaust composition to record a quantitative value of oxygen (O₂) and methane (CH₄). O₂ levels will be targeted for control below 2.1 percent while unburned hydrocarbons, measured as CH₄, will be targeted for control below 0.1 percent. Determination of the test plan covering the full operational range of the boiler is necessary to be able to examine the system’s capability to perform in all firing scenarios. Achieving the targeted oxygen level is necessary to prove the system’s control capabilities.

5. Document the test boiler performance characteristics using the existing OEM gas and air control devices. Documentation of the baseline boiler performance is necessary to calculate the improvement in boiler efficiency gained through use of the new system.

6. Calculate the actual combustion ratio throughout the test period and confirm that it is within 1.0 percent of the target stated in Objective 3 for all test variations listed in Objective 4. Calculate the boiler efficiency and emissions per Environmental Protection Agency (EPA) AP42 and confirm that it is greater than 93 percent for all test variations listed in Objective 4. Calculations of the combustion ratio and efficiency improvement are required to calculate the payback of the system.

7. Confirm that the fuel savings/efficiency improvements provide a full payback within one year of installation for the proposed system that is anticipated to cost less than $15,000 installed. Confirmation of the fuel savings and the associated payback term is necessary to determine the size of boilers that can affordably install the proposed system.

2.17.4G Outcomes

1. The gas control valve and air valve provided control gain of 1.00 and a flow rate turndown of at least 35 to 1.0 over the operating range.
2. Functional testing demonstrated that the gas valve was able to track the position of the air valve within 0.1 percent of full scale, exceeding the stated objective. However the research team elected to remove the air valve from the control system in the final test configuration.

3. Researchers developed the operation algorithm and successfully tested it on a small burner in the laboratory. Boiler operation was limited to 5.5 percent excess oxygen except for very short duration tests because of large amounts of carbon monoxide (CO) produced at low excess oxygen concentrations.

4. The initial test plan included the use of alternate fuels as well as multiple firing modes. The research team modified the test plan by having to substitute a modulating boiler with an on/off boiler. The research team did, however, collect a significant amount of test data on the substitute boiler. This allowed for excellent calculations of combustion efficiency and emissions. Analysis of the data indicated that CH₄ levels did not exceed 0.1 percent during the control testing.

5. The research team collected test data and documented boiler performance at multiple times during different seasons.

6. Test results indicated that the system is capable of controlling the excess oxygen content to within plus or minus (+/-) 0.25 percent O₂ of the targeted set point. Calculation of the combustion ratio, efficiency, and emission rate for each test was not meaningful because the test plan was modified.

7. The research team estimated that the incremental cost of the proposed system is approximately $6,000, and estimated payback is one year for a small boiler application.

2.17.5G Conclusions
1. Integration of the gas control valve and oxygen sensor/air valve enable acceptable control gain and acceptable flow turndown.

2. The gas valve was able to track the position of the air valve with impressive accuracy (within 0.1 percent of full scale).

3. It was not possible to test boiler operation at anything less than 5.5 percent excess oxygen due to excessive CO emission levels. Further testing is needed to validate the ability of the proposed concept to operate properly at very low oxygen levels (e.g., 2.1 percent excess oxygen).

4. The research team was not able to produce a test plan that accounts for the full operational spectrum of the test boiler due to equipment issues. Additional testing covering the full operational range of the boiler is needed to fully evaluate the viability of the proposed concept.
5. Full documentation of the test boiler performance characteristics was not possible due to equipment issues. Therefore it was not possible to calculate the improvement in boiler efficiency gained through use of the new system.

6. Analysis of the test data provided confirmation of the proposed system’s control capability in varying applications.

7. Incremental system cost was much less than anticipated, $6,000 compared to a target of $15,000. However it is difficult to validate performance and payback of the proposed concept without additional testing.

There are multiple variables which impact natural gas combustion efficiency, including changes in air temperature, humidity, density, varying hydrocarbon content in the fuel supply, and reliability of control devices and mechanical linkages. Variances can occur very rapidly and unpredictably. The research team adapted sensor technology from the automotive industry to monitor excess oxygen content in the exhaust gas of natural gas combustion equipment to quantify variables and provide adjustments based on a precise control valve to maintain specific excess oxygen content.

The use of variable orifice valve (IRISvalve) technology in this project demonstrated the advantages of using a control device that is capable of making very fast and very precise movements. The IRISvalve significantly outperformed the standard butterfly valve with its near unity control gain and linear behavior. The sensor technology utilizes a dedicated microprocessor to monitor and interpret the sensor data and make subsequent valve adjustments to maintain system control. The control algorithm showed the capability to maintain excess oxygen to within plus or minus (±) 0.25 percent of the set point.

Test data showed that there is a significant production of CO that may need to be addressed in a future effort. The control system demonstrated the capability to respond to variances within one or two seconds while maintaining the oxygen set point within ± 0.25 percent. This project also demonstrated that the system is able to maintain the oxygen set point while repeatedly adjusting between two distinct set points. This type of behavior is expected in low fire/high fire and modulating boilers, where different oxygen contents are desirable depending on the combustion output.

Analysis of test results showed that the control system is capable of controlling excess oxygen in the exhaust of a natural gas-fired boiler. In the test boiler, the system controlled the excess oxygen at 5.5 percent. The data also demonstrated the system’s responsiveness to varying conditions, making it suitable for application to a wide range of boiler sizes and combustion control systems.

The control system could potentially provide a simple payback of approximately one year, depending on the application and operational profile. Overall, the project successfully demonstrated that the proposed system is capable of providing excellent combustion control, and it achieves a payback of about one year on a small boiler.
2.17.6G Recommendations

The proposed technology has been evaluated and tested, and it is ready for commercialization. Further testing on large boiler systems and various combustion control systems would provide valuable feedback on missing system capabilities that need to be added. The IRISvalve technology is ideally suited for this application, the software algorithms are proven and robust, and further technological development is not needed for basic oxygen control.

The unexpected documentation of the large CO spike at the beginning of the combustion process is an area needing further study. Carbon monoxide is a poisonous gas that is regulated by the EPA at both the state and federal levels. A better understanding of the severity and commonality of this occurrence is required to quantify the need for a system capable of controlling and minimizing the CO production. This may result in the need to develop enhanced burner designs, control systems, and sensors specifically to target this issue.

The formation or reduction in NOx compounds was beyond the scope of this project. The probability for NOx formation is reduced through the reduction of excess oxygen. A follow-on study examining this in detail may provide valuable insight into future development needs.

Lumec plans to pursue large-scale adoption and testing of this technology throughout the remainder of 2013 with expectations of wide adoption. Lumec is also pursuing the adaptation of this technology for the industrial market. In large-scale industrial thermal processing systems multiple burners are used in a single furnace. Unlike a boiler, where a single combustion process is confined and manageable, these industrial applications will require a different approach to excess oxygen control.

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.

2.17.7G 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.
This technology, once fully commercialized, has the potential to yield significant fuel savings for various boiler and furnace applications across the State.

The 2012 California Gas Report\(^80\) identifies the usage of natural gas in the commercial and industrial sectors and provides predictions of usage change from 2012 through 2030. The 2011 gas usage for the core commercial industries totaled 78 billion cubic feet (BCF) and is expected to decline to an annual usage of 75 BCF by 2030. The 2011 gas usage for the non-refinery core industrial industries totaled 22 BCF and is expected to decline to an annual usage of 14 BCF by 2030.

The proposed system is designed for boilers from 30 hp and up. These boilers are used to supply heat, hot water, and steam. Restaurants represent the largest users of gas in the commercial sector and probably use the bulk of the natural gas for cooking and dishwashing activities. Other commercial usage of the proposed technology could involve the use of gas to heat large buildings with steam and hot water. The non-refinery industrial industries, except for the transportation sector, will be likely to use the proposed technology since these sectors use natural gas in industrial thermal processes and larger process boilers. Therefore in 2011 usage values, the proposed technology is probably applicable to 55 BCF in the commercial sector and 20 BCF in the industrial sector.

The proposed system could realistically achieve energy savings of 7.0 percent for a small boiler. It has not been tested on larger systems but has the same control capability as a commercial oxygen trim system. Oxygen trim systems capable of controlling excess oxygen at 3.0 percent can result in a 5.0 percent increase in efficiency improvement and subsequent fuel savings. Table 5 presents estimated fuel cost/savings based on California’s annual natural gas usage.

<table>
<thead>
<tr>
<th></th>
<th>Commercial</th>
<th></th>
<th>Industrial</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gas use per year (BCF)</strong></td>
<td>2011</td>
<td>2030</td>
<td>2011</td>
<td>2030</td>
</tr>
<tr>
<td></td>
<td>54.7</td>
<td>52.7</td>
<td>20.5</td>
<td>13.0</td>
</tr>
<tr>
<td><strong>Average Fuel Cost ($/thousand cubic feet gas)</strong></td>
<td>7.75</td>
<td>11.00</td>
<td>7.25</td>
<td>10.29</td>
</tr>
<tr>
<td><strong>Annual Fuel Cost ($ million)</strong></td>
<td>424</td>
<td>579</td>
<td>148</td>
<td>134</td>
</tr>
<tr>
<td><strong>Annual Savings ($ million)</strong></td>
<td>21.2</td>
<td>28.9</td>
<td>7.4</td>
<td>6.7</td>
</tr>
</tbody>
</table>

The proposed technology has the potential to save California commercial and industrial customers over $28 million per year based on the conservative estimates from the Codes and Enhancement Initiative. The Codes and Enhancement Initiative\(^81\) also estimates the benefits to air quality by widespread adoption of oxygen trim on boilers larger than 300 hp achieved by increased efficiency and reduced fuel use. See Table 6. The proposed system is capable of

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yielding similar reductions, but at a lower cost, which makes it applicable to a much larger range of boilers.

Table 6: Annual Emissions Reduction from Implementation of Oxygen Trim

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>NO\textsubscript{x}</th>
<th>SO\textsubscript{x}</th>
<th>CO</th>
<th>PM10</th>
<th>CO\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission reduction (pounds per year)</td>
<td>6,005</td>
<td>4,064</td>
<td>1,820</td>
<td>607</td>
<td>6,975,615</td>
</tr>
</tbody>
</table>

A boiler census was also published in 2005.\textsuperscript{82} This census provides information on the number of installed units in the United States. Using the total capacity, the number of boilers smaller than 250 hp burn 6.75 times more fuel per year than boilers larger than 250 hp. Assuming that the national trend is applicable to California, the proposed technology could realize emission reductions presented in Table 7.

Table 7: Emissions Reduction from Implementation of Proposed System

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>NO\textsubscript{x}</th>
<th>SO\textsubscript{x}</th>
<th>CO</th>
<th>PM10</th>
<th>CO\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission reduction (pounds per year)</td>
<td>46,540</td>
<td>31,500</td>
<td>14,100</td>
<td>4705</td>
<td>54,061,016</td>
</tr>
</tbody>
</table>

The key to any estimated savings and reductions is the adoption of the technology by industry. The proposed technology is significantly less expensive than competitive technologies and is easier to install. These factors indicate the proposed technology would have a better adoption rate than those presented in the Codes and Enhancement Initiative report.

2.17.8G 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 proposed concept targets commercial and industrial boiler markets in California, which, according to the 2008 California Gas Report, represent approximately 25 percent of the State’s natural gas usage. The control system could potentially provide a simple payback of approximately one year, depending on the application and operational profile. The control system demonstrated in this effort can be easily installed on existing small boilers with a broad range of combustion control technologies. The research team is also exploring the potential viability of using this concept on large boilers. Lumec, a very small manufacturing company, is developing the technology and plans to commercialize the product. Assistance from other

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parties may be needed to realize the technology’s commercial market potential. Lumec introduced this technology at the Air Conditioning, Heating, and Refrigeration trade show in Dallas, Texas, in January 2013. The response from potential customers was overwhelmingly positive. Lumec Control Products, Inc. plans to commercialize this technology within several market sectors and is actively pursuing pilot project opportunities.

Engineering/Technical

The system has yet to be evaluated on a modulating boiler. However, lab tests suggest that the system will operate correctly in this mode. Achieving Underwriters Laboratory (UL) recognition will be required for wide scale adoption. Lumec is currently under contract with UL to complete this process. The proposed concept will likely need further optimization and field testing to validate laboratory results and ensure durability and reliability in the field.

Legal/Contractual

Lumec owns an existing patent covering the enabling IRISvalve technology (US#8,132,783 B2). The software required to operate the system is proprietary and cannot be reverse engineered from the embedded microcontroller. Lumec may file an additional patent application in 2013 regarding oxygen trim utilizing the patented IRISvalve technology.

Environmental, Safety, Risk Assessments/Quality Plans

There are no obvious safety or environmental risks associated with this system design. If additional research is pursued, the integrity of the system will need to be thoroughly tested to ensure that it meets standard industry safety and permitting requirements.

Production Readiness/Commercialization

The concept needs further testing with actual modulating boilers prior to commercialization. Field testing is also required for validation of performance and reliability in a real-world working environment. Lumec, a small manufacturing company well suited for initial field testing and market launch, owns the intellectual property of the proposed concept. Partnerships with other parties/stakeholders may be required to reach full market potential.

2.18G Geothermal Heat Pump Water Heater

Awardee: Hal Slater

Principal Investigator: Hal Slater

2.18.1G Abstract

California utilities are continuously looking for new technologies and products to help meet aggressive energy efficiency and demand response (EE/DR) targets. One area of opportunity is to increase the energy efficiency of natural gas and electric water heaters.

The California Energy Commission (CEC) found that residential water heating accounts for 22.5 percent of California residential gas consumption, 3.2 percent of California’s annual energy demand, and an estimated 10 percent of CO₂ emissions. According to the American Council for
an Energy Efficiency Economy (ACEEE), air-to-water heat pump (AWHP) water heaters are the most efficient products available for purchase by consumers. The primary market opportunity for AWHP devices is replacement of residential electric resistance domestic water heaters.

The goal of this project was to determine the performance and feasibility of a water-to-water geo-thermal heat pump water heater (GHPWH), a new concept that captures available heat from cold municipal groundwater supplies and uses the captured heat to produce domestic hot water. The primary benefit of such a device is that it is inherently more efficient to capture heat from municipal water sources than ambient air. The research team established an aggressive performance target at a minimum energy factor or coefficient of performance (EF/COP) of 4.0 and an installation cost of less than $2,500.

Researchers simulated various water usage patterns in common households in order to ensure adequate extraction of heat from incoming water supplies at local ground water temperatures. The research team also fabricated and tested four prototypes, three of which were installed in homes located in unique climate zones. Each prototype cost approximately $3,000 including instrumentation. Initial laboratory test results produced an average EF/COP of 2.1 using municipal water temperature of 58° F. The average EF/COP measured at the three residential test sites was approximately 1.0. Although system performance was lower than projected, the research team was confident that further development could eventually reach performance targets and that the installation cost of a commercialized product could be less than $2,500.

**Keywords:** Geothermal, water heating, air-to-water, water-to-water, heat pump, groundwater

### 2.18.2G Introduction

California’s investor-owned utilities, Pacific Gas and Electric Company (PG&E), Southern California Edison Company (SCE), Southern California Gas Company (SoCalGas), and San Diego Gas & Electric Company (SDG&E), collectively spend about $1 billion per year supporting various energy efficiency (EE) and demand response (DR) programs and related incentives. Utilities are continuously looking for new technologies and products to help meet aggressive EE/DR targets established by the California Public Utilities Commission (CPUC). One area of opportunity is improving the efficiency and reducing greenhouse gas emissions of natural gas and electric water heaters.

In 2007 the California Energy Commission (CEC) found that residential water heating accounted for 22.5 percent of California residential gas consumption, 3.2 percent of California’s annual energy demand, and an estimated 10 percent of carbon dioxide (CO₂) emissions. The CEC also reported that 11 percent of California residences used electric water heaters, most of which were electric resistance products.

According to the American Council for an Energy Efficiency Economy (ACEEE), air-to-water heat pump (AWHP) water heaters are currently the most efficient water heating products

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AWHP products utilize electricity to extract heat from ambient air to produce domestic hot water and can reduce electricity consumption by 30 to 60 percent compared to electric resistance units. Consumers with electric resistance water heaters have been slow to adopt AWHP mostly due to higher first cost and the need for a relatively large space for the devices to operate properly.

The goal of this project was to determine the performance and feasibility of a water-to-water geo-thermal heat pump water heater (GHPWH) that captures available heat from municipal groundwater stored in a separate tank to produce domestic hot water. The proposed GHPWH has a potentially higher efficiency compared to AWHP devices because more heat can be more efficiently extracted from a groundwater source compared to ambient air. Researchers established an energy factor (EF)/coefficient of performance (COP) target of 4.0 with an installation cost of less than $2,500. If proven to be feasible, this concept could help to further reduce energy consumption in residential hot water applications. This device could be a replacement product for electric resistance water heaters.

Figure 39 describes the GHPWH process. Cold city water is collected and temporarily held in one tank. A water-to-water heat pump draws heat out of the city water further reducing the temperature of the cold water and transfers the captured heat to a hot water holding tank.

Figure 40 is a conceptual sketch of what the manufactured product might look like. The cold water tank and heat pumps shown to the left of the water heater can actually fit directly under the water heater in the elevated space that is normally required as part of the plumbing code. Underground piping is not required for installation and soil is not used to extract heat. However, the GHPWH can still be considered a geothermal water heater because the cold water supply system is provided by buried supply lines which deliver city water to a residence.


For example, the GE Geospring AWHP requires a minimum 700 cubic foot room to assure enough air to provide heat for the water heater.

Groundwater is defined as the incoming water supply into a residential building.

Energy Factor (EF) and Coefficient of Performance (COP) are assumed to be equivalent.
Researchers conducted laboratory and field tests to measure performance and determine whether a GHPWH system would be able to maintain satisfactorily or to recover default hot water temperature after hourly discharges, assuming typical household water usage patterns. Municipal cold water temperature typically ranges from 55° F to 70° F and domestic hot water is generally supplied at approximately 120° F. Researchers determined that the GHPWH concept can extract sufficient heat from cold water supply systems above 57° F. The researchers found adequate recovery of hot tank temperature for a typical household to be feasible where cold water use in volume was at least three times greater than hot water (e.g., 3:1 cold water to hot water ratio). According to the American Water Works Association, the typical ratio of cold to hot water demand is approximately four to one (4:1). Consequently, the available energy in the cold water entering a building through the city water supply system should be more than adequate to meet hot water energy requirements for most residential customers in California.
The research team fabricated and tested four prototypes. One prototype was tested in the laboratory using American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) test procedures/protocols. Researchers built three additional prototypes and installed them in homes located in different California climate zones: Climate Zone 7 (CZ7 - urban), Climate Zone 10 (CZ10 - inland), and Climate Zone 14 (CZ14 - mountainous) in an attempt to validate laboratory test results in a real-world operating environment.

The research team measured the EF/COP of all four prototypes, representing the ratio of useful energy output to the total amount of energy consumed. EE/COP measures the heat supplied divided by electric energy used for the hot water tank and heat pump. Thus more efficient appliances have higher EF/COP ratings. Laboratory test results produced an average EF/COP of 2.1 with a municipal water temperature of 58° F. The average EF/COP for the three test sites ranged from 0.86 to 1.10 with an average of 0.99. The cold to hot water usage ratio ranged from 1.9:1 to 7.25:1. The EF/COP was found to be highest (1.10) in the mountainous area (CZ14), lowest (0.86) in the inland basin (CZ10), and mid-range (1.01) in the urban zone (CZ7). Researchers subsequently made further adjustments on the unit installed in CZ10, improving EF/COP from 0.86 to 1.33. Similar adjustments and results could be expected with the other two prototypes.

Overall system performance, however, was much lower than expected, suggesting that other contributing factors might be in play, such as overnight heat loss or excessive heat pump run time. Nevertheless, initial test results were encouraging as the system exceeded the EF/COP of electric resistance water heaters at all three field test sites. Further product optimization should enable the technology to eventually reach the EF/COP performance target of 4.0. Researchers also noted that the hot water tank temperature decreased by only about 4.5° F during a six-hour test period, which appears to be within acceptable limits.

The research team also decided to calculate and compare the net gas energy factor (EF) of an optimized GHPWH device with other conventional water heating systems. See Table 8. The EF base ratings for electric water heating system options were multiplied by a factor of 0.33 since it takes about three units of gas to deliver one unit of electricity. This provided a more accurate calculation of source energy efficiency. Researchers estimated that the base EE/COP rating for an optimized GHPWH device could be as high as 4.0 since a water-to-water heat pump is inherently more efficient than an air-to-air heat pump.

<table>
<thead>
<tr>
<th></th>
<th>Electric Tank</th>
<th>Gas Tank</th>
<th>AWHP</th>
<th>Gas Tankless</th>
<th>GHPWH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated EF</td>
<td>0.92</td>
<td>0.67</td>
<td>2.50</td>
<td>0.92</td>
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<tr>
<td>Electric to Gas Factor</td>
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<td>1.00</td>
<td>0.33</td>
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<tr>
<td>Net Gas EF</td>
<td>0.31</td>
<td>0.67</td>
<td>0.83</td>
<td>0.92</td>
<td>1.32</td>
</tr>
</tbody>
</table>

Table 8: Comparison of Net Gas Energy Factor for Residential Water Heating Systems
The net gas EF (Table 8) of a fully optimized GHPWH (EF=1.32) could be about four times higher than an electric resistance tank water heater (EF=0.31) and about twice as high as a natural gas tank water heater (EF=0.67). The natural gas tank water heater is the most popular system installed in California. Further development is needed to improve performance, however, including refinement of software and hardware controls, use of variable speed pumps and more efficient heat exchangers. A more granular logging method for field testing is needed to reveal sources of inefficiency and to allow continuous monitoring of system performance. Incorporating a more intelligent control with an adjustable timer would enable regulation of temperature during system operation, such as lowering nighttime set points. The unit needs to be product engineered into a single unit incorporating both the cold and hot water tanks along with heat pump components.

Although the product could be used as an alternative to gas or electric hot water systems, the near term market is replacement of electric resistance water heaters. Adoption of GHPWH would enable consumers to reduce energy/electricity costs for water heating. Certain consumers may also be attracted to the feature of having refreshingly cooler water, especially in warmer climates. If the researchers can improve the net gas EF further, this technology could replace the common natural gas tank water heater.

The addressable market for GHPWH covers over 80 percent of all California households, the bulk of which are located along the California coast and most of the inland areas of southern California. The research team believed that a total installed cost target of $2,500 for the product is achievable as the cold and hot water tanks cost approximately $350 each and the heat pump water heater is about $1,200. The wholesale cost of the product, including controls, should cost less than $1,500 in relatively small volumes with installation under $1,000.

2.18.3G Objectives

The primary goal for this work was to determine the performance and feasibility of a GHPWH system that captures available heat from municipal groundwater and uses it to produce domestic hot water. The researchers established the following project objectives:

1. Deliver heat pump, tanks, pumps, and all required fittings to UCSD labs within the $5,700 budget requested for each unit.
2. Design typical daily cold water usage patterns for residential households using ASHRAE or DOE accepted standards.
3. Build and program a controller for heat pump and circulators with standard hardware, using University of California San Diego (UCSD) personnel.
4. Demonstrate that the EF/COP of the GHPWH device ranges between 4.0 and 6.0 at a three to one (3:1) cold-to-hot ratio in a temperate climate.
5. Chart the EF/COP for municipal water supply temperatures in California ranging from 57° F to 72° F. EF should average above 4.0.
6. Optimize cold tank and heat pump size for home testing.
7. Secure all necessary permits and assure compliance with all applicable codes.

8. Demonstrate reliable system performance for two months.

9. Confirm that the system EF was at least 4.0 and could reach as high as 25.0 if integrated with a solar thermal system. Validate that the total cost of a manufactured product could be less than $2,500, including the water heater (gas or electric) and installation.

2.18.4G Outcomes
1. The cost of each prototype was about $3,000, well under the proposed budget of $5,700.

2. The research team successfully designed and matched cold water patterns.

3. UCSD personnel successfully built a temperature-based controller which functioned as intended. Lack of time controls resulted in diminished system efficiency.

4. Test results indicated that an EF/COP of 4.0 could be reached with a temperature difference of zero. However, measured EF/COP for a more typical temperature difference of 45°F (120°F hot water tank minus 75°F cold water tank) in the laboratory was about 2.4. Laboratory testing based on ASHRAE standards produced an average EE/COP of about 2.1.

5. EF/COP laboratory test results designed to simulate various southern California water temperature conditions ranged from 2.4 to 3.0.

6. Both the 20 gallon cold tank and 50 gallon hot tank performed as expected in the lab and subsequently were used in field tests.

7. Licensed plumbers installed the prototypes for field testing and discovered that the permitting process was unique (given the two tank system) but manageable.

8. The first system was run trouble-free for five months. The other two systems required repairs but operated for at least two months.

9. Field performance was lower than expected. Total cost of a manufactured product should be less than $2,500, including the water heater (gas or electric) and installation.

2.18.5G Conclusions
1. Prototypes cost almost 50 percent less than originally expected.

2. Cold-to-hot water use varies widely in practice but is not expected to be a major issue in most cases.

3. The controller must be programmed to consider time and temperature to improve efficiency/performance.

4. The target EF/COP of 4.0 and 6.0 could not be reached during this phase of development. However initial laboratory results were promising given that the system
has yet to be optimized. Field tests indicated that there could be some unforeseen obstacles at customer sites that were not evident in the lab tests.

5. EF/COP figures across a wide range of temperatures were below targets but comparable to the most efficient AWHP products.

6. Selected cold and hot water tank sizes appear to have worked well.

7. The researchers encountered no major permitting issues, a sign that this technology does not require unique code challenges and related unforeseen costs.

8. The prototype systems demonstrated steady, consistent performance and operation. Installation costs could be higher (at least initially) because installers will not be familiar with this new product and may need specialized training.

9. Additional development and testing will be needed to identify and resolve issues impacting efficiency/performance. The research team appeared confident that manufacturing cost estimates were reasonable.

Based on test results, the researchers believed that most households using a GHPWH device would not run out of hot water if the cold to hot water use ratio were at least three to one (3:1). During a six hour cycle the hot water temperature decreased by about 4.5°F. The researchers concluded this was an acceptable drop. Test results produced a lower EF/COP than projected. Other contributing factors in the field, such as overnight heat loss and the potential for excessive run time, were not evident in the laboratory. Nevertheless the design system exceeded normal EF of electric water heaters at all three test sites and compared well to the most efficient AWHP products. Researchers were also able to make further adjustments and improve efficiency/performance to the prototype installed in the CZ10 climate zone. Additional development is expected to further improve performance. The total cost of a manufactured product should be less than $2,500, including the water heater (gas or electric) and installation.

The laboratory EF tests did not include the standby portion of the test procedure. What was measured was effectively the recovery efficiency and not the EF. This also explains the lower efficiency observed in the field compared to that observed during laboratory testing. The corrections to the outlet water temperatures in the field data should not be necessary. A better comparison would have been with the measured efficiency of the resistance water heaters in the field study houses prior to installing the GHPWH.

The researchers proved feasibility of the concept.

2.18.6G Recommendations
A more granular logging method for field testing is needed to reveal sources of inefficiency and allow continuous monitoring of system performance. Incorporating a more intelligent control with an adjustable timer would enable regulation of temperature during system operation, such as lowering nighttime set points. The researchers should engineer this technology into a single unit incorporating both the cold and hot water tanks along with heat pump components. It may also be possible to develop a triple hybrid model that extracts heat from cold water and/or
surrounding air as it is available with an electric element for backup if needed. Additional recommendations are:

- Eliminate two 50 W hot water pumps by using the wrap-around heat exchanger design used in the more efficient AWHP units containing the refrigerant on the hot side, resulting in up to 20 percent in energy savings.
- Replace the cold water tank and water pump with a three-way heat exchanger that combines air fins, a refrigerant tube, a cold water tube, and a fan.
- Revise the control logic to permit extraction of heat from the cold water whenever it is drawn into the home, regardless of the hot water demand at the time. Use the fan to allow heat extraction from air if cold water flow is insufficient.
- Include a variable-speed drive on the compressor pump to allow it to extract maximum heat from flow rates ranging from 0.5 to 3.0 gallons per minute (GPM).
- Test 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.

2.18.7G 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. Each of the three GHPWH prototypes saved about 30 kilowatt hours (kWh) per month compared to electric resistance water heaters over nine cumulative months in operation. According to ACEEE, efficiency improvements to water heaters have the potential of reducing national energy demand by over 2.25 quads with heat pump water heaters offering the best savings of all of the options studied. Specifically, ACEEE states that energy savings vary greatly across the suite of measures, from greater than 300 trillion British thermal units (Btu) for
ENERGY STAR heat pump water heaters to under 20 Btu for condensing tankless and non-condensing hybrid water heaters.

The ultimate goal is to optimize the GHPWH device to achieve an EE/COP rating of at least 4.0. Even an EF/COP rating of 3.0 would represent a 20 percent improvement (60 Btu/year savings) over the best AWHP product on the market with simpler installation requirements.

2.18.8G 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 not conducted a market analysis or customer survey. They have talked with at least one manufacturer. A.O. Smith has expressed some interest pending the results of further research and testing. Note that this product is not suitable for homes in relatively cold climate zones.

Engineering/Technical

Researchers plan to continue the development of this concept. They estimate the work will require two to three years and about $0.5 million.

Legal/Contractual

A patent law firm performed an in-depth patent search in support of an expedited examination by the U.S. Patent Office. UCSD-CONNECT participated in the vetting process. Researchers obtained a single patent (U.S. Patent 7,827,814 in November 2010) regarding the general concept of heating domestic hot water by extracting sensible heat from domestic cold water.

Environmental, Safety, Risk Assessments/ Quality Plans

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

Production Readiness/Commercialization

The concept is not yet sufficiently developed for commercialization. Additional product optimization and field testing are needed to validate the performance and reliability of the technology in a real-world working environment. A more rigorous cost analysis and business/marketing plan will help verify the market potential for this product and ensure that it compares favorably with other devices in the market.

2.19G Carbon Aerogel as an Adsorbent for Natural Gas Vehicles

Awardee: American Aerogel Corporation
Principal Investigator: Robert Mendenhall
2.19.1G Abstract

Researchers in this project modified a commercial carbon aerogel for use as a natural gas adsorbent for vehicle application. The goal of the project was to determine the feasibility of using a carbon aerogel material to increase the adsorptive properties of natural gas storage vehicle systems beyond the Department of Energy’s (DOE) target of 180 volume/volume at 35 bar (507 psi) while remaining at a commercially viable cost of $5 per pound.

The researchers modified the production process of existing carbon aerogel to increase surface area and reduce pore sizes to improve natural gas adsorption. Altering the formulation and process conditions, such as pyrolysis temperatures and activation, enabled the researchers to double the carbon aerogel surface area and manipulate its pore size, thereby enabling it to adsorb and desorb methane. They achieved volumetric capacity of 69 volume/volume ratios. This is in line with current commercially available carbon-based methane adsorbents in industrial applications. The results did not meet requirements for vehicular applications nor DOE goals.

Keywords: Adsorbed natural gas, adsorption, desorption, aerogel, carbon, carbon aerogel, natural gas vehicle

2.19.2G Introduction

Natural gas is an abundant and clean burning fuel with large and expanding reserves in the United States. Natural gas is cheaper than gasoline. In July 2013 it cost the equivalent of about $2.10 per gallon of gasoline. It burns cleaner than gasoline, with fewer criteria pollutants and carbon emissions. A switch to natural gas would reduce reliance on oil. Achieving the targets of California’s Global Warming Solutions Act (AB32) and its component part the Low Carbon Fuel Standard (LCFS) will require greater substitution of low carbon fuels like natural gas for traditional fuels. As a major contributor to California’s emissions of carbon dioxide, the transportation sector needs the technological capability to substitute larger amounts of natural gas for petroleum-based fuels. As a direct replacement for petroleum fuels, natural gas can reduce carbon dioxide emissions by 25 percent.

Natural gas fueled passenger vehicles have been extremely slow to catch on. In 2012, out of 14.5 million new cars and trucks sold in the United States, just 20,381 were natural gas fueled. By comparison, automakers sold over 50,000 plug-in electric cars. In addition to initial first cost, range is an obstacle for many potential buyers of natural gas vehicles. Since compressed natural gas is less energy dense than gasoline, it requires a bigger fuel tank, leaving less cargo and passenger space and a shorter range of about 220 miles (less than a conventional car but more than a typical electric car). Efforts to increase the energy density of natural gas include super-cooling liquefaction (LNG), higher compression ratio compressed natural gas (CNG), and

89 http://www.washingtonpost.com/blogs/wonkblog/wp/2013/05/02/natural-gas-vehicles-havent-caught-on-yet-heres-how-that-could-change/
adsorbent based systems (ANG). Compression and liquefaction require expensive, high energy demand equipment for fueling. They require thick, bulky storage equipment to handle the pressure (CNG) or cryogenic temperatures (LNG). High pressure tanks are impractical for passenger vehicles due to space and safety constraints. Adsorbed natural gas tanks can address these issues:

1. Adsorbent systems require less pressure and therefore less expensive fueling equipment. Due to the much lower compression level, low pressure ANG tanks providing cost performance characteristics similar to CNG can cut 1/2 to 1/3 from refueling infrastructure and operation costs.

2. Adsorption makes non-cylindrical storage tanks possible. As a result of the lower pressures, tanks can fit odd spaces, similar to today’s petroleum tanks. This allows passenger vehicles to incorporate natural gas tanks into their design without losing space or other design considerations.

3. Adsorbed natural gas is capable of providing the same range as CNG with only a fraction of the pressure. Compressing natural gas to 208 V/V requires 3600 psi. Petroleum has an energy density four times that of the DOE adsorption target, but because of price and environmental and resource accessibility issues, adsorbed natural gas could become highly competitive with traditional petroleum passenger vehicles.

The research team proposed to create and test various reformulations of their commercial version of carbon aerogel with the goal of optimizing its volumetric capacity for natural gas storage with a target of 180 V/V to meet vehicle usage needs. Formulations focused on known properties of efficient adsorbent materials: surface area, density, and porosity. The researchers chose carbon-based aerogels because activated carbon is commonly used in natural gas/methane adsorption/desorption and is the basis of their commercial aerogel.

2.19.3G Objectives

The goal of this project was to determine the feasibility of using a carbon aerogel material to increase the adsorptive properties of natural gas storage systems beyond the Department of Energy’s target of 180 volume/volume at a pressure of 35 bar (507 psi) while remaining at a commercially viable material cost of $5 per pound. The researchers established the following objectives:

1. Demonstrate that the test system is capable of measuring v/v and internal pressure with an error of +/- 5 percent.

2. Measure baseline natural gas adsorption capabilities using current aerogel formulation with porosities greater than 1—5 nanometers (nm).

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90 Aerogel is a synthetic porous ultralight material derived from a gel in which the liquid component of the gel is replaced with a gas. The result is a solid with extremely low density and low thermal conductivity. The first aerogels were from silica, with later development of aerogels based on alumina, chromia tin dioxide, and carbon.
3. Measure porosities between 1—5 nm while maximizing surface area.

4. Demonstrate that the material will meet or exceed the Department of Energy target: 180 V/V at 35 bar (507 psi).

5. Confirm that the material production cost is commercially viable at $5/lb.

2.19.4G Outcomes

1. The researchers designed and calibrated testing apparatus and documented an error range of +/- 15 percent.

2. The researchers verified that natural gas adsorption/desorption amounts were negligible for unmodified aerogel material.

3. The researchers modified samples of their proprietary aerogel, varying resin ratios, pyrolysis time and temperature, chemical activation (e.g., with potassium hydroxide), and other processes. They received physical testing results from Kodak Corp. that showed wide variation in pore sizes and surface area. The researchers found that high resin to catalyst ratios achieved the smaller than five nanometers (<5 nm) pore size target and that pyrolysis temperature and other process changes increased the surface area to 957 m²/g. Compressing the aerogel provided additional improvements in gross pore size and surface area.

4. The researchers tested aerogels modified under different regimens and measured the highest volumetric adsorption/desorption capacity at 69 V/V. Figure 41 shows the capacity of various materials including DARCO⁹¹ (used as a baseline standard) and a commercial industry carbon-based adsorption material for comparison.

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⁹¹ DARCO is an acid washed, granular activated carbon with an advertised approximate surface area of 600 m²/g and 12—20 mesh size.
5. The researchers did not estimate manufacturing cost, having determined that the capacity for the best of the modified aerogels failed to achieve, by a factor of two and one half, the target of 180 V/V.

2.19.5G Conclusions

1. The test apparatus was capable of measuring adsorption/desorption capacity with an accuracy of +/- 15 percent. This result did not meet the objective.

2. Unmodified carbon aerogel had effectively zero adsorption/desorption capacity. The researchers completed this objective.

3. Pore sizes less than approximately five nanometers and greater than 950 square meters per gram surface area were achieved. The researchers met this objective.

4. Under certain treatments and activation with potassium hydroxide, carbon aerogel can achieve an approximate 70 V/V adsorption/desorption capacity at 35 bar, in line with commercial adsorbents. The researchers did not achieve established performance levels.

5. The researchers did not estimate manufacturing cost because they did not meet the storage goal. They did not meet this objective.

The researchers did not demonstrate the commercial feasibility of the concept for vehicle application. They have demonstrated the technical feasibility of achieving meaningful volumetric capacity through treatment of aerogels and achieved capacity comparable to current commercial products in other applications.
2.19.6G Recommendations
The Program Administrator recommends the following actions:

1. Complete an assessment of maximum adsorb/desorb rate and compare this to vehicle needs. With nano-sized porosity, the migration of methane within the aerogel may be slow.

2. Evaluate and test the potential for cracking or other mechanical breakdown of the aerogel under vibration and other mechanical stress and the impact on volumetric storage capacity for a given volume.

3. Continue to increase bulk density and pore space to increase volumetric capacity while commercializing the current aerogel in applications with less demanding requirements, such as welding canisters. This may include fuel gasses other than methane, such as acetylene.

4. Document the cost of production of current 69 V/V aerogel and provide approximate cost to produce advanced aerogels with increased volumetric capacity.

5. Consider using other activation agents beyond potassium hydroxide.

6. Determine if there is any degradation of volumetric capacity after multiple adsorb/desorb cycles.

7. Investigate and document the resistance to fire of charged (i.e., with stored natural gas) aerogel and the necessity for special fire suppression techniques. Determine the potential for extremely rapid decomposition of the aerogel under fire conditions.

2.19.7G 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. Secondary benefit is reduced environmental impact of the California energy supply and distribution system.

Achieving the low carbon fuel standard has been estimated by numerous market economists as potentially increasing the cost of transportation fuels in California by 15 percent to over 30 percent. Substituting natural gas for petroleum-derived fuels or biofuels with low carbon
intensity could provide consumers with lower cost fuel while simultaneously lowering carbon emissions by 25 percent. Other consumer benefits of natural gas fueling include:

- More stable fuel prices relative to gasoline due to less dependency on foreign oil since most natural gas is domestically produced with a vastly expanded resource base through hydraulic fracturing.
- Decreased ground level ozone from lower emissions of carbon monoxide, volatile organic compounds, and nitrous oxide emissions.

Quantifying the public benefits before demonstration of commercial feasibility in vehicle use would be highly speculative.

2.19.8G 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 will focus commercialization activities on the market for ANG canisters rather than ANG vehicles. The project team has produced a first generation material that is comparable to commercial carbons in non-vehicle application. The viable market now is for ANG canisters for welding and other industrial supplies. The research team has identified a potential customer. It will continue materials development.

Engineering/Technical

The research team plans to determine engineering and technical requirements after development of an aerogel with adequate volumetric capacity for the vehicle market. They have requested requirements from commercial vendors for other less demanding and more current applications.

Legal/Contractual

There are no patentable developments from this EISG work, but the base aerogel (Aerocore) is a patented commercial product.

Environmental, Safety, Risk Assessments/Quality Plans

There are no known environmental risks, but there are potential safety risks associated with volumes of natural gas stored in vessels that may rupture with associated breakage of delicate aerogel. The aerogel would be less prone to breakage if powdered and compressed as suggested by the research team. Given the flammable carbon base of the aerogel combined with flammable natural gas, rupture or leakage may pose special concerns in vehicles.
Production Readiness/Commercialization

The product is not ready for commercialization in the vehicle market. It may be ready for commercialization in other applications such as natural gas and other fuel gas canisters.

2.20TNG Application of Novelty Spark Plug in Compressed Natural Gas Engines

Awardee: Multispark, LLC
Principal Investigators: Scott Applebaum

2.20.1TNG Abstract
This project assessed the feasibility of using a novelty spark plug design in a natural gas fueled bus in relation to four main criteria: fuel economy, horsepower, torque, and emissions. The bus engine was the heavy duty Cummings ISL-G 250. The research team designed and built a replacement spark plug and conducted tests using a city bus mounted to a chassis dynamometer. They also measured fuel economy and endurance in a month long operational test on standard city bus routes.

The researchers demonstrated that there were emissions reductions and horsepower and torque improvements using the novelty spark plug versus the original equipment Cummins spark plug. The team recorded acceleration times at 2.1 seconds or 5.8 percent improvement over the Cummins spark plug and measured torque numbers demonstrating an improvement of 5.9 percent.

The researchers found that average emissions data shown in the Central Business District test comparison reflected a 26.44 percent reduction in total hydrocarbons, a 9.92 percent reduction in carbon monoxide, a 16.58 percent reduction in particulate matter, a 23.81 percent reduction in methane, and an increase of 16.67 percent in oxides of nitrogen. Carbon dioxide emissions were 2 percent higher for the novelty spark plug. The increase in oxides of nitrogen was the only area where project objectives were not achieved. The research team recommended testing that would allow modifications to the factory engine control module to change the air to fuel ratio to optimize the lowering of oxides of nitrogen and carbon dioxide emissions at the expense of hydrocarbon and carbon monoxide emissions.

The month-long operational test showed a savings of 5.4 percent in fuel use with the same bus over the previous year’s equivalent time period data.

Keywords: Compressed natural gas engine, spark plugs, torque, horsepower, carbon monoxide, hydrocarbon, non-methane hydrocarbons, oxides of nitrogen, carbon dioxide, particulate matter, total hydrocarbons

2.20.2TNG Introduction
Compressed natural gas (CNG) continues to prove itself as a viable transportation fuel, particularly in heavy duty vehicle applications. It is growing in use in light duty vehicles as well. This both displaces petroleum and decreases emissions attributable to transportation in
California's air basins. However an engine powered by CNG has less horsepower and torque than diesel engines and does not produce the same mileage. Improvements in these areas, while continuing to lower emissions, are of a crucial value in California.

The research team evaluated the merits of a specialized PowerSTAR® spark plug for use in compressed natural gas (CNG) engines. The public benefits of the wide use of this novelty spark plug in metro transit buses in California would be an improvement by about 5 percent in mileage and a lowering in hydrocarbon (HC), carbon monoxide (CO), and particulate matter (PM) emissions. In California most urban transit buses run on CNG fuel. The bus fleets in Los Angeles, San Francisco, San Diego, San Bernardino, Riverside, and Orange counties, as well as University of California schools, all run on CNG. There are 2221 CNG buses in LA Metro alone that travel 60,000 miles a year on average. At 3.13 miles per gallon, the cost to fuel this fleet at $3 per gallon is about $128 M per year. The use of the novelty spark plug could potentially save LA Metro $6.8 M per year in fuel costs. The cost of the novelty spark plug is in line with the current original equipment manufacturers (OEM) spark plugs, so the savings realized in fuel economy would be direct savings. The lowering of harmful emissions in urban transit buses would lower health risks and environmental damage in urban regions throughout California.

To test a novelty spark plug for CNG vehicles, the research team designed, built, and tested two new novelty spark plugs against the original equipment manufacturer’s part. The IR-3 was the Cummins spark plug specified for the engine. It is also the only replacement spark plug and the spark plug used to certify their 2010 CARB emissions compliance. The novelty designs were based on the company’s previous experience in developing spark plugs for the motorcycle and automotive markets. This was the company’s first spark plug design developed for larger heavy duty engines and the first for natural gas fuels. See Figure 42.

**Figure 42: Comparison of PowerSTAR and Standard Sparking**

| PowerSTAR | Standard Sparking |
The researchers designed and manufactured two versions of the PowerSTAR design (STAR) to fit the novelty ZS2 sub-assembly spark plug. The first design was an eight pointed STAR similar to the STAR developed for motorcycles. A second design was based on a double pointed pentagon STAR pattern. When assembled, the researchers identified the two design types as ZS2-3 and ZS2-3D. The 3 specifies the approximate gap in mm. The D is for the double tip design. The two STAR designs are shown below in Figure 43.

Figure 43: Five Double Pointed STAR and Eight Pointed STAR Electrode

2.20.3TNG Objectives

The goal of this project was to determine the feasibility of using a novel spark plug design in a natural gas vehicle powered by the Cummins ISL-G 250 compressed natural gas fueled engine and to establish the performance, fuel economy, and emissions reduction merits of the new design(s). The ISL-G is the only heavy duty compressed natural gas fueled engine that is 2010 California Air Resource Board certified. It is used by transit buses, school buses, and municipal trucks in California and throughout the United States.

The researchers established the following project objectives:

1. Develop the proper heat range for a compressed natural gas novelty spark plug that is similar to the original equipment spark plug by measuring the electrode.

2. Demonstrate that the existing STAR design will last longer than a single nickel electrode by at least 20 percent.

3. Confirm that the contracted manufacturer’s base plug meets the design specifications.

4. Confirm that the quality of prototype STAR is within design specification tolerances.

5. Evaluate the quality of the prototype built by verifying that the gaps (0.015”) are within tolerance and that all points spark on the test equipment.

6. Demonstrate the sparking of the STAR points by showing that all the points produce a spark and spark consistently in open air and in a pressure chamber pressurized to 20 pounds per square inch.

7. Demonstrate availability of vehicle and test facilities.

8. Demonstrate that the prototype performs well, with no unusual noises coming from the engine. Examine color of spark tip to determine combustion chamber temperature is within 500—700° C range.
9. Compare the torque, horsepower, and air/fuel ratios versus revolutions/minute for both the original equipment spark plug and the novelty plug on a dynamometer.

10. Test hydrocarbon, carbon monoxide, and oxide of nitrogen levels using a Federal Transportation Protocol to determine they are lower than baseline levels. See 12 below.

11. Confirm that fuel economy meets the 5—20 percent improvement range: baseline 2.5—3.5 miles/gallon versus PowerSTAR 2.63—4.20 miles/gallon.

12. Demonstrate that the measured hydrocarbon, carbon monoxide, and oxides of nitrogen levels are lower by at least 5 percent: baseline hydrocarbons 0.13, oxides of nitrogen 0.1, carbon monoxide 1.2 in comparison to novelty hydrocarbon 0.12, oxides of nitrogen 0.095, carbon monoxide 1.14.

13. Confirm that the novelty spark plug in a compressed natural gas engine has similar efficiencies to those in a gasoline fueled engine.

2.20.4TNG Outcomes

1. The proper heat range of the original equipment spark plug was duplicated by measuring the electrode lengths and verified by the novelty spark plugs functioning in the bus engine.

2. New star designs were based on the existing star designs used in gasoline engines. The design was produced with at least 20 percent more measurable surface area.

3. The contracted manufacturer’s sub-assembly met the specifications. The prototypes had to be screened due to the manufacturing variances of the center electrode.

4. The quality of the prototype star met all the specifications and build quality was sufficient for testing.

5. The measured gaps of the prototypes were within the tolerances to allow all the points to spark on the test equipment. Due to the small gap of 0.015” as compared to the larger gaps in gasoline engines of 0.040” and larger, the researchers needed to adjust the gapping tools due to expansion of the shims during the heat of welding process.

6. The prototypes were able to generate sparks in both the still air and 20 pounds per square inch test chamber testers.

7. The research team was successful in finding a test facility and in finding a transit bus company that would loan a bus for testing.

8. When the prototype spark plugs were installed in the bus, the bus produced no unusual noises. In fact the engine ran smoother, as noted by the operator and mechanic. Combustion temperature was not able be verified directly but through the proper functioning of the engine under load.

9. The researchers obtained acceleration profiles, emissions, and fuel economy test results on a specially built Mustang Heavy Duty Dynamometer. Torque numbers increased by
5—10 percent from baseline 730 foot pounds @ 1300 rpm. Overall data from the dynamometer indicated the novelty plugs produced an increase in both horsepower and torque that resulted in decreased acceleration time for the 30 to 60 miles per hour tests.

10. The research team conducted emissions and fuel economy runs using the Central Business District test cycle. See 12 below. All the data objectives were met, except for oxides of nitrogen, where the novelty spark plugs for oxides of nitrogen measured 0.07 for both designs. This number exceeded the objective by 26 percent.

11. For the dynamometer fuel economy tests, the standard deviations overlapped, so they were not statistically different. As a result, the researchers used the fuel miles per gallon numbers developed during the month-long field test. The researchers noted that the June 2010 miles per gallon for bus #1201 showed the average equivalent miles per gallon recorded by Omnitrans to be 3.13 miles per gallon. During the field test trial the team recorded an average of 3.30 miles/gallon for the novelty spark plug. The team saw an improvement of 5.4 percent in fuel economy when the data from the month-long field trial were compared and averaged over the June time period from 2010 and the full month of June 2011 for the same bus. This met the 5—20 percent improvement objective for fuel economy.

12. The researchers compared the average emissions data from the IR-3 with the ZS2-3 novelty plug data. These data showed a 26.44 percent reduction in total hydrocarbons, a 9.92 percent reduction in carbon dioxide, a 16.58 percent reduction in particulate matter, a 23.81 percent reduction in methane, a 16.67 percent increase in non-methane hydrocarbons, and an increase in of 16.67 percent in oxides of nitrogen. It should be noted that the non-methane hydrocarbons component of hydrocarbons was less than 7 percent of the total hydrocarbons emissions. The carbon dioxide emissions were 2 percent higher for the ZS2-3 spark plug. This might have been because of the increase in intake temperature and the air/fuel curves programmed into the engine control module. The objectives were not met for oxides of nitrogen where the novelty spark plugs oxides of nitrogen measured 0.07 for both designs. This number exceeded the objective by 26 percent.

13. When the research team compared the compressed natural gas engine data with the efficiencies seen in gasoline engines tests, it found similar results. Emissions were reduced by 20 to 30 percent. Improvements in performance, torque, and horsepower were in the 5 percent to 10 percent range. Fuel economy test results from the field tests showed similar savings. Gasoline engines showed savings of 5—20 percent, and the compressed natural gas fueled bus running the novelty spark plug showed a saving of 5.4 percent in miles per gallon for the month-long test.
2.20.5TNG Conclusions
The researchers proved the feasibility of the novelty spark plug in a natural gas engine.

1. The research team concluded that the novelty PowerSTAR (STAR) spark plug was similar to the original equipment spark plug by measuring it.

2. The research team concluded that the novelty spark plug would last longer by showing that the total surface area was 20 percent larger.

3. The research team concluded that contracted manufacturer’s base spark met all the design specifications.

4. The research team concluded that the prototype STARs were within the design specifications.

5. The research team concluded that the novelty spark plug gaps were all within the specified range by measuring them with a feeler gauge.

6. The research team concluded that the prototype spark plugs were functioning by demonstration of the sparking on the open air and pressure chamber testers.

7. The research team demonstrated the availability of a test vehicle.

8. The research team concluded that the novelty spark plugs performed well by installing them in a bus and warming up the engine over a 10 minute period.

9. The research team concluded that using the Urban Test Cycle for measurements was a valid way to compare the differences in torque, horsepower, and air/fuel ratios. Test results included 4.0—6.0 percent higher horsepower and 5.0—6.5 percent higher torque.

10. Based on the test results, the research team found that the total hydrocarbons and carbon monoxide levels were reduced, with the only change being the spark plug. The researchers also observed an improvement in acceleration performance over the Cummins IR-3 original equipment manufactured spark plug. The engine ran more efficiently even with the air/fuel ratio running toward the leaner end of the exhaust air/fuel ratio curves. Additionally, the team concluded that with the oxides of nitrogen levels slightly higher, it was likely that the combustion temperature was increased due to the lean condition, a desired outcome in a compressed natural gas fueled engine. Furthermore, when the researchers used a three-way catalytic converter, decreases in carbon monoxide tended to increase oxides of nitrogen emissions. The three-way catalyst may have affected some results.

11. From the results of the month-long field test, the research team concluded that the novelty spark plug showed miles per gallon improvement of 5—20 percent.
12. The research team concluded that the novelty spark plug lowered emission levels by at least 5 percent. Summary of the emission findings were:

- 26.4 percent lower total hydrocarbons
- 10 percent lower carbon monoxide
- 16 percent lower particulate matter
- 24 percent lower methane
- percent lower ammonia
- Oxides of nitrogen, carbon dioxide, and non-methane hydrocarbons were not statistically different at this air/fuel ratio

13. The research team was able to verify similar test results to those found in other tests using gasoline fueled engines. In a gasoline engine, the research team found some PowerSTAR spark plugs lowered oxides of nitrogen up to 5.0 percent and reduced carbon monoxide and hydrocarbons at the same time. In the compressed natural gas fueled engine, oxides of nitrogen remained essentially the same, while carbon monoxide and hydrocarbons were reduced. If the engine control module program were modified slightly and allowed the stoichiometric air/fuel ratio to move toward a richer air/fuel ratio, the fuel economy numbers from the dynamometer would have shown considerable improvements.

2.20.6TNG Recommendations

Overall the research is promising, and the research team identified a number of recommendations. The most critical of those is the need to address the increase in oxides of nitrogen emissions. If further study and development can show lowered oxides of nitrogen emissions, either alone or in combination of other features, the use of the product will have a greater value in a California application.

The research team recommended further testing on an engine dynamometer to determine whether differences in test results between the STAR designs were the results of heat transfer due to the metal quantity of the STAR or the shape of the STAR itself. This would require running tests with different variations of the designs in an atmosphere-controlled environment. The team also recommended testing at multiple steady state points where none of the variables could change from one spark plug to another.

The research team recommended testing that would allow modifications to the factory engine command module (ECM) to change the air to fuel ratio to optimize the lowering of NOx and CO2 emissions at the expense of HC and CO emissions. These types of modifications are available in the automotive aftermarket to optimize power and fuel economy. The California Air Resources Board certifies these aftermarket chip modifications to the ECM.
The research team recommended that this type of testing should be done in a controlled lab with an engine dynamometer where the intake air temperature as well as other variables can be controlled.

The research team recommended testing in other engines applications such as stationary compressor engines where CNG fuel is used. The United States Environmental Protection Agency recently issued changes to emissions for pipeline compressor engines (EPA Federal Register. June 28, 2011, Vol. 76, No. 124, p. 37954-37978).

The research team recommended a research study to help quantify the savings to California ratepayers in reduced fuel use and lowered emissions.

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.

**2.20.7TNG 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 to reduce environmental impacts from transportation-associated air pollution related to natural gas use in terms of lower hydrocarbon, carbon monoxide, and particulate matter emissions.

The research team found that the novelty spark plug lowered emission levels by at least 5 percent. In particular, the results were:

- 26.4 percent lower total hydrocarbons
- 10 percent lower carbon monoxide
- 16 percent lower particulate matter
- 24 percent lower methane
- percent lower ammonia
The 5.0 percent improvement in miles per gallon that the researchers found in the field trials would also lower emission outputs through a reduction in fuel usage.

In addition to environmental benefits, the product would produce monetary savings through fuel use reductions. For example, there are 2221 CNG buses in LA Metro region that put 60,000 miles a year on average on a transit bus. At 3.13 MPG, the cost to fuel this fleet at $3 per gallon is about $128 M. The use of the novelty spark plug could potentially save LA Metro $6.8 M a year in fuel costs.

2.20.8TNG 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 research team has a commercialization partner commitment from Omnitrans. This transit company has purchased enough spark plugs for 12 buses in its fleet and is field testing them. The product price point is market competitive. The research team indicated that its spark plugs are not priced more than the OEM Cummins IR-3 spark plug. The IR-3 retails for $40; the ZS2-3 retails for $36—$40 depending on the quantity purchased.

Engineering/Technical

Final testing, in particular the use of an engine dynamometer, is the critical next step. A key component of this is to assess oxides of nitrogen emissions. The research team estimated about one more year of testing is needed, at about $200,000. All specifications are in place for product design and production pending final testing.

Legal/Contractual

Three patents had been acquired before the EISG grant. None have been acquired since the grant.

Environmental, Safety, Risk Assessments/Quality Plans

There are plans for additional testing in these areas.

Production Readiness/Commercialization

The research team is working with organizations to address funding for the product. These include organizations such as CONNECT in San Diego. CONNECT is a regional program that catalyzes the creation of innovative technology and life sciences products by linking inventors and entrepreneurs with the resources they need for success.
2.21TNG  Multi-Fuel Supercompound Engine Efficiency Analysis

Awardee:  David Onstenk
Principal Investigators:  David Onstenk

2.21.1TNG  Abstract

The purpose of this project was to investigate the potential use of spark ignition supercharged compound cycle gasoline engines for vehicle, heavy equipment, and distributed generation markets. Supercharged compound (supercompound) engines can achieve very high levels of boost with increased expansion efficiency and reduced exhaust temperatures. This technique has the potential of improving brake efficiency by 72 percent for light duty trucks. If successful, the concept could reduce the use of petroleum fuels and carbon emissions for highway transportation applications by up to 40 percent. Potential energy savings for California consumers could be in the magnitude of billions of dollars per year compared to conventional alternatives. Full development and commercialization costs could be moderate to high. Additional weight and size issues may restrict the use of this concept in vehicles.

The research team developed a proof-of-concept engine using a combination of engine testing and computer simulation techniques to help predict performance potential. It developed a quasi-steady, non-ideal gas, zero dimensional thermodynamic engine simulation program using Excel Visual Basic for Applications. The team first modeled stock and supercompound configurations of a 1.6L BMW engine using GT Power and Excel and then validated the results with stock engine testing. The researchers generated final estimates for supercompound configurations in Excel and analyzed performance based on 25 percent engine load. Initial results were promising. Compared to a stock BMW engine, researchers were able to exceed target performance by more than a factor of two, generating brake efficiency gains from 43 to 71 percent at 25 percent engine loading with two to seven bars of boost.

Additional research is needed to develop this technology further. In the near term the researchers plan to develop and test prototype supercompound cycle two liter Ecotec I4 engines. Piston based supercompound engines (this project) should be compared to turbocompound engines, especially diesel turbocompound engines currently available.

Keywords: Supercharger, compound cycle, hyperbar, natural gas, gasoline engine, ultra-low carbon, energy conversion, load brake efficiency, light truck engine

2.21.2TNG  Introduction

According to the 2010 California Integrated Energy Policy Report,\textsuperscript{92} annual consumption of petroleum fuels in 2030 (including gasoline, diesel, and jet fuel) is forecast to increase by 4 to 11 percent compared to 2007 consumption figures. Although gasoline consumption is expected to gradually decrease over time, sharp increases are expected in the use of diesel and jet fuels which more than offset the decrease in gasoline use. At the current average price of $4.00 per

gallon, petroleum fuel consumption costs for transportation in California are projected to exceed $100 billion per year by 2030. Failure to address continuing reliance on petroleum fuels and escalating fuel costs from growing demand could cause economic hardship and increasing energy security concerns for the United States and California.

Escalating use of petroleum fuels has an adverse impact on the environment due to the release of nitrous oxides (NO\textsubscript{x}) and greenhouse gas (GHG) emissions. NO\textsubscript{x} emissions often react with volatile organic compounds (VOCs) in the presence of sunlight, forming photochemical smog that can cause damage to lung tissue. In 2006 California enacted Assembly Bill (AB) 32, the Global Warming Solutions Act, which required the California Air Resources Board (CARB) “...to adopt a statewide greenhouse gas emissions limit equivalent to the statewide greenhouse gas emissions levels in 1990 to be achieved by 2020.” One of many greenhouse gas reduction measures CARB adopted in accordance with AB 32 was the Low Carbon Fuel Standard (LCFS). The LCFS mandates a reduction of not less than 10 percent in the carbon intensity of California’s transportation fuels by 2020.\textsuperscript{93} One way to achieve this mandate is to accelerate the adoption of alternative fuel vehicles. However alternate fuels are not yet widely distributed, and what is available is costly. Another approach is to improve significantly the efficiency of internal combustion engines and vehicles.

Light truck engines, the subject of this project, are most often diesel cycle engines that operate at a higher efficiency than Otto cycle engines. Current engine architecture (based on Otto, Diesel, Atkinson, and Miller cycles) compresses and expands gas in the same cylinder. Engine efficiency can be improved by increasing the expansion ratio, effectively creating a higher compression ratio. Compression ratios for current diesel cycle engines are limited by emission standards and glow plug life. Otto cycle engines are compression limited by engine knock and spark plug life. Even if that can be mitigated, peak efficiency for the Otto cycle is limited to a mechanical compression ratio of about 16:1 because friction and heat losses grow exponentially with higher compression ratios. Diesel engine manufacturers have experimented with compression ratios as high as 30:1.

The goal of this project was to evaluate the performance of a spark ignited supercharged compound cycle engine using software simulation. The long term goal was to increase engine efficiency significantly, with initial focus on light duty trucks. Researchers claimed they were unable to locate prior documentation on piston compound cycle engines. They surmised this was due to historically low petroleum fuel prices and daunting technical challenges. However steam powered, multi-piston compound engines were first invented in 1781. This technique was first employed on a Cornish beam engine in 1804. Around 1850 compound engines were first introduced into Lancashire, England, textile mills. These engines were also commercially deployed in riverboats and locomotives in the nineteenth century.

In the twentieth century Wright Aeronautical developed the Wright R-3350 turbo compound, an air cooled, double row, 18 cylinder, static radial aircraft engine displacing 3,350 in. This

engine could produce up to 3,700 takeoff horsepower. Cruise fuel consumption could be as low as 0.40 lb/hp/hr. Wright Aeronautical Division, a subsidiary of the Curtiss-Wright Corporation, produced many models of R-3350s between 1940 and 1960. Turbo compounding was used rather than piston compounding to reduce weight and size. The turbine (turbo) was mechanically connected to the crankshaft. These engines were used on the DC-7B and the Super Constellation aircraft. The turbine is referred to as a blowdown turbine (or power recovery turbine) since it recovers the energy developed in the exhaust manifold, essentially expanding the compression ratio.

Some modern heavy truck diesel engine manufacturers have incorporated turbo compounding into their modern designs. Examples include the Detroit Diesel DD15 and a Scania turbo compound engine in production since 2001. By inventing a new type of turbo compounding system, the DD15 engineers found a way to add 50 hp and improve fuel economy by 5 percent. The turbo compound axial power turbine transfers power directly to the piston engine flywheel. The project researchers believe that the supercharged, piston, compound cycle architecture has the potential to completely displace conventional engines and minimize the need for expensive alternative fuel vehicles. The researchers’ compound engines use two or more pistons to expand the high pressure gases from each combustion event, allowing total expansion ratios to be multiplied several times from the base compression ratio. Figure 44 shows a comparative flow diagram. Decoupling of compression and expansion ratios enables a lower compression ratio in the primary cylinders resulting in reduced knock, friction, and heat losses with very high levels of boost. Total expansion is only limited by the maximum engine pressure and the efficiency of the secondary expansion system.

Piston based compounding engine technologies investigated in this project could achieve an expansion ratio as high as 32:1, assuming an 8:1 compression ratio in the combustion cylinders and a 4:1 ratio in the compound cylinders. The researchers calculated thermodynamic cycle efficiency to be as high as 59 percent. The low compression ratio and advanced cycle techniques enable up to seven bars of boost with multistage turbocharging, intercooling, and direct injection based on the use of 91 octane gasoline. At 25 percent engine loading, the researchers projected that this concept engine has the potential to increase cycle efficiency by 13 percent, reduce process losses by up to 4 percent, and increase brake efficiency from 24.2 to 41.6 percent.
The research team developed a concept engine using a combination of engine testing and computer simulation techniques to predict performance potential. It developed a quasi-steady, non-ideal gas, zero dimensional thermodynamic engine simulation program using Excel Visual Basic for Applications. The researchers first modeled stock and supercompound configurations of a 1.6L BMW engine (using GT Power and Excel) and then validated the results with stock engine testing. The team generated final estimates for supercompound configurations in Excel and analyzed them based on 25 percent engine load. Initial results were promising. Compared to a stock BMW engine, researchers were able to exceed target performance by over a factor of two, generating brake efficiency gains from 43 to 71 percent at 25 percent engine loading with two to seven bars of boost.

Optimized supercompound cycle engines have the potential of improving engine efficiency by 60—115 percent compared to current Otto cycle design, depending on the cylinder size, duty cycle, level of technology, charging system efficiency, type of fuel, and the maximum cylinder pressure of the design. For instance, a 2.0 liter I4 two stage turbocharged supercompound cycle gasoline engine could produce up to 477 foot-pounds of torque along with a 72 percent improvement in brake efficiency. This would surpass the best gasoline, diesel, hybrid, or battery electric solutions available today. The new engine design is expected to have significantly shorter payback periods than any of these alternatives.

The research team has planned the next phase of research. Researchers plan to develop and test prototype supercompound cycle two liter Ecotec I4 engines. They selected the GM turbocharged 2.0 liter I4 Ecotec engine platform for the proof-of-concept to minimize cost of building initial prototypes. Nearly all of the hardware needed to produce prototypes is available off-the-shelf from aftermarket suppliers, and the platform is well developed for high pressure racing applications.
2.21.3 TNG Objectives

The goal of this project was to determine the feasibility and potential use of spark ignition supercharged compound cycle piston engines for vehicle, heavy equipment, and distributed generation markets. The researchers established the following project objectives:

1. Establish stock engine efficiency performance by testing, estimated to be 306 grams per kilowatt hour (kWh) at 25 percent engine load (2,500 rpm) and 354 grams per kWh for the nine point mean using 91 octane gasoline.

2. Demonstrate stock engine simulation agreement for efficiency to within plus or minus 5 percent at 25 percent engine load (2,500 rpm) estimated to be at 306 grams per kWh using 91 octane gasoline. This objective was to cross-validate the two simulation models.

3. Demonstrate stock engine simulation accuracy for efficiency to within plus or minus 5 percent of test data at 25 percent engine load (2,500 rpm), estimated at 306 grams per kWh using 91 octane gasoline. This objective was to validate models with test data.

4. Demonstrate supercompound engine simulation agreement for efficiency to within plus or minus 5 percent at 25 percent load (2,500 rpm), estimated at 235 grams per kWh using 91 octane gasoline.

5. Demonstrate thermal efficiency improvement of 30 percent or more above the stock engine configuration at 25 percent engine load (2,500 rpm), equivalent to a 23 percent reduction of brake specific fuel consumption (BSFC), estimated at 235 grams per kWh using 91 octane gasoline.

2.21.4 TNG Outcomes

1. The research exceeded the target of stock engine efficiency performance. Test results were at 342.1 grams per kWh at 25 percent load (2,500 rpm) and 368 grams per kWh for the nine point mean using 91 octane gasoline.

2. Stock efficiency was within plus or minus 5 percent at 25 percent engine load (2,500 rpm): 345.9 grams per kWh with GT Power and 343.1 grams per kWh with VBA (-0.8 percent).

3. VBA and GT Power validations with the BMW stock engine testing data were within +/-0.3 percent and +/-1.1 percent, respectively.

4. The researchers demonstrated simulation agreement for supercompound efficiency to within plus or minus 5 percent at 25 percent load (2,500 rpm): 269 grams per kWh with GT Power, 260 grams per kWh with Excel (-3.5 percent) with an 8:1 compression ratio and three bars of boost in a supercompound configuration.

5. The researchers demonstrated thermal efficiency improvements of 71 percent above the stock engine configuration at 25 percent load (2,500rpm), equivalent to a 42 percent reduction in BSFC, estimated at 198 grams per kWh with 91 octane gasoline.
2.21.5TNG Conclusions

1. The researchers performed engine testing at 21 operating points, providing a well-populated brake efficiency map.

2. VBA program validations with the GT Power program were within plus or minus 0.8 percent, bettering the goal of plus or minus 5 percent.

3. VBA and GT Power validations with the BMW stock engine testing data met this project objective.

4. Despite critical limitations of the GT Power program which produced false excessive heat loss errors in the transfer circuit, validation of the supercompound configuration was within plus or minus 3.5 percent at 25 percent load (2,500 rpm), within the objective precision of plus or minus 5 percent.

5. Final results for 25 percent load (2,500 rpm) brake efficiency gains were 71 percent using gasoline, more than twice the project objective of 30 percent.

Researchers were able to demonstrate the potential feasibility of spark ignited supercharged compound cycle engines using a combination of software modeling techniques and engine test results. The Excel VBA program exceeded the original plans and expectations for precision, function, and flexibility. The final outcome was that both the software tools and the proof-of-concept results were successfully completed to enable further development of these technologies. Testing of a supercompound engine was beyond the scope of this project. All conclusions were based on computer modeling.

The approach taken in this project has the potential to offer another path to high efficiency light and heavy duty vehicle markets. Note that all tests and simulations in this project were conducted with gasoline fuel. If all future truck engines were run on gasoline instead of diesel fuel using the supercompound concept engine, the petroleum refining industry would need to engage in major rework of its facilities. Gasoline prices could escalate.

While the researchers met their goals, they did not describe a practical power plant based on the technology. Any power plant using supercharging, compounding (piston or turbo), intercoolers, multistage turbocharging, hyperbar compression, and advanced electronics has the potential to be costly, difficult to maintain, and perhaps large and heavy. In addition, this project did not include the effects of super compounding on engine emissions. This technology will only move forward with a committed partner currently in the engine business. That partner will need to convert this technology into a viable product.

2.21.6TNG Recommendations

The research team appeared confident that it could obtain additional funding to develop the technology further and build and test engine prototypes. If the team can validate engine performance, the portfolio of intellectual property could then be used to build strategic partnerships with industry stakeholders and attract private capital. As part of the additional test program, the Program Administrator recommends that the research team focus on the
following items:

- Develop a technical development plan. This plan must include steps to meet current and future California vehicle emissions regulations.
- Develop an engineering specification for the potential engine in each application.
- Develop a possible product configuration for a light truck.
- Develop a possible product configuration for a distributed energy application.
- Build and test several prototypes.
- Test in the three to four bar boost range to establish the performance characteristics of the new engine design.
- Retain an independent expert to validate technical results.
- Pursue a strategic partnership with a manufacturing partner who is capable of bringing this technology to market.
- Monitor the results of the U.S. Department of Energy DEER (Diesel Efficiency and Emissions Research) Program.

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.

2.21.7TNG 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 the use of alternative fuels

The primary benefit to the ratepayer from this research is improved transportation energy efficiency. Supercompound engines, if successful, have the potential to improve the efficiency of internal combustion engines for surface transportation, heavy equipment, and distributed generation applications which currently consume petroleum fuels. These new engine concepts could potentially replace existing four stoke gasoline and diesel engines above 50 kW.
The use of supercompound engine solutions could push the estimated average transportation energy conversion efficiency to approximately 55 percent, a 57 percent improvement compared to advanced conventional (Otto cycle) engine packages which could be envisioned over the next few decades. Therefore, highway transportation energy demand and carbon emissions could be reduced by as much as 57 percent. Potential energy savings for California consumers could reach $79 billion per year by 2040.94 The total market potential for these products is 2.5 million engines per year in California by 2040.

The research team acknowledged that the automotive and truck industries are expected to continue making incremental improvements to conventional engine and power train designs over the next few decades. Diesel engines currently available can have efficiencies as high as 40 percent. However supercompound engines could achieve engine efficiencies of 55 percent.

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

The researchers presented their results to engine researchers with close ties to industry across Europe and two engine suppliers and received positive response. They plan to present the technologies to vehicle manufacturers soon. The researchers are monitoring the progress of patents, industry actions, technology adoption rates, fuel prices, competing technologies, taxation, and regulatory changes.

Engineering/Technical

The researchers plan to pursue private and grant funding for development and testing of gasoline supercompound engines. The research team estimates the cost of this initial phase will be in the range of $2 to $5 million. It plans to perform three-dimensional computational fluid dynamics (CFD) and chemical kinetics modeling to gain an understanding of fundamental engine design principles.

Legal/Contractual

The researchers conducted an informal literature search and produced no evidence of potential infringement on existing patents or intellectual property. No new patents have been filed. All technologies are held as trade secrets until the researchers secure adequate funding for foreign filings.

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95 Based on estimated petroleum fuel consumption of 23 billion gallons per year in 2040 (per 2010 California Integrated Energy Policy Report forecast for 2030), $6 per gallon estimated retail price for petroleum fuels and 57 percent energy savings compared to state-of-the-art engines.
The research team will need to ensure that the engine designs meet all industry environmental, emissions, and safety codes; standards; reliability standards; and regulations.

Production Readiness/Commercialization

The concept is not yet sufficiently developed for commercialization.

**2.22TE Bonding of Metal-Plastic Composites for Lightweight, Fuel Efficient Vehicles**

**Awardee:** University of California, Los Angeles

**Principal Investigators:** Robert F. Hicks

**2.22.1TE Abstract**

Replacing steel with steel/carbon fiber reinforced epoxy laminates in the exterior panels of automobiles could improve fuel efficiency of the vehicles through reduced weight. It could also reduce electricity consumption associated with the processing of steel in the vehicle market.

Adhesive bonding of the steel to the carbon fiber reinforced epoxy laminates is preferable to other joining techniques since it yields a continuous bond between the two substrates, minimizes stress, and acts as a buffer between the metal and plastic to absorb impact. However, improper surface preparation prior to bonding can lead to weak adhesive joints which fail at the interface. The goal of this project was to prove the feasibility of using atmospheric pressure plasma for surface preparation of steel for use in carbon fiber epoxy laminates.

The researchers found that activation of the surfaces occurred following exposure to an atmospheric pressure He/O₂ plasma at 200 watts applied power. The water contact angles of 410 steel and carbon fiber reinforced epoxy laminate were reduced from 69.8° and 65.6°, respectively, to a final water contact angle of 24.2° for both substrates. Lap shear results demonstrated a 150 percent increase in bond strength between carbon fiber epoxy laminates and a greater than 80 percent increase between stainless steel test coupons. The 1/16 inch (1.6 mm) thick steel/carbon fiber reinforced epoxy laminates reproduced the damage resistance properties of sheet stainless steel while reducing the panel weight by 64 percent. These panels have a materials cost of $7.14 for the composite compared to $3.39 for steel.

The researchers met the mechanical goals and demonstrated technical feasibility of using plasma activation to improve bonding of laminate layers. They did not show economic feasibility.

**Keywords:** Polymer, composite, steel, epoxy, adhesion, bonding, atmospheric plasma, plasma activation
2.22.2TE Introduction

In 2007 Californians consumed over 19.5 billion gallons of gasoline and diesel.95 This large consumption has associated economic, environmental, and security issues that have long put transportation fuel consumption at or near the top of State energy policy. Numerous programs, including standards, R&D, incentives, land use planning, and the like are aimed at reducing California’s consumption of transportation fuel. One of the long term and promising areas for fuel use reduction is lessening the weight of vehicles through the use of composite and alternative materials.

The use of composite materials to lighten vehicles has been restricted to date largely because of manufacturing cost and structural performance issues. High strength composites tend to have high associated costs, while lower cost composites tend to have low structural strength or suffer delamination resulting from low adhesion between composite components in multi-layer laminates.

In this project researchers developed a new process for bonding a metal layer and a polymer layer to form a laminate combining steel and composite material. The process uses in-line atmospheric pressure He/O₂ plasma at 200 watts applied power to activate the metal’s physical surface. This facilitates improved adhesive bonding of the second layer made up of polymer and fiber. The results indicated that better wetting of the metal surface by the polymer results in improved adhesion and true bonding of the two layers. Wetting is measured by the water contact angle which is the angle formed by a surface and the side of a bead of water on that surface.

2.22.3TE Objectives

The goal of this project was to determine the feasibility of replacing steel body panels in vehicles with lightweight metal-polymer composites in laminates. The researchers established the following project objectives:

1. Demonstrate reduced water contact angles (WCA) of metal and composite surfaces to below 20°.
2. Show that less than 20° WCA may be achieved at surface scan rates >1.0 cm/s. Demonstrate 100 percent cohesive failure of the bond and a minimum lap shear force for failure of 5000 lbs per in².
3. Demonstrate that metal-plastic composites meet or exceed static and dynamic impact performance equal to sheet steel 1.5 mm thick.
4. Confirm from the project findings that composite materials can achieve the same mechanical performance as sheet steel with a panel weight reduction from 100 lbs to 50 lbs.
5. Confirm from the project findings that metal-polymer composites can be produced at a cost no greater than $15 for a panel of the same size as sheet metal costing $10.

96  http://www.energyalmanac.ca.gov/transportation/summary.html#fuel
2.22.4TE Outcomes

1. The researchers measured the effect of plasma activation on water contact angle of polypropylene (PP), polyetheretherketone (PEEK), and carbon fiber reinforced epoxy (CFRE) surfaces. Table 9 presents the results. Following activation with the He/O₂ plasma, the water contact angles of PP and PEEK were reduced to 18.5° and less than 5°, respectively.

<table>
<thead>
<tr>
<th>Sample</th>
<th>WCA before</th>
<th>WCA after</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>86.6°</td>
<td>&lt;5°</td>
</tr>
<tr>
<td>PEEK</td>
<td>88.3°</td>
<td>18.5°</td>
</tr>
<tr>
<td>CFRE</td>
<td>80.6°</td>
<td>17.7°</td>
</tr>
</tbody>
</table>

The researchers also measured the water contact angle of automobile steel and carbon fiber reinforced epoxy laminate before and after exposure to He/O₂ and He/N₂ plasma to determine the rate of activation. Table 10 shows the water contact angle of steel and the carbon fiber reinforced epoxy laminate before and after plasma treatment as well as the rate of WCA reduction.

<table>
<thead>
<tr>
<th>Material</th>
<th>Plasma</th>
<th>Initial WCA</th>
<th>Final WCA</th>
<th>Rate constant (sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>He/O₂</td>
<td>69.8°</td>
<td>24.2°</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>He/N₂</td>
<td>62.5°</td>
<td>23.8°</td>
<td>0.26</td>
</tr>
<tr>
<td>Carbon-Fiber/Epoxy</td>
<td>He/O₂</td>
<td>65.6°</td>
<td>24.2°</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>He/N₂</td>
<td>79.0°</td>
<td>16.9°</td>
<td>0.76</td>
</tr>
</tbody>
</table>

2. The researchers measured the change in WCA at different scan speeds to determine the effect of exposure on the rate of WCA improvement. The He/O₂ plasma improved the WCA at a rate that was roughly twice that of the He/N₂ plasma. The researchers found that approximately ten seconds of exposure was required to achieve significant WCA reduction, after which no significant reduction occurred.

3. The researchers conducted a series of impact tests on the laminate to determine what thickness of CFRE laminate would reproduce the mechanical properties of sheet steel, using 18 gage sheet steel as control samples. The researchers found that the laminated CFRE
experienced different damage type but not significantly worse damage. The damage area in the CFRE sample was more localized but had fiber fracture, while the sheet steel had continuous deformation over a larger area.

4. The researchers found that the 1/8 inch (3.2 mm) thick laminate duplicated the performance of the sheet steel. The researchers produced composite materials with a weight reduction of 64 percent compared to sheet steel, while still maintaining the impact properties of bulk sheet steel.

5. The researchers compared the material only cost to produce the laminate compared to sheet steel. Table 11 shows these costs.

<table>
<thead>
<tr>
<th>Stainless steel</th>
<th>Cost</th>
<th>1/8&quot; thick panel</th>
<th>Cost</th>
<th>1/16&quot; thick panel</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 gage steel</td>
<td>$3.39</td>
<td>CFRE composite</td>
<td>$14.29</td>
<td>CFRE composite</td>
<td>$7.14</td>
</tr>
</tbody>
</table>

2.22.5TE Conclusions

1. The researchers successfully reduced the water contact angles (WCA) to less than 20° for each of the composites tested. They met this project objective.

2. Examination of the bond surfaces after failure showed a >95 percent cohesive failure of the bond line when the surfaces were activated with 10 scans of He/O₂ plasma. Cohesive failure indicates that the bond at the interface between the adhesive and the substrates is stronger than the adhesive itself. Beyond this, further increases in the bond strength could only be achieved with changes to the adhesive but not through additional surface preparation. The researchers did not meet the objective of achieving the water contact angle reduction with a scan rate of >1.0 cm/s.

3. The composite material experienced less damage than 18 gauge stainless steel when subjected to an impact test. The researchers met this project objective.

4. Composite materials with a weight reduction of 64 percent provided impact properties comparable to bulk sheet steel. The researchers met this project objective.

5. The materials cost to produce the composites was over 200 percent and as much as 420 percent of the cost of sheet steel. The researchers did not meet this project objective.

Overall, the researchers met the mechanical goals and demonstrated technical feasibility of using plasma activation to improve bonding of laminate layers. They did not show economic feasibility. Automobile manufacturers will look at tradeoffs between any new materials and the existing proven materials. General Motors, BMW, and Daimler Benz are planning to use carbon fiber materials for body panels in selected 2013 and 2014 models. The cost of carbon fiber materials, while declining rapidly, is still about 10 times that of steel.
2.22.6TE Recommendations

The Program Administrator recommends an integrated development program to move the concept to commercial readiness and application. Such an integrated program would include the following necessary activities:

- Complete a comprehensive cost analysis that includes labor costs as well as materials costs. This would enable the researchers to undertake a comparative life cycle cost analysis.
- Develop a cost reduction program with a definite goal.
- Compare the cost goal of this material with that of carbon fiber technology which is currently going into limited production.
- Test whether higher applied power plasma (i.e., hotter plasma) would reduce needed exposure time and increase scan rate.
- Begin development of engineering and manufacturing process development leading to automatic production of sheet laminates and automotive component manufacturing.
- Analyze the effects of differential thermal expansion and of flash rusting between the two layers of laminate on the physical performance and durability of the laminate.
- Undertake full scale crash tests or simulations to determine safety related issues such as crushing and splintering of the laminates polymer layer.
- Develop repair techniques for the laminate material. Repair costs after automobile accidents must be equal or lower than those for steel panels.
- Determine if the process is applicable to complex geometry for structural components in addition to flat panels for exterior use.
- Investigate the laminate’s behavior under different manufacturing techniques such as forming, milling, drilling, and cutting.
- Develop a recycling process for end-of-life laminate materials.

The researchers found that formation of carboxylic acid groups were important in the improved adhesion. They should determine whether chemical activation (chemically forming carboxylic acid groups) of the laminate layers would provide similar or better overall performance at lower costs.

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.

**2.22.7TE 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 the use of alternative fuels

The primary benefit to the ratepayer from this research is improved transportation efficiency. An auto industry rule of thumb suggests that every 10 percent reduction in vehicle weight yields a 5 percent improvement in fuel economy. For a midsize car, making doors, hood, and trunk out of the lighter material could save 140 pounds or about 4 percent of vehicle weight. If manufacturers substituted these materials for major parts of the car’s base structure (frame, driveline, suspension supports, etc.), savings could increase to ~470 pounds or 12 percent.96

Using the laminate technology described here could potentially improve vehicle mileage by 2 percent to 6 percent, or from an assumed base of 25 miles per gallon (MPG) to 25.5 or 26.5 MPG. For a typical family, this would save approximately 16 to 46 gallons of gas per year if it travels 20,000 miles. At current gasoline prices of approximately $3.80 per gallon, this would save that family from $60 to $175 in fuel costs or $420 to $1225 over an assumed seven year ownership. In all of California, if 10 percent of the vehicles had such weight-saving technology, an annual reduction of 39 million to 117 million gallons could be achieved. The new materials should not add more cost to the vehicle than the potential fuel savings. Until costs are reduced there will be no benefit to California.

Lighter weight automobile technology also has benefit to the emerging electric vehicle market. Comparable savings or range extension could add impetus to market demand for electric vehicles.

**2.22.8TE 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.

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Marketing/Connection to the Market

Surfx Technologies LLC, Culver City, California, has expressed interest in becoming a commercial partner to finish developing this technology. Commercialization will likely occur first in the aerospace industry. The plasma preparation process will find applications in this market earlier than the automotive market due to the higher value added for aerospace parts. Commercialization in the automobile industry would occur later as the cost of composite materials became competitive with sheet steel.

Engineering/Technical

The researchers plan to develop engineering requirements specifications.

Legal/Contractual

The researchers plan to apply for a patent. They have not disclosed results of their research in any paper or publicly disclosed the concept.

Environmental, Safety, Risk Assessments/Quality Plans

The most critical environmental and safety risk with full-scale application of the composite sheets in actual vehicles is from collision impact. The significance of this issue can only be determined after the crash tests noted above are completed.

Production Readiness/Commercialization

The process is not yet ready for commercial application.

2.23TE Smart Photovoltaic PHEV/EV Charging System Using Second-Life Lithium Batteries

Awardee: University of California, Davis
Principal Investigators: Jae Wan Park

2.23.1TE Abstract

Current plug-in hybrid vehicles and fully electric vehicles utilize lithium ion batteries. These batteries have a finite lifetime for use in the vehicle before range is compromised. At that point the batteries must be replaced even though they continue to perform, albeit at a lower level. This project proposed using the partially spent lithium ion battery packs, charged by solar energy, to function in a stationary charging system for plug-in electric vehicles. The researchers suggested a 2.2 kW photovoltaic array and a nominal 17.2 kWh second-life battery pack would be sufficient to support the energy requirement of a full-size electric vehicle with a driving range of 40 miles. The researchers demonstrated the operation of a charging system, but not without key technical shortcomings and analytical flaws. Some shortcomings were attributable to project duration: the one year time frame was insufficient to address optimization of system parameters and long term storage data of second-life lithium batteries. The research therefore failed to address sufficiently the influence of lifetime degradation of the second-life battery and
the resultant impact for commercialization of the system. The project did not address electrical grid interface issues and substantially underestimated the system costs versus benefits.

**Keywords:** Solar photovoltaic energy, plug-in electric vehicles, secondary use/second-life lithium ion battery

### 2.23.2TE Introduction

Many people regard plug-in hybrid electric vehicles (PHEV) as a promising technology because they consume less gasoline than conventional cars. However California’s current mix of electricity generation contains carbon based fuels such as natural gas (42 percent in 2010) and out-of-state coal (7 percent in 2010). In contrast, solar power is a favored energy source because it can be converted to electricity with almost zero net greenhouse gas (GHG) emissions.

PHEV lithium ion batteries have a limited life in a vehicle before performance degrades due to diminished storage capacity. However the degraded battery still has a significant level of performance useful for other duties. As a second-life battery it could be used for non-traction applications. A second-life battery as an energy storage device, powered by renewable solar energy, could be used to deliver approximately 3,000 kWh per year. This is sufficient to drive a full-size PHEV up to 12,500 miles per year. That could eliminate the need for 450 gallons of gasoline per vehicle (assuming the current CAFE standard of 27.5 mpg gasoline fuel economy), save $1,680 in fuel cost, and save about 4,000 kg of CO₂ emissions. The strongest public benefit to California would be the reduction of tailpipe emissions from light duty vehicles. Other benefits include the advancement of renewable energy and innovation in the transportation sector.

The objective of this project was to develop and test a charging system for PHEVs and other electric drive vehicles using second-life batteries recharged with solar PV panels. The researchers proposed using a residential PV system (2.2 kW, fixed mount, tilted south equal to local latitude) with 12 kWh energy storage to generate, store, and deliver approximately 3,000 kWh energy to a load per year. Previous research in this field has proven the concept of using solar power to support vehicles to be technically feasible. The development of a vehicle charging station represents a new, innovative application of renewable energy for the transportation sector. The system demonstrated in this research is different than the state-of-the-art electric vehicle charging methods. Residential charging of electric vehicles is most often accomplished by drawing energy from the electric grid. A scenario with thousands of PHEVs plugging into the grid on a daily basis creates a challenge for power generators in that they must have the capacity to support the as yet unpredictable energy demand of an electric vehicle fleet. There is currently no large scale commercial product that allows electric vehicle drivers to charge their vehicles using only renewable energy. The results of this research could lead to innovative incorporation of renewable energy into the transportation sector, cost savings for California electric vehicle drivers, and reduced strain on the electric grid.
2.23.3TE Objectives

The goal of this project was to prove the feasibility of a battery charging station for electric drive vehicles that is powered by solar photovoltaic panels and supported by high power lithium traction batteries. The researchers established the following project objectives:

1. Develop a PV array that can generate 1.5 kW at peak daily irradiance. The research team sized the photovoltaic array based on the desired energy storage capacity (10 kWh) and footprint (15 m²).

2. Provide 12 kWh energy storage capacity. The research team designed the energy storage system (second-life lithium ion battery) with margin to account for capacity fade and imbalance of the batteries and efficiency losses in the discharge path.

3. Store 10 kWh per day in the storage system from the PV array with 96 percent efficiency.

4. Achieve 10 kWh charge/discharge per cycle for 1,200 cycles. The research team selected a target of 1,200 cycles because it represents approximately four years of operation (6 cycles per week, 50 weeks per year). Four years of additional use of a traction battery signifies approximately a 50 percent extension of the OEM warranty.

5. Allow no charging using grid electricity (0 kWh) except during off peak hours. The research team wanted to limit the additional load on the electrical grid created by the PHEV/EV in this study with an emphasis on avoiding the grid during peak hours, which are typically times when solar radiation is available.

6. Generate and store 10 kWh within 10 hours of irradiance with a footprint that is no more than 15 m².

7. Deliver 10 kWh to PHEV/EV within 8 hours. The research team assumed that a PV-based charging system would be viable in the PHEV/EV market if the charging time is equivalent to or faster than the time it would take to charge from a grid connected power outlet.

8. Demonstrate ability to build a system for $4,000. For this project, the research team assumed the cost of a production level charging system should be comparable to an upgrade over conventional (Level 1) charging. Residential installation of Level 2 charging and associated utility bills for a period of four years represents an estimated cost of $4,000.

2.23.4TE Outcomes

1. The researchers used a scaled-down PV array to demonstrate a peak power output of greater than 500 watts. They concluded that a full-scale PV array would generate approximately three times the energy output and would therefore be capable of generating 1.5 kW at peak daily irradiance.

2. The researchers successfully constructed a battery pack with a capacity of 14.3 kWh. However if all banks were limited by the capacity of the weakest link, the capacity
would fall to 13.4 kWh. In one test of actual discharge capacity, the capacity fell to 11.3 kWh.

3. Based on data acquired through a demonstration using the reduced (720 watt) PV array, the researchers concluded that it is possible to generate and store 10 kWh of energy or more with the use of a full-scale PV array. However the current demonstration system used manual switches as circuit breakers to control the charging/discharging functions.

4. Based on using one cell, the results of the cycle life test suggested that the battery pack can support at least 1,200 daily cycles of operation.

5. No outcome was achieved for this objective since the research team elected to focus on off-grid operation for the first year of the project.

6. A calibrated simulation of the charging system showed that the charging system was capable of storing 10 kWh of energy on most days of the year for several locations in California, e.g., Sacramento and Los Angeles. While the PV modules used for demonstration were capable of meeting the daily 10 kWh energy generation target, the required footprint of the array of MSX-60 modules was greater than the 15 m² limit. The footprint was 23 m².

7. The battery successfully delivered over 10 kWh to a load in less than eight hours.

8. The cost of PV modules and lithium ion batteries are steadily decreasing, but they still carry a significant initial investment. The researchers projected the cost of building and installing a residential solar PV charging system (SPCS) to be approximately $11,200.

2.23.5TE Conclusions

1. The research team demonstrated with a scaled-down model that a PV array can generate 1.5 kW at peak daily irradiance.

2. The research team successfully constructed a battery pack for which the capacity of all banks was 14.3 kWh, well over the 12 kWh goal. However if all banks were limited by the capacity of the weakest link, the capacity would fall to 13.4 kWh. In one test of actual discharge capacity, the capacity fell to 11.3 kWh.

3. Based on data acquired through a demonstration using the reduced (720 watt) PV array, the research team concluded that it is possible to generate and store 10 kWh of energy or more with the use of a full-scale PV array.

4. Based on using one cell, the results of the cycle life test suggest that the battery pack can support at least 1,200 daily cycles of operation.

5. No outcome was achieved for the objective to allow no charging using grid electricity (0 kWh) during peak hours, since the research team elected to focus on off-grid operation for the first year of this project. Therefore there was no demonstration of how this system would interact with the grid.
6. The research team did not demonstrate that the system could generate and store 10 kWh within 10 hours of irradiance with a footprint that was no more than 15 m².

7. The battery successfully delivered over 10 kWh to a load in less than eight hours. The power delivery components accommodated a dynamic power demand from the vehicle’s on-board charger. The system was demonstrated to discharge 11.3 kWh within 7.3 hours.

8. The research team did not demonstrate the ability to build a system for $4,000. The total cost of building and installing a residential SPCS was projected to be approximately $11,200. But this did not take into account costs for project permitting that can add up to $1,000, depending on the jurisdiction within California.

The researchers did not establish the feasibility of the photovoltaic PHEV/EV charging system using second-life lithium batteries as proposed. The cost and availability of second-life batteries has not been established. There could be a strong market for second-life batteries in the next decade as the traction batteries on model year 2011-2012 PEVs begin to show capacity fade. However, there is not much supporting research that determines exactly when traction batteries will need to be replaced. While having some positive results, the research undertaken did not meet the proposed objectives. Substantial additional research is needed.

2.23.6TE Recommendations
The Program Administrator recommends the following activities to advance the proposed concept toward commercialization:

1. Evaluate the issues associated with long term storage of used batteries, including capacity fade of the batteries as a function of number of cycles, used battery management, charging protocols, and component optimization.

2. Interface with electric utilities. A smart grid interface would allow the PV array to sync with the grid and deliver energy when the solar photovoltaic charging system (SPCS) storage battery is at 100 percent charge, thus increasing the system energy harvest. A grid interface would also allow the PHEV to finish charging using low cost night-time grid electricity during days when insufficient PV energy was stored in the SPCS battery.

3. Develop a high level controller design and test it.

4. Address commercialization issues. Demonstrate product life cycle cost effectiveness for residential users. Obtain an acceptable and viable footprint for residential application, compliance with residential building and safety codes, and product cost reduction
2.23.7TE 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 the use of alternative fuels

The primary benefit to the ratepayer from this research is reduced use of alternative fuels. Gasoline usage would be replaced with solar energy. The photovoltaic PHEV charging system using second-life lithium batteries as proposed in this research could generate approximately 3000 kWh of energy per year. Assuming a typical electric drive efficiency of 250 Wh/mile, this amount of energy translates to around 12,500 miles per year that drivers of plug-in electric vehicles could travel on renewable energy. Many concepts for plug-in electric vehicle technology are hybrid designs that allow the vehicle to be driven on electricity and/or gasoline. Therefore the benefit of this system can be realized through reduced gasoline use. Given the current corporate average fuel economy standard of 27.5 mpg for gasoline powered drive trains, this system eliminates the need for up to 450 gallons of gasoline per vehicle per year. Along with the increase in usage of alternative fuels, and therefore the decrease in gasoline usage, come other benefits. If each gallon of gasoline is responsible for 8.8 kg of CO₂, the carbon emissions saved by operating this system could be on the order of 4,000 kg per vehicle per year.

Consumer savings are very important to technology deployment. Assuming a gasoline price of $3.75/gallon, customers could expect to save nearly $1,700 per year on transportation fuel costs by utilizing stored solar energy. These savings assume that all transportation energy is provided by the photovoltaic system. With a system cost of $4,000, simple payback could be achieved in 2.3 years. At a system cost of $11,200, it would take 6.6 years for simple payback. If a residential user had to take a home improvement loan for one of these systems, the actual payback period could be considerably longer. If the consumer lived in an area that does not have 10 hours of sunshine every day of the year, he would need to either purchase electricity or gasoline to make up the shortfall. Any purchase of additional energy would also lengthen the payback period.

2.23.8TE 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 have not indicated when they will undertake a market analysis or survey potential customers for interest in the product. They do indicate that the concept could easily be extended from the residential (light duty vehicle market) to the commercial/industrial vehicle market.

Engineering/Technical

Although researchers have discussed a general development plan, they have not created a specific plan. The goal of the next year of research is a visible public demonstration of the product on the UC Davis campus. The research team has acquired $120,000 and is pursuing $1 million in funding to continue the project and further demonstration efforts.

Legal/Contractual

The researchers have not filed a patent application.

Environmental, Safety, Risk Assessments/Quality Plans

At the present level of assessment, the researchers have not identified issues nor proposed any environmental, safety, risk assessment, or quality plans.

Production Readiness/Commercialization

While the researchers indicate that partnering is not needed for commercialization, there is no established commercialization plan. The commercialization of the product is dependent on a reliable source of second-life battery components.

2.24TE Community Integrated Agriculture Development

Awardee: Mogavero Notestine Associates
Principal Investigators: David Mogavero

2.24.1TE Abstract

This project assessed the potential energy and environmental benefits of reintegrating housing and farm development in a 10 acre plot consisting of a five acre farm and a five acre, 100 unit apartment complex. Projected synergies from integrated operation included reduced residential vehicle miles traveled for food production and residential procurement through on-site purchase of farm products, common processing of food and agricultural wastes, and recycling of residential wastewater. Researchers also considered benefits from on-site renewable generation options. The study, including its extensive appendix, provides data and analysis that could be useful in further evaluation of this approach.

Keywords: Integrated development, urban agriculture, Sacramento urban infill, vehicle mile travel reduction, graywater, blackwater, compost, greenhouse gas emissions
2.24.2TE Introduction
The current practice of geographically divorcing locations for housing development and food production can result in significant energy and greenhouse gas (GHG) impacts from the transportation associated with moving agricultural products from farm to residence. Potential synergies from a common water and waste treatment system are also unavailable due to this separation.

If these two core activities could be reintegrated, reduction in vehicle miles traveled (VMT) for producing and procuring perishable foods, as well as reduced energy and water demands, could be possible. This could offer the California ratepayer lower costs and reduced carbon emissions.

This project proposed demonstrating these benefits through modeling co-location of housing and agriculture in smaller in-fill locations that would be available in existing or new development. Careful design of both the housing and farming systems could allow households to purchase some agricultural products on-site and process much of the combined household and farm waste and water streams locally, reducing transportation and processing requirements.

2.24.4TE Outcomes
1. In the conventional residential development baseline scenario, VMT is 65.9 per household per day, energy use is 4,720 kWh per household per year, and water use is 675 gallons per household per day. Of the total household waste generated, 25.4 percent is food waste and 42.8 percent is other organic waste, totaling 68.2 percent of the total compostable waste.

2. The researchers created four alternatives: vary site location, balance farm production with residential construction, identify targeted wholesale distribution opportunities, and identify food waste transportation reductions.

3. The integrated development prototypes resulted in VMT reduction to 35.4 VMT/household/day, a food transportation reduction to 0.63 tons CO2e/year/household, and reduced energy required to produce a calorie of food to 0.00000174 kWh/calorie.

4. The researchers identified several candidates for evaluation in the following areas:
   - Energy sources: wind turbine, windspire, solar hot water (HW), photovoltaic (PV), hybrid solar HW and PV, PV therm, and heat recovery from wastewater
   - Water sources: rainwater from roofs and landscape, graywater, blackwater, reused processed water
   - Organic sources: simple composting of a combined waste stream from household and farm wastes

5. Results were very similar for the two selected combined scenarios, as shown in Tables 12 and 13. The two differed primarily in their water use reduction strategies.
6. Development scenario B showed the largest integrated non-transportation energy reduction.

7. Both Integrated Development scenarios showed better results than target, shown in Table 14.
Table 13: Summary of Integrated Development B

<table>
<thead>
<tr>
<th>Options</th>
<th>Energy (Therms)</th>
<th>Energy (kWh/yr)</th>
<th>Water (gpy)</th>
<th>Organics Waste (lbs)*</th>
<th>Organics Liquid Fertilizer (N, lbs)</th>
<th>Transportation (VMT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>15,000</td>
<td>420,324</td>
<td>11,661,491</td>
<td>163,200</td>
<td>980</td>
<td>2,401,335</td>
</tr>
<tr>
<td>Carbon Conversion metric ton</td>
<td>75.00</td>
<td>297.00</td>
<td>17,385</td>
<td>80.00</td>
<td>1.59</td>
<td>1,000.56</td>
</tr>
<tr>
<td>Energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Windspire (wind turbine)</td>
<td></td>
<td>-22,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solar Hot Water</td>
<td>-6,400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photovoltaic</td>
<td></td>
<td>-427,451</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nexus E Water Heat Recovery</td>
<td>-2,700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainwater Storage Epic - Buildings</td>
<td></td>
<td>-1,073,893</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainwater Storage Epic - Landscape</td>
<td></td>
<td>-1,064,629</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Greywater</td>
<td></td>
<td></td>
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<tr>
<td>Blackwater</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Living Machine</td>
<td>13,424</td>
<td>-5,584,500</td>
<td></td>
<td></td>
<td>-3,728</td>
<td></td>
</tr>
<tr>
<td>Conservation</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Reuse Process Water (30% evap loss)</td>
<td></td>
<td>-185,325</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Organics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste from residential</td>
<td></td>
<td>-81,206</td>
<td></td>
<td></td>
<td>-450,000</td>
<td></td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>farm next to residential</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-359,306</td>
</tr>
<tr>
<td>On-site farm product consumption (CSA)</td>
<td></td>
<td>pounds of food produced</td>
<td>balanced</td>
<td></td>
<td></td>
<td>-49,644</td>
</tr>
<tr>
<td>On-site farmers market</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-46,644</td>
</tr>
<tr>
<td>Remaining Net Total</td>
<td>5,900</td>
<td>-15,703</td>
<td>3,753,144</td>
<td>81,994</td>
<td>-2,748.00</td>
<td>1,495,741</td>
</tr>
<tr>
<td>Carbon conversion</td>
<td>29.50</td>
<td>-11.10</td>
<td>5.595</td>
<td>61.00</td>
<td>-4.48</td>
<td>623.23</td>
</tr>
</tbody>
</table>

Total Carbon metric ton: 703.74
net CO2e/yr per household: 7.04

186
8. Annual Integrated Development GHG emissions/household was reduced to 7.43 and 7.04 mtCO\textsubscript{2}e in scenarios A and B, respectively.

### 2.24.3TE Objectives

The goal of this project was to determine the feasibility of achieving transportation, energy, water, and organic resource demand reductions by integrating a farm with suburban in-fill housing. The researchers established the following project objectives:

1. Obtain transportation, energy, water, and organics resource demand data for traditional non-integrated development from existing documents from Sacramento Area Council of Governments (SACOG), Sacramento Municipal Utilities District (SMUD), California Department of Water Resources (DWR), and Integrated Waste Management Board (IWMB). Obtain current code and design standard data for modern residential development baseline. Develop parameters for the prototypical farm.

2. Identify four transportation energy and GHG reduction alternatives to the baseline for analysis in the integrated development.

3. Demonstrate reduction to 41.3 VMT/household/day, reduction to 0.637 tons CO\textsubscript{2}e/year/household for food transportation, and reduction to 0.0000005815 kWh / calorie of food produced in the integrated model.

4. Identify and evaluate three energy technologies, three water technologies, and three organics technologies.

5. Demonstrate two development scenarios that combine non-transportation technologies in an integrated system.

6. Select an optimally functioning integrated system that yields the greatest non-transportation energy reduction for the integrated development project.
7. Demonstrate resource demand reduction in the integrated development to 221 gpd/household water, 7,905 kWh/household/year energy, 325 pounds/household/year food waste.

8. Demonstrate reduction to 0.1130 mtCO2e/year/household emissions.

2.24.5TE Conclusions
The researchers met all but Objective 8 for the project and provided extensive data and analysis of the work in a detailed final report. The comprehensive set of appendices could be useful to others interested in a similar approach. Considerations of cost effectiveness, potential regulatory and land use issues, and market acceptance were not within the scope of this project. In their absence, conclusions about commercial application of the studied approach would be premature.

1. The researchers identified appropriate current benchmarks for all items in the objective.

2. The selected alternative scenarios were appropriate and represented a reasonable span of likely alternatives.

3. The researchers selected an effective mix of development options that offered the potential to meet targets for VMT and CO2e, but fell short of the target for energy per food calorie produced.

4. The wide variety of evaluation candidates and their detailed description in the comprehensive appendices provided a basis for making final selections for study in subsequent tasks.

5. Both non-transportation integrated scenarios showed significant reductions in targeted items.

6. Scenario B was the superior alternative.

7. Both integrated scenarios showed results exceeding target for household resource demand.

8. Although reductions in annual GHG emissions were found in both scenarios, neither approached the very aggressive target set in the objectives.

2.24.6TE Recommendations
The scope of this research was limited to testing feasibility of integrated options taken at face value, unconstrained by the numerous challenges inherent in bringing a system to market for real-world operation. Next steps leading to a prototype, including many acknowledged by the researchers in the final report, should include:

1. Marketing studies to determine public interest in the concept and willingness to participate in the related housing, farming, community supported agriculture, water and waste recycling aspects of the operation.
2. Detailed analysis to verify that selected components would perform as required in the field over reasonable life spans.

3. Site and technology selection compatible with prevailing legal, regulatory, code, and community standards.

4. Cost/benefit analysis to ensure that environmental benefits are appropriate to initial and ongoing costs of the project.

2.24.7TE 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 the use of alternative fuels

The primary benefit to the ratepayer from this research was targeted to be improved transportation energy efficiency. If community integrated agriculture development similar to that studied in this research could be brought to successful commercial deployment, a measurable reduction in vehicle miles traveled associated with agricultural food production and travel to consumers’ homes could be possible. There could also be reductions in transportation associated with food and domestic waste treatment. The total fuel and emissions savings in California would depend on market acceptance, which was not tested in this research.

2.24.8TE 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

No public acceptance or other marketing research was proposed in the grant, but was proposed as a critical next step. Reported results were not constrained by this concern.

Engineering/Technical

The researchers used available data that was extensively described in an appendix without challenge or modification.

Legal/Contractual

The need for careful assessment of legal issues was acknowledged as a critical next step. No patents exist.
Environmental, Safety, Risk Assessments/ Quality Plans

The researchers acknowledged the need for careful assessment of these issues as a critical next step.

Production Readiness/Commercialization

The researchers characterized this study as a first step and provided a road map for tasks leading to potential commercialization.

2.25TE  Seamless Mechanized Charging Interface for EV/PHEV

Awardee:  Green Dot Transportation Inc.
Principal Investigators:  Satyajit Patwardhan

2.25.1TE  Abstract

With the proliferation of electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV), consumers are increasingly experiencing the inconvenience of daily charging. This is particularly true for home garage locations where more than 90 percent of the charging events occur, and it is also where the chore of charging is a daily occurrence.

The EV industry has already recognized the need for a hands-free charging technology to provide a more positive user experience. Under this EISG grant the research team developed the first practical conductive hands-free charging technology. This is a conductive system as opposed to an inductive technology that industry is presently trying to develop. Inductive chargers waste 10—25 percent energy into heat and also generate high levels of magnetic fields hazardous to pets, pacemakers, and structural members of a garage.

The CrossBar technology developed in this project has a pair of bars with conductor geometries such that their cross point located anywhere on the bars will establish multiple conductive paths needed for charging. It trades off the mechanical complexity for added power electronics.

The first generation of the technology developed here is rated for 240 V AC and 32 A. It tolerates up to 14” × 16” of parking misalignment and up to ± 10° of yaw misalignment. The system exceeds the contact quality as well as robustness requirements. Being conductive, it transfers the charging power with better than 99 percent efficiency. High efficiency and elimination of magnetic fields permit this technology to be scalable to high power levels necessary for quick charging.

Keywords: Hands-free, charging, conductive, electric vehicle(s), EV, PHEV, quick charging
2.25.2TE Introduction

The full realization of petroleum displacement and reduced air quality emissions resulting from substantial penetration of electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) into the California vehicle marketplace will be highly influenced by consumer behavior and habits. Charging requirements for such vehicles are one principal impediment. A reliable and seamless charging system developed under this EISG grant could be a key to successful deployment of EVs and PHEVs. In a survey conducted by the research team, almost half of the consumers otherwise not interested in EVs indicated that hands-free convenience would change their minds about EVs in a favorable direction.

Two important facts make the EV/PHEV refueling process less convenient for consumers:

1. Most cost effective EV/PHEVs need ten times more frequent refueling compared to their fossil fuel counterparts. Specifically, the average commute distance in California is 22 miles each way; average fuel efficiency is 25 miles per gallon. An average gas tank of 16.5 gallons will last for 9.3 commute days. In contrast, a full charge will last between 1 and 1.8 days. Chevy Volt has an all electric range of about 40 miles, and Nissan Leaf has an average range of 80 miles.

2. Charging cycles typically last 4 to 8 hours (Chevy Volt four hours at 240 VAC, 15 A and Nissan Leaf eight hours at 240 VAC, 15 A) as opposed to less than 10 minutes refueling for a typical gasoline fueled passenger car.

Unless this inconvenience is addressed, the missed charge cycles will end up costing California commuters gasoline for the next commute day. Thus the cost of missed charge cycles can be calculated as follows: average carbon dioxide (CO₂) emission per gallon of gasoline is 19.4 lb. Combining this with average commute distance in California and average fuel efficiency, one can calculate the typical carbon footprint of a missed charge cycle to be 34 lb of CO₂ for an average commute. With about 12.8 million commuters in California, if each commuter forgot to charge once per month, environmental costs would quickly add up to 2.4 megatons of CO₂ per year and 12 million barrels of oil.

In addition, the technology developed in this project would produce electricity savings. The average daily electricity need of an EV is 24 kWh. When compared to competing inductive technology, which can be up to 75 percent efficient for normal parking accuracies, hands-free charging technology developed under this grant would further save 8 kWh energy per charge cycle or 2.9 MWh of saving per year per charger.

With the advent of automatic and seamless charging technology developed under this EISG grant, there would be negligible dependence on consumer behavior modification for successful adoption and maximum utilization of electric vehicles. This would allow California ratepayers to reap the benefits of a larger pool of grid connected PHEVs and EVs while saving the environmental costs of missed charge cycles.

This charging connection development brings together innovations in several technical domains such as geometry, materials, surface interactions, surface topology, power electronics, electrical
interlock, software, radio frequency (RF) communication, and mechanical packaging. Figure 45 displays the overall concept along with electrical connections, interlock, and geometry definition.

**Figure 45: Overall Concept Including Electrical Connections, Interlock, and Geometry Definition**

The charging connection developed in this EISG project is the first conductive technology to automatically connect EVs to the charging infrastructure. In its basic form the technology comprises two bars, each with a series of independent electrical contacts. One of the bars is placed on an actuating mechanism on the ground and is moved toward the second bar, which is mounted on the underbelly of the vehicle. Depending on the parked position of the vehicle with respect to the ground, an arbitrary pair of regions from each of the bars overlaps. At that point a microprocessor, along with appropriate power switches, scans all contacts and identifies the mating pairs. Only those contacts in a circuit between the power source and battery are connected, with all other contacts being electrically excluded. Mechanical and sensing complexity of searching and precisely locating mating contactors is eliminated, and the same functionality is encapsulated in power electronics, making the technology robust and reliable.
2.25.3TE Objectives

The goal in this project was to determine the feasibility of a practical hands-free charging technology producing a high quality conductive connection between the parking stall and an electric vehicle parked within the normal parking ability of a typical driver. In its basic form, the technology comprises two bars, each with a series of independent electrical contacts. One of the bars is placed on an actuating mechanism on the ground and is moved towards the second bar, which is mounted on the underbelly of the vehicle. Depending on the parked position of the vehicle with respect to the ground, an arbitrary pair of regions from each of the bars overlaps. At that point a microprocessor, along with appropriate power switches, scans all contacts, identifies the mating pairs, and connects those contacts in a circuit between the power source and battery, with all other contacts electrically excluded.

This is a conductive system as opposed to the inductive technology that industry is presently trying to develop. Inductive chargers waste 10—25 percent energy into heat and also generate high levels of magnetic fields hazardous to pets, pacemakers, and structural members of garages.

The researchers established the following project objectives:

1. Design a hands-free charging system for EVs.
2. Realize a charging system that demonstrates the ability to connect a vehicle to the grid within ±20 cm and ±10° misalignment.
3. Develop a test stand and demonstrate that it is capable of positioning a vehicle connector within at least ±20 cm and ±10° misalignment.
4. Demonstrate that the charging system can perform repeated operation for at least 1000 cycles of operations with random misalignment within ±20 cm of lateral and longitudinal directions, ±10° of yaw angle and contact resistance no greater and 100 mΩ.
5. Confirm from project findings that the technology can be mass produced for $100/device manufacturing cost.
6. Confirm from project findings that seamless charging will save environmental costs within 10 missed charging cycles per year.
7. Confirm from the project findings that seamless charging technology can save two million tons of CO₂/year for California.
8. Conduct component level tests on the mating contactors and document the effect of contact force on contact resistance for different contact geometries and the effect of exposure to ASTM-B117 test protocol on the contact resistance.
2.25.4TE Outcomes

1. The researchers successfully designed a conductive hands-free charging system for EVs.

2. The researchers demonstrated the charging system could connect a vehicle to the grid within ±20 cm and ±10° misalignment.

3. The research team designed and built a test stand comprising a rectangular platform with wheels at each corner. The test stand was capable of being positioned at an arbitrary lateral/longitudinal/angular offset with respect to the ground side mechanism, thus achieving Objective 3 while being able to measure its position with respect to the ground side mechanism.

4. The research team was able to demonstrate all except one property during operation. See Table 15. A slightly shorter range in the longitudinal direction was the consequence of some early stage design choices. Since this was not due to an inherent limitation of the tested technology, it can be resolved in the next iteration of the design after verifying the actual range requirements.

<table>
<thead>
<tr>
<th>Actual</th>
<th>Target</th>
<th>Obj. Met</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral range: ± 20.32cm</td>
<td>± 20 cm</td>
<td>yes</td>
</tr>
<tr>
<td>Longitudinal range: ± 17.8cm</td>
<td>± 20 cm</td>
<td>no</td>
</tr>
<tr>
<td>Yaw range: ±10°</td>
<td>±10°</td>
<td>yes</td>
</tr>
<tr>
<td>Reliability: 1000 cycles</td>
<td>1000 cycles</td>
<td>yes</td>
</tr>
<tr>
<td>Contact Quality: 10 ~ 24 mΩ</td>
<td>&lt; 100 mΩ</td>
<td>yes</td>
</tr>
</tbody>
</table>

5. This objective was not met. Instead of being able to demonstrate that the technology can be mass produced for $100/device, the production estimate was approximately $478. In the short term this target objective is difficult to meet. However the cost of a hands-free changing device is about the same as available manual chargers. Due to the key simplifications enabled by the proposed connection technology, the incremental cost of a hands-free device is still within an acceptable price point range as noted in consumer surveys. The primary findings of the survey are:

- Most consumers consider some form of hands-free charging to be beneficial. Only 1.3 percent of the surveyed said they would be happy with manual charging. About 32 percent indicated they would want to have hands-free convenience.

- Most of the consumers (about 81 percent) were willing to attach a value ranging between $200 and $1000 for this convenience. A small percentage (9 percent) indicated willingness to pay more than $1000.
• About half of the individuals (45 percent) otherwise not interested in EVs said they would change their minds if hands-free convenience were available.

6. The research confirmed that seamless charging would save environmental costs within 10 missed charging cycles per year. As can be seen in Figure 46 below, even when a consumer forgets to charge 1.4 days (rounded to 2 days per year), the technology developed in this project would benefit the environment.

**Figure 46: Sensitivity Analysis for LCA with Respect to Consumer Behavior**

7. The research team met this objective by demonstrating that the environmental savings would be greater than two million tons of CO₂/year for California.

8. This objective was met through component level tests on the mating contactors and documentation of the effect of contact force on contact resistance for different contact geometries and the effect of exposure to ASTM-B117 test protocol on the contact resistance.

2.25.5TE Conclusions

Based on the work conducted in this project, the conclusions are:

1. The project team developed a conductive hands-free charging technology for EVs and PHEVs.

2. The researchers met this Objective.

3. The researchers fabricated a test stand able to position the vehicle side at an arbitrary but measurable position with respect to the ground side, thus meeting this Objective.
4. The charger was able to establish a high quality (low contact resistance) charging connection across a wide range of parking misalignments without involving robotic search or intrusive vehicle guides.

- The charging system demonstrated a very low contact resistance (10 mΩ—24 mΩ) across 14” (longitudinal) × 16” (lateral) parking misalignments.
- The charging system demonstrated acceptance of at least ±10° of yaw misalignment, while still delivering high quality contact (10 mΩ—24 mΩ).
- The system showed no sign of degradation in contact resistance or in physical condition after 1000 cycles of operation. Although testing was stopped after 1000 cycles, the system reliability was estimated to be substantially more than 1000 cycles.

5. The mechanical complexity of the entire system was moderate and the entire system can be manufactured for under $500. While this did not meet program objectives, survey data compiled under Objective 6 indicate it can be considered in line with the consumer acceptance for the usefulness of the product.

6. The research confirmed that seamless charging will save environmental costs within 10 missed charging cycles per year.

7. The system delivers hands-free convenience without any environmental penalty. By eliminating the missed charge cycles, the system can save California up to 2 megatons of CO₂ emissions and 12 million barrels of oil per year.

8. Component level tests have proved that the system is robust against abuses and can deliver very high quality of connection. Contact resistance near 1.5 mΩ was achieved even after exposure to ASTM-B117 (salt and fog) test protocol.

Several key engineering innovations resulted in delivering a reliable charging connection to an arbitrarily parked EV. Even for well aligned connectors and switchgear, it is typically a challenge to deliver contact resistance consistently in the low mΩ range. This is frequently due to sub miniaturized contacts in such devices, where the problem of maintaining consistent operating conditions such as pressure and sliding across a large array of contactors is difficult. The design developed in this project was specifically targeted to address these technical challenges by taking advantage of larger geometries and having multiple redundant conduction paths, at least one of which is optimal. The researchers proved feasibility.

2.25.6TE Recommendations

The next step for this technology is to conduct testing in real life environments. The testing should be based on and use industry standards. Such tests can be categorized into three groups: environmental simulation testing such as high-low temperature, icing-freezing, salt and fog, rain, altitude, sand and dust tests; dynamics and vibration testing such as random, sine, shock, seismic, acceleration testing; and electrical testing. Following completion of the testing, a final redesign should be compatible with large volume production processes. As a process, the steps would be:
1. Undergo in-vehicle reliability and functionality tests. The tests should include: environmental simulation testing, dynamics and vibration testing, and electrical testing.

2. Gather data with actual use cases.

3. Go through regulatory certification testing using protocols developed by Underwriters Laboratory (UL) and others.

4. Conduct another round of redesign to include all the changes and improvements resulting from in-vehicle testing, certification testing, and use case data, and modify the design to make use of mass production processes.

While the research team indicated that it has discussed the technology with major automakers, a partnership(s) should also be garnered during this time.

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.

2.25.7TE 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 the use of alternative fuels

The primary benefit to the ratepayer from this research emanates from reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and NG production and use.

Apart from convenience to drivers, a conservative estimate of environmental savings offered by reliable hands-free charging for California is estimated to be 2.4 megatons of CO₂ and 12 million barrels of oil per year. When compared to its competition, this technology would further save up to 2.2 MWh of electricity every year for every charger. In a recent survey conducted by the project team, almost half of the individuals who were otherwise not interested in EVs said they would change their minds if a hands-free charger were available. A hands-free charger without environmental penalties would promote deeper EV penetration. This would allow California ratepayers to reap the benefits of a larger pool of grid connected PHEVs and EVs.
2.25.8TE  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

Green Dot does not have financial and market strength to undertake commercialization. The researchers identified Tier 1 auto suppliers (e.g., Delphi, Siemens, and Johnson Controls) as potential marketing partners.

Engineering/Technical

The researchers estimated that they would need about one year and $0.5 million to complete engineering work and produce a prototype. Additional funds would be needed for tooling once commercialization commenced.

Legal/Contractual

The research team has one patent, US #12168137. This is a utility generic technology patent describing the overall concept of CrossBar. The team also has two other patent applications describing design details that are in different stages of prosecution, US #13413646 and US #13413647.

Environmental, Safety, Risk Assessments/Quality Plans

These plans must be addressed during the completion of the engineering work. Appropriate codes and standards must be addressed.

Production Readiness/Commercialization

The researchers plan to work with an electric vehicle manufacturer to begin the commercialization process.

2.26TE  Impacts of Plug-in Hybrid Electric Vehicles on Distribution Network Reliability

Awardee: University of Toledo

Principal Investigators: Lingfeng Wang

2.26.1TE  Abstract

Plug-in hybrid electric vehicles (PHEV) are emerging as a new source of distributed energy resources for the power grid. PHEVs can be interconnected to the power grid at the distribution level, and their charging/discharging pattern can significantly affect the local distribution system reliability. Given this potential, the research team assessed the feasibility of using probabilistic integrative modeling and evaluation methods to determine accurately the impacts of large fleets of PHEVs on the distribution network reliability by accounting for various uncertainty factors. Based on probabilistic analysis, the research team developed integrated reliability models of power systems including PHEV integration and then used efficient
reliability evaluation schemes to calculate a set of reliability indices. It also investigated reliability-aware optimization schemes for integration of large fleets of PHEVs in planning and operation of modern grid systems. Finally, the research team developed a graphical user interface-based simulator, which it demonstrated to test a wide range of PHEV integration scenarios. The simulation platform facilitated quicker and more informed decision-making by simulating and quantifying the interactions between the PHEV fleet and power grids. The study provided a basis for informed decision-making under uncertainties of PHEV penetration in power system planning and operations in the California electricity market. This work advances the state of the art by developing integrated probabilistic reliability models and evaluation methods for distribution networks with PHEV integration in smart grid applications.

**Keywords:** Plug-in hybrid electric vehicles, distribution networks, power system reliability, stochastic modeling, power quality, electric transportation, simulation software, wind power, smart grid.

### 2.26.2TE Introduction

The California energy problem addressed in this project was how to continue to acquire the environmental benefits associated with plug-in hybrid electric vehicles while ensuring an efficient and compatible integration of battery charging/discharging into the local electricity distribution system. Electric transportation is a promising technology to lower environmental impact and increase energy security by displacing imported oil with domestically produced electricity. While these pluggable vehicles bridge the connections between the power grid and the transportation sector, a large fleet of plug-in hybrid electric vehicles (PHEV) can significantly change the load shape and impact the reliability of the local distribution system. A high penetration of PHEVs in the near future would lead to an increase in electrical load demand. The new load demand would pose a challenge to the power system, especially in local distribution grids. In the distribution system, the large load demand caused by PHEVs may increase the peak load and cause voltage and frequency deviation. PHEVs can also increase total harmonic distortion (THD) in the system. The high harmonic current, together with the increased peak load, may damage the transformers in the distribution system. At the same time, different charging and discharging timings could lead to different load shapes, which, if managed, could also improve the system reliability options to integrate effectively other resources, such as wind power.

Given this potential, the research team assessed the feasibility of using probabilistic integrative modeling and evaluation methods to determine accurately the impacts of large fleets of PHEVs on the distribution network reliability by accounting for various uncertainty factors. Based on probabilistic analysis, the research team developed integrated reliability models of power systems including PHEV integration and then used efficient reliability evaluation schemes to calculate a set of reliability indices. It also investigated reliability-aware optimization schemes for integration of large fleets of PHEVs in planning and operation of modern grid systems. Finally, the research team developed a graphical user interface (GUI)-based simulator, which it demonstrated to test a wide range of PHEV integration scenarios. The simulation platform
facilitated quicker and more informed decision-making by quantifying the interactions between
the PHEV fleet and the power grid.

The research results from this project could provide benefits to California in planning and
operating a large number of PHEVs, consistent with an effective, efficient, and reliable use of
the local distribution system. The developed simulator could be used immediately by various
energy sector planners and operators in California. The widespread deployment of PHEVs
could bring public benefits to California, including reducing greenhouse gas (GHG) emissions,
reducing energy cost, decreasing energy consumption, and improving energy security.

From a research perspective, the research team proposed to advance significantly the state of
the art by developing integrated probabilistic reliability models of distribution networks
including PHEVs for both security and adequacy analyses. Using reliability analysis approaches
to quantify the impact of PHEV penetration on distribution networks would also significantly
advance the state of the art. In addition, the research team proposed to model the potential to
increase the use of alternative energy resources, such as electricity generated by wind, when
battery charging is effectively linked to the grid. This research also investigated the impact of
large-scale penetration of PHEVs on power system adequacy.

2.26.3TE Objectives

The research team set a goal to determine the feasibility of using probabilistic integrative
modeling and evaluation methods to determine more accurately the impacts of large fleets of
plug-in hybrid electric vehicles on distribution network reliability in a smart grid environment.
The project objectives were to:

1. Develop more comprehensive models than existing PHEV market penetration models
   and demonstrate the developed models are 12—15 percent more accurate than existing
   work.

2. Confirm the new models are properly integrated to assess distribution system effects for
   various evaluation scenarios and demonstrate 12—15 percent higher accuracy than the
   existing work. Note Figure 47 below.

   **Figure 47: Example of the PHEV Load Profile Modeling Framework**
3. Demonstrate that different PHEV integration models have different impacts on overall system security and the developed models are 12—15 percent more accurate than the existing work.

4. Demonstrate that different PHEV integration models have different impacts on overall system adequacy and the developed models are at least 5 percent more accurate than the existing work.
   - Demonstrate at least 5 percent distribution reliability can be improved through optimization.
   - Demonstrate at least 5 percent more intermittent renewable resources can be integrated through optimization.
   - Demonstrate at least 10 percent lower emissions can be achieved through optimization.
   - Demonstrate at least 5 percent cost reduction through optimization.

5. Demonstrate that the developed simulation platform runs properly with all the required functionalities for various evaluation cases. As compared with the existing methods, the evaluation efficiency will increase by at least 60 percent using this tool.

2.26.4TE Outcomes

The research team demonstrated the following outcomes in response to each objective:

1. The existing PHEV market penetration model accuracy is tied to its prediction accuracy based on travel survey data. The research team compared the accuracy of the proposed stochastic fuzzy model with a straightforward model of PHEVs. The proposed fuzzy model predicted the travel distance, and an optimization algorithm tuned the parameters and rules of the fuzzy model. Since different parameters and fuzzy rules lead to different accuracy values, the objective of the optimization algorithm was to minimize the prediction error of the proposed model. The algorithm halted at the maximum iteration number of 1,000, and the corresponding prediction error was 0.188. Therefore the accuracy of the proposed model was 81.2 percent.

2. The researchers established a stochastic fuzzy model for PHEV penetration and made assumptions close to real-world scenarios in terms of the beginning time of PHEV charging, the initial state of charge (SOC), and the departure time. This research gave a comprehensive analysis of the relationships between voltage deviation, load factor, load variance, and feeder losses. Following development of the PHEV penetration models, the research team integrated them into reliability models for the distribution grid that also account for intermittent renewable resources. The stochastic condition-dependent reliability model developed for the distribution network provided a consistent benefit regarding the accuracy of the integrated system modeling. As compared to the straightforward model with constant forced outage rates, the overall accuracy for the integrated PHEV and distribution system was improved by at least 80.6 percent based...
on the accuracy improvement contributed by the stochastic PHEV penetration modeling above and in comparison to the accuracy of the straightforward model, calculated at 0.6 percent. Thus, by comparing these two models, the researchers found that accuracy was significantly improved by about 80.6 percent (i.e., 81.2 percent minus 0.6 percent) using the proposed stochastic model.

3. The simulations were carried out using different objective functions at different PHEV penetration levels of 10 percent, 20 percent, 50 percent, and 100 percent. Figure 48 provides an example of the load demand curves for different charging algorithms at multiple PHEV penetration levels.

**Figure 48: Load Demand Curves for Different Charging Algorithms at 50 Percent PHEV Penetration Level**
Comparative results for the stochastic fuzzy model versus the straightforward model demonstrate in Table 16 and Table 17 that different PHEV integration models have different impacts on the overall system security, and the accuracy improvement achieved varies from 7.5 percent to 19.7 percent.

**Table 16: Peak Load Demand for Different Models**

<table>
<thead>
<tr>
<th>Models</th>
<th>Smart Charging</th>
<th>Uncontrolled Charging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stochastic Fuzzy Model</td>
<td>370 kW</td>
<td>430 kW</td>
</tr>
<tr>
<td>Straightforward Model</td>
<td>400 kW</td>
<td>500 kW</td>
</tr>
<tr>
<td>Improvement Percentage</td>
<td>7.5%</td>
<td>14.0%</td>
</tr>
</tbody>
</table>

**Table 17: Maximum Voltage Deviation for Different Models**

<table>
<thead>
<tr>
<th>Models</th>
<th>Smart Charging</th>
<th>Uncontrolled Charging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stochastic Fuzzy Model</td>
<td>10.6 V</td>
<td>12.2 V</td>
</tr>
<tr>
<td>Straightforward Model</td>
<td>11.9 V</td>
<td>15.2 V</td>
</tr>
<tr>
<td>Improvement Percentage</td>
<td>10.9%</td>
<td>19.7%</td>
</tr>
</tbody>
</table>

4 The researchers reported the following results:

- Compared to uncontrolled charging, Table 18 illustrates the reliability improvement after applying the smart charging strategy. When the penetration level of PHEVs is relatively low, the system reliability indices are significantly improved. The maximum improvement of 99.9 percent can be achieved for System Average Interruption Duration Index with 50 percent penetration level of PHEVs. However the improvement becomes less evident at very high penetration level. Thus the proposed smart charging strategy is able to improve the distribution network reliability at different penetration levels.

**Table 18: Average Values of the Reliability Indices Using Different Models**

<p>| Indices                              | Improvement (%) |</p>
<table>
<thead>
<tr>
<th></th>
<th>10% PHEVs</th>
<th>20% PHEVs</th>
<th>50% PHEVs</th>
<th>100% PHEVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Average Interruption Frequency Index</td>
<td>97.4</td>
<td>99.5</td>
<td>99.6</td>
<td>8.7</td>
</tr>
<tr>
<td>System Average Interruption Duration Index</td>
<td>99.1</td>
<td>99.8</td>
<td>99.9</td>
<td>8.8</td>
</tr>
<tr>
<td>Customer Average Interruption Duration Index</td>
<td>67.6</td>
<td>67.0</td>
<td>64.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Average Service Availability Index</td>
<td>8.4</td>
<td>48.0</td>
<td>61.5</td>
<td>6.0</td>
</tr>
</tbody>
</table>
The research team demonstrated that PHEVs and wind power are two energy resources that can complement each other for increasing their respective penetrations if they are well coordinated. Generally, wind power and household load demand do not match each other well in different time periods. Figure 49 indicates that the peak household load demand occurs approximately from 6:00 pm to 10:00 pm, and the peak wind power supply occurs approximately from 1:00 am to 4:00 am. Without PHEVs, the wind power at its peak power supply cannot be fully utilized to feed the household load demand even though a large amount of wind power is available then.

**Figure 49: Typical Wind Power Curve and Household Load Demand of the Studied System**

Research outcomes are illustrated in Figure 50 below.
Simulation results demonstrated that the higher the charging demand is, the less wind power will be wasted, and thus installed wind power capacity could be less. The improvement of wind power utilization is shown in Table 19. It can be seen from the table that 45.4 percent to 100 percent more intermittent renewable resources could be integrated using smart charging.

Table 19: Wasted Wind Power at Different PHEV Penetration Levels

<table>
<thead>
<tr>
<th>PHEV penetration level</th>
<th>Wasted wind power (KWh)</th>
<th>Improvement between uncontrolled and smart charging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without PHEV</td>
<td>Uncontrolled Charging</td>
</tr>
<tr>
<td>10%</td>
<td>607</td>
<td>545</td>
</tr>
<tr>
<td>20%</td>
<td>607</td>
<td>545</td>
</tr>
<tr>
<td>50%</td>
<td>607</td>
<td>486</td>
</tr>
<tr>
<td>100%</td>
<td>607</td>
<td>358</td>
</tr>
</tbody>
</table>

- Since the utilization of wind power reduces the amount of electrical power purchased from thermal generators, GHG emission is reduced accordingly. The simulation results are illustrated in Table 20. It can be seen from the Table that 5.9—0.7 percent less emissions would be produced using smart charging.
Table 20: Reduced GHG Emission at Different PHEV Penetration Levels

<table>
<thead>
<tr>
<th>PHEV penetration level</th>
<th>Reduced GHG emission (Kg)</th>
<th>Improvement between uncontrolled and smart charging</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without PHEV</td>
<td>Uncontrolled Charging</td>
</tr>
<tr>
<td>10%</td>
<td>1259</td>
<td>1279</td>
</tr>
<tr>
<td>20%</td>
<td>1259</td>
<td>1279</td>
</tr>
<tr>
<td>50%</td>
<td>1259</td>
<td>1297</td>
</tr>
<tr>
<td>100%</td>
<td>1259</td>
<td>1337</td>
</tr>
</tbody>
</table>

- Figure 51 shows the charging cost of PHEVs using different charging algorithms at multiple PHEV penetration levels. The algorithm with an objective function of minimizing the charging cost leads to the least charging cost, and other smart charging algorithms also result in very low charging cost. In general, their performances in reducing charging cost are quite similar, since the basic principle of all smart charging algorithms is to arrange the charging activities to off-peak hours. When uncoordinated charging is applied, the charging cost is very high since the charging mostly takes place at peak hours when the electricity price is high. Table 21 lists the percentages of cost reduction using different smart charging algorithms when compared to uncontrolled charging. The results show a 22 percent to 37 percent cost reduction.
The research team successfully developed a graphical user interface-based simulation platform and fully detailed it in research results. The simulation experiences of this program demonstrated that the software contains all the required functionalities for a broad range of evaluation cases. As compared with the existing methods, evaluation efficiency was increased by at least 80 percent using this tool.
The researchers presented a methodology to evaluate the impact of PHEV integration on the distribution grid. The simulation results showed large deviations in load voltage when PHEVs were charged without control. The simulation results confirmed that the proposed control method produced similar results compared to other control methods at low PHEV penetration levels. When PHEV penetration levels increased, the proposed control method resulted in a better performance by reducing the voltage deviation and flattening the system load demand. The simulation confirmed that a vehicle-to-grid strategy exhibits a better performance at low PHEV penetration levels.

This research investigated the impact of large-scale penetration of PHEVs on power system adequacy. The simulation results indicated the comprehensive stochastic model was able to reflect practical conditions, and smart charging was capable of improving the power supply adequacy in the presence of high PHEV penetration. The researchers developed a user-friendly simulator for planning and operating large PHEV fleets. It was used to test various scenarios for quantifying the impacts of PHEV penetration as well as provide optimal solutions for best managing PHEVs.

The following conclusions can be drawn with respect to the stipulated project objectives:

- Stochastic modeling of PHEV penetration is able to reflect practical scenarios based on travel survey data.
- Integrated, stochastic modeling of PHEVs and distribution systems can be used for more accurately quantifying the impact of PHEV integration on distribution network reliability. The integrated distribution network and PHEV fleet model have proved to be suitable for reliability assessment by accounting for various uncertain factors.
- Different PHEV integration models have different impacts on overall system security, and the developed models were able to improve the accuracy.
- Different PHEV integration models have different impacts on overall system adequacy, and the developed models were able to improve the accuracy.
- The researchers showed that intelligent optimization was effective in deriving the optimal charging/discharging schemes for a large fleet of PHEVs by reducing the total cost, reducing pollutant emissions, and increasing the overall system reliability.
- The simulator developed is useful for simulating various practical scenarios by providing users with high flexibility. This software package could be a commercial product since numerous parties in the electricity sector and the transportation sector could use such a tool for aiding their decision-making.

The researchers met most of their objectives. It is difficult to determine feasibility in a modeling project. Acceptance in the marketplace will be the test of feasibility.
2.26.6TE Recommendations

The Program Administrator recommends the following additional work to enhance the functions, features, and usability of the developed simulator:

- Include a more comprehensive set of factors in PHEV penetration modeling. These include charging priorities, vehicle types and their respective market penetrations, and some random user behaviors.

- Expand the frequency analysis to include several interconnected systems. Treat the tie line capacity and spinning reserves in each area as constraints. Quantify the impacts of PHEV penetration on both load frequency control and primary frequency control.

- Include a distribution system with more elements (e.g., underground cables used in distribution networks of urban areas) in the reliability assessment.

- Extend the current work on vehicle charging at the residential level to other charging scenarios such as charging at dedicated charging stations.

The new models and reliability analysis methods could assist various related parties in preparing procedures for power system planning and operations in the presence of high penetration of electric transportation. Utility companies, transportation planners, Cal-ISO, and other energy regulators are the primary potential users of the developed software package.

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.

2.26.7TE 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 the use of alternative fuels

The primary benefits to the ratepayer from this research are reduced greenhouse gas emissions or reduced health and environmental impacts from transportation associated air pollution related to electricity and natural gas production and use.
The widespread deployment of PHEVs can bring many public benefits to California, including reduced greenhouse gas (GHG) emissions, reduced energy cost, decreased energy consumption, and improved energy security.

Project results showed that greenhouse gas emissions of conventional vehicles and hybrid vehicles are 450g CO\(\text{e}/\text{mile}\) and 290g CO\(\text{e}/\text{mile}\), respectively. Assuming PHEV charging efficiency is 92 percent, experts estimate that the energy consumed by PHEVs corresponds to CO\(2\) emissions of about 310 g CO\(\text{e}/\text{kWh}\). The Chevrolet Volt PHEV, with an electric efficiency of about 0.34 kWh/mile (the equivalent GHG emission of a PHEV in electrical mode is 105 g CO\(\text{e}/\text{mile}\)), produces a 79 percent GHG emission reduction compared to conventional vehicles powered by gasoline.

2.26.8TE 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

No significant marketing has taken place.

Engineering/Technical

The researchers projected completion of the model in about nine additional months of work with a nominal need for additional funding.

Legal/Contractual

There is no added patent information or contract received since the EISG grant.

Environmental, Safety, Risk Assessments/Quality Plans

Since this is principally an analytic tool, there is no need for environmental or safety plans. There is a need for risk assessment. The assessment should determine the effects of possible erroneous outputs of the model.

Production Readiness/Commercialization

The Commercialization and Technology Transfer Center at the University of Toledo, Ohio, will help commercialize the product. A commercialization plan is under development, but it is not ready. When the plan is completed, product information will be distributed to respective commercial and industrial companies.
Reducing Mobile Air Conditioner Power Consumption in Hybrid Electric Vehicles

Awardee: University of California, Riverside
Principal Investigators: Heejung Jung

Abstract

The power consumed by an air conditioner accounts for a significant fraction of the total power used by electric vehicles (EVs). The fraction is especially high for hybrid and plug-in hybrid vehicles. While the research in this project focused on testing of a plug-in hybrid vehicle, the results are applicable to hybrid, plug-in hybrid, and electric vehicle technology. This study examined the effect of partial and full recirculation of cabin air on power consumption of mobile air conditioners. Real-time mobile air conditioner power consumption was recorded by an On Board Diagnostic or OBD-II monitor. The researchers also used vehicle mileage testing to measure the effect of cabin air recirculation. The data showed that vehicle mileage improved with increased cabin air recirculation. The other objective of cabin air recirculation is to improve cabin air quality. The study found air recirculation significantly reduced in-cabin particle concentrations. Partial air recirculation obtained the benefits of better mileage and air quality, while suppressing the side effect of increased cabin CO₂ concentration. The study concluded that partial recirculation of cabin air is an excellent and immediate way to increase electric vehicle mileage and improve cabin air quality.

Keywords: Vehicle power consumption, mobile air conditioner, air recirculation, hybrid vehicle

Introduction

The California energy problem addressed in this project was how to continue to acquire the energy and environmental benefits associated with hybrid, plug-in hybrid, and electric vehicle technology. Due to its high gasoline mileage, this technology represents a solution to reducing both energy use and air pollution in California. However, there are constraints. It is known, but not well quantified, that use of a vehicle or mobile air conditioner (MAC) consumes significant power, which lowers vehicle mileage. Due to the highly efficient and therefore smaller size of an electric vehicle’s power plant, the MAC system can reduce electric vehicle mileage by 38 percent in an urban driving environment. The research team demonstrated that implementing open or closed loop air recirculation can create mileage savings benefiting California in reduced automotive emissions, reduced power plant emissions, and lower costs to California consumers. Such a saving is approximately 22—38 percent improvement in mileage with the use of ACR (recirculated air conditioning) over ACF (fresh air conditioning).

California drivers run their air conditioning (AC) systems about 13 percent of their total driving time. However, this percentage is likely to increase if temperatures rise. The California Department of Transportation reports that the average driver drives 13,000 miles annually. Using an average kWh/100mi value of 30 and the 22—38 percent reduction in AC fuel consumption translates into a savings of 11,407,500—13,689,000 kWh annually for all EVs. At $0.15 per kWh, this reduction would save between $1,711,125 and $2,053,350 annually.
California. In addition, there could be an unquantifiable but clear benefit to California’s local electricity distribution system due to a diminished need for battery charging.

Based on PG&E’s estimate that 0.562 lbs. of carbon dioxide (CO₂) are emitted per kWh of electricity in California, the reduction in electricity from MAC efficiency improvements would correspond to 3,205—3,847 fewer tons of CO₂ emitted by vehicles in California per year.

The research innovation proposed in this project was the development of a recirculation air duty cycle to reduce power consumption of the MAC and concurrently to minimize particulate concentration in the passenger cabin. There has been no attempt by industry or academia to control the recirculation air duty cycle for either purpose stated above. The proposed research focused on plug-in hybrid electric vehicles. However this work could be extended to electric vehicles (EVs) or other conventional vehicles. The research focused on three tasks:

1. Build an integrated measurement system. Install a gaseous portable emission measurement system (PEMS) to measure CO₂ from a tailpipe and an energy communication unit (ECU) communication system to record engine speed and fuel consumption data in a test vehicle.

2. Build an air recirculation system with additional control and measurement to monitor the percent of fresh air versus recirculated air provided by the air conditioning system.

3. Perform an on-road test and analyze the data to evaluate power consumption of the AC, evaluate improvement in cabin air quality by air recirculation, and develop optimum recirculation strategy.

The research team noted that there are other approaches to reduce the power consumption of MACs, such as improving the efficiency of each cooling subsystem, and to improve cabin air quality, such as installing a better cabin air filtration system. These approaches should be encouraged to further reduce MAC power consumption and enhance cabin air quality. However, the proposed research provided an innovative and immediate solution at minimum cost and maximum feasibility.

2.27.3TE Objectives

The goal of this research was to determine the feasibility of a continuous recirculation air duty cycle to reduce a vehicle’s air conditioner power consumption, as well as to reduce ultrafine particle concentrations inside the vehicle cabin.

The researchers established the following objectives:

1. Demonstrate the proposed on-board measurement systems function well under real-world driving conditions.

2. Demonstrate on-road testing is capable of measuring the fuel consumption rate within ±5 percent.

3. Demonstrate that the air recirculation system can control recirculation from 5 percent to 95 percent, within an error of ±5 percent.
4. Demonstrate that the on/off recirculation system can lower model cabin CO₂ concentration from approximately 4000 ppm to 440 ppm in one minute.

5. Compare project findings on percent fuel consumption for AC usage during real-world driving conditions with percent fuel consumption of AC usage of 5—20 percent from environmental chamber study.

6. Demonstrate that the optimized recirculation strategy reduces AC power consumption by 10 percent to 35 percent and lowers particle concentration in the cabin by a factor of 10.

Two new objectives emerged during the research efforts:

7. Quantify MAC power consumption as a function of ambient air temperatures.

8. Quantify MAC power consumption for an additional plug-in hybrid test vehicle.

2.27.4TE Outcomes

Evaluation and characterization of the climate control air conditioning performance on a hybrid platform requires a combination of OBD II monitoring, instrumentation, and system control. GPS provides time, location, speed, and road grade information, while the OBD II provides vehicle state and performance information. To perform the research, the team developed hardware for simultaneously monitoring OBD II and GPS data. This is displayed in Figure 52.

**Figure 52: On-Board Telematics with Integrated OBD II Data Interpretation**

![Hardware Architecture Diagram](image)
The proposed on-board measurement systems functioned well under real-world driving conditions. The method using OBD-II parameters turned out to be accurate as well as reliable in addressing research objectives.

2 Considering the lack of information and standards, the research team decided to determine and compare mileage with three different methods using tests at the CE-CERT/UCR chassis dynamometer facility. The three methods were:

- A reference method using bag sampling
- A method using data from OBD II parameters
- A method using tailpipe CO2 measurements using a portable emission measurement system (PEMS)

Using the various methods, a total of four different sets of tests were done: AC on full with air recirculation (ACR), AC off condition (ACO), AC on with fresh air mode (ACF), and AC on with partial recirculation (ACP).

Selected results from using the portable emission measurement system or PEMS are displayed in Figure 53.

Figure 53: PEMS Fuel Economy Comparing ACO, ACR, and ACF

Values are relative to ACO fuel economy using carbon balance method.
The use of an indoor environment ruled out the effects of wind and solar. However, through separate on-road testing, the study also determined repeatability of the on-road test for vehicle mileage using the OBD-II method. The test vehicle was run on charge depletion mode consuming energy stored in batteries. For the case of ACR, ACO, ACF and ACP this study found the coefficients of variation of fuel economy in kWh/100 miles were 3.6, 5.8, 4.2, and 2.3 percent, respectively.

To undertake its project, the research team rented test vehicles. Due to the complexity and liability of using a rental car, the team could only demonstrate full and one partial (20 percent) recirculation condition. The researchers could not achieve controlling the recirculation door from 5 to 95 percent as proposed. This was due to lack of public information on electric diagrams of the Toyota Prius test car, and the researchers could not perform major disassembly of a rented car. The team decided to manually prop the recirculation door at a constant angle to see the effect of fractional recirculation. This resulted in ~20 percent recirculation. This decision did not affect achieving the main goal of the project. It does represent an area of future research.

The research team demonstrated that the recirculation system can lower model cabin CO₂ concentration rapidly. To accomplish this, it chose full air recirculation with fan speed 2 until the cabin CO₂ concentration reached 4000ppm. Then the mode was changed to fresh air and the fan speed was set at maximum. The researchers placed a sample probe one inch deep into one of vent openings on the dashboard and monitored CO₂ concentrations at all times.

Considering that the background CO₂ was 400ppm and that there was uncertainty in this range, the initial goal of lowering CO₂ concentration from 4000 to 440 ppm was quite ambitious. The researchers determined the time constant to be 0.632. See Figure 54. This is on the same order that was predicted in the proposal.
Due to the lack of information in literature on AC consumption for a plug-in hybrid Prius, the research team could not compare the test data with results from environmental chamber tests. Instead it compared project findings on percent fuel consumption for AC usage during real-world driving conditions with percent fuel consumption of AC usage results during a federal test procedure driving cycle in a controlled air ventilation system chassis dynamometer.

The researchers conducted the on-road test at charge depletion mode. When a Toyota Prius is in charge depletion mode, it automatically puts the vehicle in an economy operation to save power consumption. During the on-road test of about three miles, the AC power consumption percentage to the total vehicle power ranged from 9 percent to 14.5 percent over a 21°C to 35°C outside temperature range. In comparison, for the test using a chassis dynamometer, the vehicle was on charge sustaining mode. During charge sustaining mode AC power consumption percentage of the total vehicle power ranged from 22 percent to 38 percent over outside temperatures ranging from 29°C to 36°C.

MAC power consumption on percent fuel consumption ranged from 9 percent to 14.5 percent when tests were done on the driving route. MAC power consumption measured from the chassis test on SC03 cycle (a United States Environmental Protection Agency test method) ranged from 22 percent to 38 percent. The MAC power consumption varied significantly based on a driving cycle. These results led to the creation of additional
Objective 7. In essence, the results showed that AC power consumption varied directly and proportionally with temperature.

Results from the chassis test showed that MAC power consumption (shown in kwh/100 mi) was reduced by 38 percent during full recirculation compared to no recirculation with the air conditioning on.

On-road testing performed on a local surface road where traffic interference was minimal showed that MAC power consumption fell by 22 percent during full recirculation compared to no recirculation with the AC on. The SC03 cycle was much more severe for AC performance, yet the fuel saving effect was about the same as the less severe on-road test route. Another type of on-road test was conducted for longer distance and included both local and highway driving. However, due to uncontrollable and therefore unrepeatable traffic conditions, comparisons could not be made successfully.

The researchers used an Electrical Aerosol Detector (EAD) and a low range CO₂ monitor to measure total particle concentration and CO₂ in the cabin. They monitored improvement of cabin air quality in terms of particle diameter concentrations. Particle diameter was proportional to total particle surface area. The researchers compared particle diameter concentrations for the three tests. The results are displayed in Figure 55.

The researchers found air quality improved by a factor of five due to air recirculation. Cabin air quality improved due to the cabin air passing through the cabin air filter multiple times.

Researchers also tested partial recirculation and found it to behave similarly to ACF in that it was heavily influenced by ambient conditions due to its 20 percent recirculation. However it reached low particle diameter concentration similar to ACR.

The particle diameter concentration fell by a factor of five during full recirculation.
MAC power consumption depends on outside ambient temperature. The researchers performed the test in different weather conditions. They set the AC at automatic control mode so that the MAC could modulate the power consumption accounting for external weather condition through the built-in HVAC ECU program.

Small differences in AC power consumption among the ACR, ACF, and ACR were difficult to distinguish. However the difference was readily distinguishable during the SC03 test, a specified United States Environmental Protection Agency test method. SC03 is a more severe AC performance test and will therefore magnify differences. The same trend could be seen when AC power consumption was normalized by total vehicle power consumed. However, when the researchers plotted vehicle mileage obtained from OBD-II parameters against ambient air temperatures in Figure 56, the small MAC power consumption difference, which was not distinguishable during the on-road test, became apparent.

Figure 56 shows that either partial or full air recirculation reduces MAC power consumption, leading to better vehicle mileage or fuel economy. This result suggests that vehicle mileage is a good indicator to examine the effect of MAC power consumption.
Researchers tested a Nissan Leaf plug-in electric vehicle for three of the HVAC conditions: AC on fresh air, AC off, and AC on full recirculate. The AC power consumption was $y = 0.007x + 0.1091$, where $y$ was the AC power consumption as a percent of total power and $x$ was the ambient temperature in degrees C. The Nissan Leaf’s trend had a steeper slope than the Toyota Prius, indicating that the Leaf expended more energy than the Toyota Prius for its AC system. The Leaf’s AC power consumption range was also higher than the Toyota Prius when it was operating in EV mode but similar in range to the Toyota Prius normal hybrid mode.

As shown in Figure 57, the Leaf was more efficient than the Toyota Prius, most notably in the AC off case. Nonetheless, as the research team only included four records of the data for the Leaf, further study is needed to make a conclusive comparison between the Leaf and the Toyota Prius.
2.27.5TE Conclusions

This study proved feasibility of cabin air recirculation control as a means to reduce mobile air conditioner power consumption and to improve cabin air quality. Partial recirculation effectively suppressed the rise of cabin CO₂ concentrations while lowering particle concentrations by factor of 75 percent over the fresh air condition. Full air recirculation showed improvement in fuel economy of 22 percent over full fresh air conditions in on-road tests.

1. The project found that MAC power consumption and vehicle mileage can be accurately obtained by recording OBD II parameters using an OBD II scan tool. This method and device are appropriate to evaluate MAC power consumption of hybrid vehicles including plug-in hybrid vehicles.

2. The method using OBD-II parameters resulted in quantification of fuel economy with 2 percent to 6 percent of coefficient of variation. This compares to the predicted ±5 percent error.

3. The researchers could not achieve controlling the recirculation door from 5 percent to 95 percent as proposed. The team decided to manually prop the recirculation door at a constant angle to see the effect of fractional recirculation. This resulted in ~20 percent recirculation. This decision did not affect achieving the main goal of the project.

4. Time response test results determined the time constant as one minute, which was fast enough for recirculation air control.
5. MAC power consumption on percent fuel consumption ranged from 8 percent to 12 percent when tests were done on the driving route developed in this study. MAC power consumption measured from the chassis test on the SC03 cycle ranged from 22 percent to 38 percent. The MAC power consumption varied significantly based on the driving cycle.

6. Researchers observed a factor of five improvement in cabin air quality during full recirculation. Even during 20 percent partial recirculation they observed similarly low particle diameter concentration compared to full recirculation. Some variations in the results were due to the influence of ambient air concentrations.

7. Temperature dependence was well distinguishable during the three mile on-road test. The AC power consumption was \( y = 0.003x + 0.0322 \), where \( y \) was the AC power consumption as a percent of total power and \( x \) was the ambient temperature in degrees C. The temperature dependence was less distinguishable during the SC03 test. This can be attributable to the fact that there was no solar radiation inside the dynamometer test facility during the SC03 test. This work also demonstrated that either partial or full air recirculation reduces MAC power consumption and leads to better vehicle mileage. This result suggests that vehicle mileage is a good indicator of the effect of MAC power consumption.

8. Overall the Leaf was more efficient than the Toyota Prius, most notably in the AC off case. Since the research team could only include four records of data for the Leaf, further study is needed to make a conclusive comparison between the Leaf and the Toyota Prius.

2.27.6TE   Recommendations

Additional work needs to be accomplished to enhance the functions, features, and usability of the developed simulator. The Program Administrator recommends the following research objectives to advance the current technology and bring the product to market:

- Determine if BMW has a similar solution that would preclude the continued development of this work on public funds.
- Conduct more rigorous (therefore more costly) tests using new AC 17 cycle in the environmental chamber for better quantification of the result.
- Demonstrate that the air recirculation system can control recirculation from 5 to 95 percent, within an error of ±5 percent.
- Obtain a partner actively involved in automotive air conditioners to facilitate commercialization.
- Determine if there is any patentable intellectual property.

Additional funding by a public agency should only be considered if private industry is not pursuing similar goals with similar approaches.
2.27.7TE 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 the 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.

California Air Resources Board has a strong interest in hybrid and plug-in hybrid vehicles. It projects that the number of high efficiency vehicles, such as electric vehicles and plug-in hybrid vehicles, will increase and will improve air quality significantly. However, MACs consume a significant fraction of energy during the summertime, reducing their benefits. The outcome of this study suggested adoption of partial recirculation can achieve higher vehicle mileage and cleaner cabin air quality.

If the predicted 450,000 EVs in California in 2015 take advantage of the 22—38 percent improvement in MAC power consumption, this would translate into a savings of 11,407,500—13,689,000 kWh annually for all EVs in 2015. Annual savings could be $1,711,125—$2,053,350 in costs and 3,205—3,847 fewer tons of CO₂ emitted by vehicles.
2.27.8TE 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

No significant marketing has taken place. BMW is also undertaking research in this area.

Engineering/Technical

There is no major obstacle for open loop air circulation control. A closed loop control system would require the development of a low cost cabin CO\textsubscript{2} sensor.

Legal/Contractual

No additional patent information or contracts have been received since the EISG grant.

Environmental, Safety, Risk Assessments/ Quality Plans

Environmental and other risk assessments were not conducted as part of this project and will be required as part of commercialization.

Production Readiness/Commercialization

The idea was publicly disclosed during the invention disclosure process.