



CALIFORNIA
ENERGY
COMMISSION

ENERGY INNOVATIONS SMALL GRANT PROGRAM
Renewable Energy Technologies

**PROCESS FOR CONVERTING
SEWAGE SLUDGE AND MUNICIPAL
SOLID WASTES TO CLEAN FUELS**

FEASIBILITY ANALYSIS

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PREFACE

The Public Interest Energy Research (PIER) Program 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 PIER Program, managed by the California Energy Commission (Commission), annually awards up to \$62 million of which \$2 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to \$75,000 for promising proof-of-concept energy research.

PIER funding efforts are focused on the following six RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
 - Appendix A: Final Report (under separate cover)
 - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:

<http://www.energy.ca.gov/research/innovations>

or contact the EISG Program Administrator at (619) 594-1049 or email

eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at

<http://www.energy.ca.gov/research/index.html>.

Executive Summary

Introduction

Most new power plants being installed in California are Gas Turbine Combined Cycle (GTCC) plants that burn increasingly expensive natural gas and fuel oil to produce electricity at up to 60% efficiency. These plants can be installed in less than half the time and at less than half the cost of new coal-fired plants and Integrated Gasification Combined Cycle (IGCC) plants that use cheap dirty fuels, but are less than 42% efficient. A new system is needed to adapt the new plants to cheaper fuels, while maintaining their efficiency and environmental performance.

This project researched the feasibility of a supercritical water gasification (SCWG) process to convert compost made from municipal solid wastes and sewage sludge to clean energetic gases. The expectation is to reduce the fuel costs of GTCC plants and to improve both efficiency and environmental performance of existing steam power plants.

Objectives

1. Determine the feasibility of using SCWG to gasify composted municipal solid waste/sludge, consisting of at least 23 wt% solids, with a minimum 96% conversion of carbon to gas.
2. Verify through visual inspection that no significant erosion, corrosion and deposition occurred inside the bench-scale SCWG system.
3. Assess the feasibility of recycling resulting liquids for “zero effluent” design.
4. Update and validate simplified thermodynamic computer simulation and a life cycle cost models that can be used to predict system performance with various fuels.

Outcomes

1. Use of SCWG to gasify composted municipal solid waste/sludge is feasible by a wide margin:
 - We produced a pumpable slurry mixture containing 40 wt% solids, exceeding the target goal by 74%.
 - The bench-scale system converted over 98% of the carbon in the slurry to energetic gases and steam, including clean pressurized methane, hydrocarbons and carbon oxides in less than one minute, which is twice as fast as the target time.
2. No noticeable erosion, corrosion or deposition was observed in the test equipment.
3. Total suspended solids in the liquid effluent was less than 10%, supporting the feasibility of recycling liquids for slurry preparation after filtering to provide a “zero effluent” design. No toxic materials were produced that would limit disposal of the residue in a landfill.
4. A thermodynamic computer simulation model and a life cycle cost model were prepared, however, there was insufficient funding in the current project to validate the models over a range of inputs, including the test data. Equilibrium compositions were assumed to be sufficiently close to expected commercial operations to provide preliminary predictions of system performance. Results of the computer simulations included:

- Projected 62% thermal efficiency to electric power for the entire proposed hybrid plant. Projected efficiency for retrofit in an existing steam power plant is 52%.
- Projected capital costs of \$1,100/kWh for a new hybrid plant, with projected cost of baseload power generation at \$100/MWh.
- Projected capital costs of \$500/kWh for retrofit to an existing GTCC plant, with projected cost of baseload power generation at \$50/MWh.
- Retrofits for repowering existing Steam plants are competitive with GTCC plants burning natural gas costing \$3.00 or more /million Btu.

Conclusions

1. The test results support the continued investigation of composted municipal waste as an economical fuel source for GTCC and existing steam power plants.
2. We demonstrated that compost made from municipal solid wastes and sewage sludge can be made into a slurry with 40 wt% solids, which significantly increases the range of applications, including the production of valuable byproducts, such as hydrogen. This mixture tended to clog in the 1/4" preheater tube which was completely alleviated by changing to 3/8" tubing. This problem is not expected in larger tubes.
3. The project successfully demonstrated that the compost slurry can be used in a SCWG process to produce energetic gases and steam, including approximately 35% gaseous hydrocarbons and hydrogen, the largest fraction being methane. The remaining 65% of the carbon in the feed was converted mainly to CO₂ and a small amount of CO. The CO₂ can be separated for reduced emissions. It is unknown what effect compost grinding had on residence time for gasification. It is also unknown what impact scaling up the reactor tubes will have on the SCWG process.
4. Sufficient yield data was collected to determine gas composition, perform a carbon balance and perform a preliminary evaluation of recycling liquids after filtering for slurry preparation. While no corrosion, erosion or deposition was observed after running the tests, the tests conducted were not designed to accurately assess those effects over long-term testing.
5. Environmentally, based on residence time and projected full scale HRSG tubes, a standard module of 100 HRSG tubes per 25 MW turbine can consume an estimated 170 tons of composted municipal solid waste per day, reducing it to approximately 34 tons of inorganic material.
6. The results of the computer simulation models are encouraging in terms of supporting an economic case for commercialization; however, the models still include many assumptions that remain to be validated.

Benefits to California

This project contributed to the Public Interest Energy Research (PIER) program objective of improving energy cost of California electricity through the use of inexpensive biomass fuels. The project also contributes to the PIER objective of improving the environmental risk by diverting waste streams away from landfills.

Successful commercialization of SCWG technologies could promote business opportunities in several industries, including process development, waste disposal, electrical generation, pollution control and transportation fuels.

Recommendations

The next research step is to scale up the critical elements of the SCWG system to eliminate the problems associated with the bench-scale system used in the current project and to conduct a series of tests that more accurately represent anticipated operational conditions. General Atomics in San Diego is currently constructing a scaled up SCWG test rig with full-scale HRSG reactor tubes that would be suitable for answering the outstanding technical questions. The following technical questions need to be answered:

- Test a full range of slurry concentrations in full size reactor tubes to identify the associated impact on steam and fuel gas production.
- Identify the optimum level of grinding required (if any) for trouble free gasification in full size reactor tubes,
- Confirm slurry distribution in a 10-tube inlet manifold for scale-up to a commercial plant,
- Confirm that the energy balance for SCWG is the same using full size reactor tubes,
- Evaluate the longer-term potential for corrosion, erosion or deposition,
- Test condensate for yield and quality and cleaning methods for recycle to slurry preparation,
- Test ash for beneficial use or land filling,
- Test mild operating conditions for byproduct yields and quality, including liquid hydrocarbons and carbon,
- Refine computer models and economic feasibility analyses for retrofit to existing gas turbines and boilers, and
- Collect and test fuel gases for combustibility in existing gas turbines, fuel cells and boilers.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: <http://www.energy.ca.gov/research/innovations> and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop- ment	5 Product Develop- ment	6 Demon- stration	7 Market Transfor- mation	8 Commer- cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/ Public Benefits/ Cost								

The Program Administrator’s assessment was based on the following supporting details:

Marketing/Connection to the Market. The project has submitted a Preliminary Business Plan detailing the product development to market. While the plan is quite detailed and pertinent to the issues of Gate 3, we believe that it presents a somewhat optimistic timeline from "proof of feasibility" to a marketable product. Future activity should include revision and updates to this plan as the California energy picture has changed since this plan was authored, particularly the cost of natural gas. Additionally, potential commercializers should be contacted and interviewed to provide feedback from currently identified potential customers as well as to identify additional customers and stakeholders.

Engineering/Technical. This project successfully demonstrated that composted municipal solid waste/sewage sludge can be gasified using the Supercritical Water Gasification process. Additional testing is needed to understand and optimize the operating parameters for the process. The Program Administrator concurs with the recommendations from the executive summary that the HRSG reactor tube test rig under construction at General Atomic, which permits full control over the SCWG process, is the appropriate test bed for evaluation of the following open issues.

1. **Test a range of slurry concentrations.** Conduct tests over the useful range of slurry concentrations using full-scale (One inch diameter) HRSG reactor tubes. Tests should be designed to provide the following information:

- Identify the relationship between solids concentration and associated impact on steam and fuel gas production,
 - Determine the optimum level of grinding required (if any) for trouble free gasification in full size reactor tubes,
 - Determine the energy balance for SCWG using a range of slurry concentrations and full size reactor tubes,
 - Determine if the fuel gases produced require additional processing to be used in existing gas turbines, fuel cells and boilers.
2. **Evaluate the Effluent.** Determine the potential of a zero-effluent design:
 - Test condensate for yield and quality and cleaning methods for recycle to slurry preparation,
 - Test ash for beneficial use or land filling,
 - Test mild operating conditions for byproduct yields and quality, including liquid hydrocarbons and carbon,
 3. **Hardware Specific Investigations.** Design factors to be considered:
 - Evaluate the longer-term potential for corrosion, erosion or deposition,
 - Confirm slurry distribution in a 10-tube inlet manifold for scale-up to a 100 tube commercial plant,
 4. **Test Planning.** Develop criteria and test plans for field experiments,
 5. **Provide updated estimates.** Refine computer models and economic feasibility analyses for retrofit to existing gas turbines and boilers.

Legal/Contractual. Intellectual property related to the core technology is protected by patent. Identified commercializers should be asked to submit existing and projected sales data as part of the process for selecting a commercializer for this technology.

Environmental, Safety, Risk Assessments/ Quality Plans. Some assessment of environmental impact has been done related to diversion of municipal solid waste and sewage sludge waste streams and the recycling of process water. Initial drafts of the following Quality Plans are needed prior to initiation of Stage 4 development activity; Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety.

Strategic. This product has no known critical dependencies on other projects under development by PIER or elsewhere. It is believed to be unique to this project with limited or no impact on other PIER projects.

Production Readiness/Commercialization. General Atomics Corp. in San Diego has been selected as the Research, Development and Demonstration collaborator. Their commitment to this project is evidenced by the SCWG pilot plant under construction in their "State of the Art" testing laboratory located at their Sorrento Valley facility in San Diego. Top candidates for commercializing partner remain to be identified and interviewed. However, a plan to accomplish selection of the partner has been identified.

Public Benefits. PIER research public benefits are defined as follows:

- 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 public benefit offered by the proposed technology is to make electrical energy more affordable in California. This will be accomplished by reducing the cost per KW of power generated by using composted municipal solid waste and sewage sludge as a fuel source in a combined cycle plant using super critical water gasification. A conservative lifecycle cost analysis was performed using the following assumptions:

- 50 MW combined cycle power plant using SCWG process
- 30 year plant life
- Capital cost of \$1200/KW
- O&M cost of \$.005/KW
- Thermal efficiency of 50%
- 75% availability
- Fuel costs of \$2.24Mil/year (\$1.00/Mbtu)

Based on the above assumptions the proposed plant could produce power for approximately \$.024/KW which is competitive. The major urban areas in California could conservatively divert sufficient municipal solid wastes and sewage sludge to support ten 50MW plants.

The proposed cost of fuel (\$1.00/Mbtu) assumes that tipping fees will fund the majority of the costs associated with processing the waste streams into compost. This assumption is a risk factor that would need to be further assessed in the business plan.

Additional benefits to California include:

- Diverting biomass from the landfills reduces greenhouse gasses which can escape into the atmosphere and toxic effluents which can contaminate water supplies. A report prepared by the National Renewable Energy Laboratory, "The Value of the Benefits of U.S. Biomass Power," by G. Morris, places a value on this benefit alone at \$0.047/KW generated from biomass.
- Use of renewable biomass for fuel produces a reliable fuel source and reduces California's dependency on limited domestic or expensive foreign fossil fuels.
- Use of MSW and sewage sludge for fuel reduces the volume of this waste material by 80%, which extends the life of existing landfills and reduces the need for new landfills.

Program Administrator Assessment:

After taking into consideration: (a) research findings in the grant project, (b) overall development status as determined by stages and gates 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 follow on funding within the PIER program.

Receiving follow on 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.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)