



CALIFORNIA
ENERGY
COMMISSION

ENERGY INNOVATIONS SMALL GRANT PROGRAM
Renewable Energy Technologies

Counter Rotating Wind Turbine System

FEASIBILITY ANALYSIS

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Gray Davis, Governor

CALIFORNIA ENERGY COMMISSION

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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>.

Counter Rotating Wind Turbine System

EISG # 00-09

| | |
|-------------------------|------------------------------------|
| Awardee: | Appa Technology Initiatives |
| Principal Investigator: | Kari Appa |
| PI Contact Info: | (949) 458-7314; appa33@pacbell.net |
| Grant Funding: | \$74,915 |
| Grant Term: | February 2001 – April 2002 |

Introduction

Most wind turbines in the world are single rotor systems, which provide simplicity, reliability and durability. Over the years, improvements have enhanced energy conversion efficiency of these single rotor systems. For example, blades have better aerodynamic characteristics, gears with reduced noise have better torque transmission efficiency, and alternators have better electrical efficiency. However, despite these improvements, single rotor systems are able to convert only a small fraction of the total wind stream energy into electrical energy.

Albert Betz predicted the maximum energy conversion efficiency of 59% when the axial wind speed is reduced by $2/3^{\text{rd}}$ across a single rotor disc. However, practical wind turbines convert less than 40% of the wind energy into electrical energy. Hence, nearly 60% of the potential wind energy escapes without being harnessed. According to C. G. Curtis, the primary reason may be that a single rotor cannot be designed to achieve large changes in velocity or enthalpy. He therefore introduced the concept of velocity compounding using multiple rotors in tandem. This principle appears to be applicable to wind turbines as well.

This project investigated the power production and performance characteristics of a contra rotating wind turbine system.

Objectives

The goal of this project was to determine the feasibility of improving wind energy conversion efficiency by utilizing a contra rotating wind turbine system. The researcher established the following project objectives:

1. Investigate performance of a contra-rotating dual rotor system as a means of enhancing wind energy conversion efficiency, targeting reduction of energy costs (\$/kWh) by 30%.
2. Develop designs for the contra-rotating dual rotor system for a low cost wind turbine (\$/kW). The designs should allow early and economical transition to the utility scale wind turbines.

Outcomes

1. The project fabricated a prototype contra-rotating wind turbine system. The project team then installed the assembled unit on a 50-ft tower at the Oak Creek Energy Systems facility in Mojave, California. Tests conducted over a period of four months showed:
 - a. At lower rotor speeds, energy extraction increased by up to 40% over an equivalent single rotor wind turbine.

- b. No detectable buffeting of the turbine blades occurred.
 - c. Bending stress on the supporting tower was reduced by the contra rotating system over the single rotor system
2. The study identified design solutions to the problem of transmitting the net torque generated by a contra-rotating turbine system to an existing electrical power-generating unit. Because these solutions make use of existing hardware, they depend on the configuration of the existing equipment on the targeted wind farm. Two separate solutions are presented.

Conclusions

1. The field tests demonstrated that power conversion efficiency could be increased up to 40% by using a wind turbine with a contra-rotating rotor system versus a wind turbine with only one rotor. This increase will result in increased energy generation from a given tower installation, but the researcher did not relate back to the reduced energy cost target.
2. Power conversion efficiency was high at low rotor speeds, suggesting applicability of contra rotating turbines to large utility scale wind turbines that rotate at 16-20 rpm.
3. Buffeting can be a fatal problem leading to premature failure of a wind turbine. It is encouraging that buffeting did not occur on the contra rotating rotor system.
4. The contra-rotating system reduces bending stress on the tower. This reduced bending stress results when the torques produced by two rotors counterbalance each other.
5. There is a good prospect for a utility scale contra rotating turbine system to produce from 30% to 50% more energy from high and low speed wind farms in California. This prospect needs confirmation through further testing.
6. If the prospect of extracting additional energy as suggested in item 5 above is confirmed, this technology should find a market in the retrofit of existing wind farms. The project identified two fundamentally different approaches:
 - a. If the existing generator is provided with a dual winding (twin-generator) system, the same generator can be used for higher power rating. In this case, the shaft rotation power from the contra-rotating turbine is reversed in direction by a torque hub and combined with the existing turbine's power, both rotors driving the same generator.
 - b. If the existing generator is not provided with a twin-generator system, a second generator and the contra-rotating turbine can be added in a back-to-back fashion to the rear of the existing generator. This may require a new mounting platform or simply brackets to attach to the existing platform.

Benefits to California

Successful commercialization of contra-rotating wind turbine systems could reduce the cost of electricity to California ratepayers, promote increased power production, and stimulate business and employment opportunities in wind turbine industries within California. These benefits would occur by producing more wind-generated power per acre of land and by using common facilities such as support towers and possibly generators. At this time, wind-generated electricity is the most economical renewable energy. In California, wind energy production is highest in the afternoon to early evening time period. This is also the time that demand for electricity peaks

in California. Currently these demand peaks are met with relatively costly simple-cycle combustion turbines. Increasing wind power production would offset the need to run these “back-up” turbines. Air quality would also improve since simple cycle combustion turbines have relatively high emissions of NO_x and CO.

Recommendations

The present study demonstrated the feasibility of a contra-rotating wind turbine system by using readily available components. The next step is to design, build and test a utility scale, grid-connected wind turbine system. A major task in the next steps is to assess cost effectiveness of the counter-rotating design.

The suggested next steps are as follows:

1. Select a grid-connected environment in the 50 to 100 kW power rating range.
2. Design and build the units to a cost target.
3. Team with a wind power production company to install one or more units.
4. Conduct power production performance studies with grid-connected power loading for a period of one year or more.
5. Assess the cost-effectiveness of dual rotor system versus the single rotor system using available data.
6. After successful completion of this study, plan to transition the technology by licensing to manufacturers or utility providers.

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. The Development Assessment Matrix below summarizes this assessment. Shaded bars 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 in 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 Generati on | 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

ATI has just completed the preliminary demonstration of feasibility of a contra rotating wind turbine system. The present study shows the applicability of the contra rotating wind turbine system to utility scale turbines. If this is confirmed with additional tests, there appears to be a huge market for upgrading existing wind farms as well as for new utility scale contra rotating wind turbine systems. Oak Creek Energy Systems (OCES) has encouraged ATI to conduct additional tests to demonstrate the merits of contra rotating wind turbine systems under various model and environmental situations. OCES has offered to support field tests in their utility environment.

Engineering/Technical

This project successfully demonstrated that the contra rotating rotor system could extract up to 40% or more energy from the wind stream than a single rotor under some conditions. The next step is to verify these results in a grid-connected environment. ATI has developed a concept of contra-rotating system power transmission unit to drive an existing grid-connected induction generator. OCES has agreed to provide field test support and a 50 kW induction generator unit for use in this test program.

Suggested Program:

1. Select a test site that is interconnected to the utility grid with a 50 to 100 kW power rating.
2. Design a counter rotating system using a generator/transmission coupling system and stall regulated rotor blades.
3. Conduct excess power production performance studies with grid connected power loading for a period of one year or more. Assess economics of contra rotating system of new as well as retrofitted configurations versus single rotor systems.
4. Team with a wind power production company such as Oak Creek Power Systems Inc. to install several of high power rated units of approximately 250 kW output.
5. Plan to transition the technology by licensing to manufacturers and utility operators after successful completion of this study.

Legal/Contractual

The awardee has filed three US Patent applications. Two patents have been issued and one is in pending. These are:

1. Kari Appa, "Jet Assisted Counter Rotating Wind Turbine". US Patent No. 6,127,739, October 3, 2000.
2. Kari Appa, "Contra-Rotating Wind Turbine System". US Patent No. 6,278,197 B1, August 21, 2001
3. Kari Appa, "Jet Assisted Hybrid Wind Turbine System", (in Pending, Jc996 U. S. PTO 09/894345, submitted 06/28/2001)

Environmental, Safety, Risk Assessments/ Quality Plans

ATI will use readily available wind turbine components that pose no harm to personnel health or environment. Quality plans to be drafted or modified for use include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental.

Strategic

This product has no known critical dependencies on other projects under development by PIER or elsewhere

Production Readiness/Commercialization

The present technology needs additional evaluation to qualify for commercialization. The project has not selected an organization to commercialize the technology. Oak Creek Energy Systems may continue to act an IR&D partner.

Public Benefits

Public benefits derived from PIER research and development 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 derives from reduced environmental impacts of the California electricity supply or transmission or distribution system. The feasibility tests have demonstrated significant benefit to low speed rotors such as utility scale wind turbines. If additional demonstrations confirm these results, currently existing and new future wind farms may use contra-rotating rotor systems to enhance energy production 40% or more from the same wind stream.

For small volume construction and based on a 250 kW turbine, the cost of one contra-rotating turbine is estimated at \$15000, with the generator/transmission coupling another \$18000. A new yaw support system and retrofit labor is estimated to cost \$10000. This totals \$43000 for what the data indicated to be at least a 100 kW increase in generation capacity. Assuming a wind farm power capacity of 30% and \$0.035 per kW-hr, this increased capacity would provide a simple payback period of less than 5 years. That is, $100 \text{ kW} \times 30\% \times 8640 \text{ hr/year} \times \$0.035 / \text{kWh} = \$9072/ \text{year}$ of income and $\$43000 / \$9072 / \text{year} = 4.74$ years simple payback.

The costs of a contra rotating turbine system are strongly dependent on the retrofitting of original equipment. For many configurations, economies of scale will result in quicker payback for larger installations.

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 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)