Arnold Schwarzenegger
Governor

BUILD AND TEST A 3 KILOWATT PROTOTYPE OF A COAXIAL, MULTI-ROTOR WIND TURBINE

INDEPENDENT ASSESSMENT REPORT

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Public Interest Energy Research Program
Energy Innovations Small Grants Program

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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.

PIER funding efforts are focused on the following research, development, and demonstration (RD&D) program areas:

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

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million, of which 5 percent is allocated to the Energy Innovation Small Grant (EISG) Program. The EISG Program is administered by the San Diego State University Foundation through the California State University, which is under contract with the California Energy Commission.

The EISG Program conducts up to six solicitations a year and awards grants for promising proof-of-concept energy research.

The EISG Program Administrator prepares an Independent Assessment Report (IAR) on all completed grant projects. The IAR provides a concise summary and independent assessment of the grant project to provide the California Energy Commission and the general public with information that would assist in making subsequent funding decisions. The IAR is organized into the following sections:

- Introduction
- Project Objectives
- Project Outcomes (relative to objectives)
- Conclusions
- Recommendations
- Benefits to California
- Overall Technology 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 IAR, please visit the EISG program page on the California Energy Commission's website at: http://www.energy.ca.gov/research/innovations or contact the EISG Program Administrator at (619) 594-1049, or e-mail at: eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the California Energy Commission's website at http://www.energy.ca.gov/research/index.html.

Abstract

Increasing the power of wind turbines, by increasing rotor diameter, results in engineering challenges of excessive blade weight, excessive torque, and low rotor RPM, requiring a gearbox. By combining seven separate rotors to spin a common driveshaft, this research demonstrates a new method to increase the swept area and power production of a wind turbine, without increasing diameter. The resulting high RPM shaft rotation directly drives the generator, needing no gearbox. Six months of testing at the facilities of Windtesting.com in Tehachapi, CA confirm reliable operation. Seven 7-foot (2.1 m) diameter rotors produced 4500 watts in winds of 27 mph (12 m/s), compared to 690 watts for one rotor. Spacing between rotors, and an offset angle from the wind direction, providing fresh wind to each rotor, for 5 to 6 times the power at all wind speeds. Winds up to 45 mph (20 m/s) produced continuous full power output and smooth operation, proving a new method of over-speed protection. Results exceeded targeted output goal, achieving a best-case scenario. Therefore, a new method to multiply the power output of a wind turbine, without increasing the diameter, is demonstrated, reducing the array turbine, with its known advantages, to a single moving part. The data generated from this research provides a scientific basis of comparison using industry-standard blades, to prove that multiple rotors mounted to a common driveshaft can effectively work together to generate vastly more power than a single rotor of the same diameter, validating a promising direction in wind turbine design.

Keywords: wind turbine, multi-rotor, array turbine, direct-drive generator, power, renewable energy, electricity, wind energy, offshore wind, RPS

Introduction

Harvesting California's wind generation potential depends on availability of cost effective, reliable, environmentally compatible wind turbines. The trend toward ever-larger rotors to harness more power at a given location leads to several design challenges which may limit this approach's ability to optimize three key drivers. Larger blades produce less power for the amount of material required. Blade weight varies as the cube of diameter, whereas power varies as the square of diameter. The slower rotation of large blades requires gearing to drive a generator (or a specially-designed low-speed generator), and since torque increases with the cube of diameter, gearbox design and maintenance are negatively impacted. For many stakeholders, the larger, slower-turning rotors exacerbate visual environmental impacts.

A wind turbine design that would produce equivalent or better power as the single-rotor approach without introducing the burdens associated with larger rotor sizes described above could reduce cost, improve reliability, and reduce visual impacts. This could translate into lower electricity costs to California ratepayers, and result in a larger quantity of renewable energy from wind available to the state.

The researcher designed and tested a self-aiming turbine that used multiple rotors mounted on a common driveshaft, thereby eliminating the need for a gearbox, and drastically reducing rotor size compared to a single rotor unit of similar power output. An innovative turbine mounting mechanism which allows the shaft to tilt as much as 25 degrees from horizontal exposed each set of blades to fresher wind, and helped protect them from high wind events.

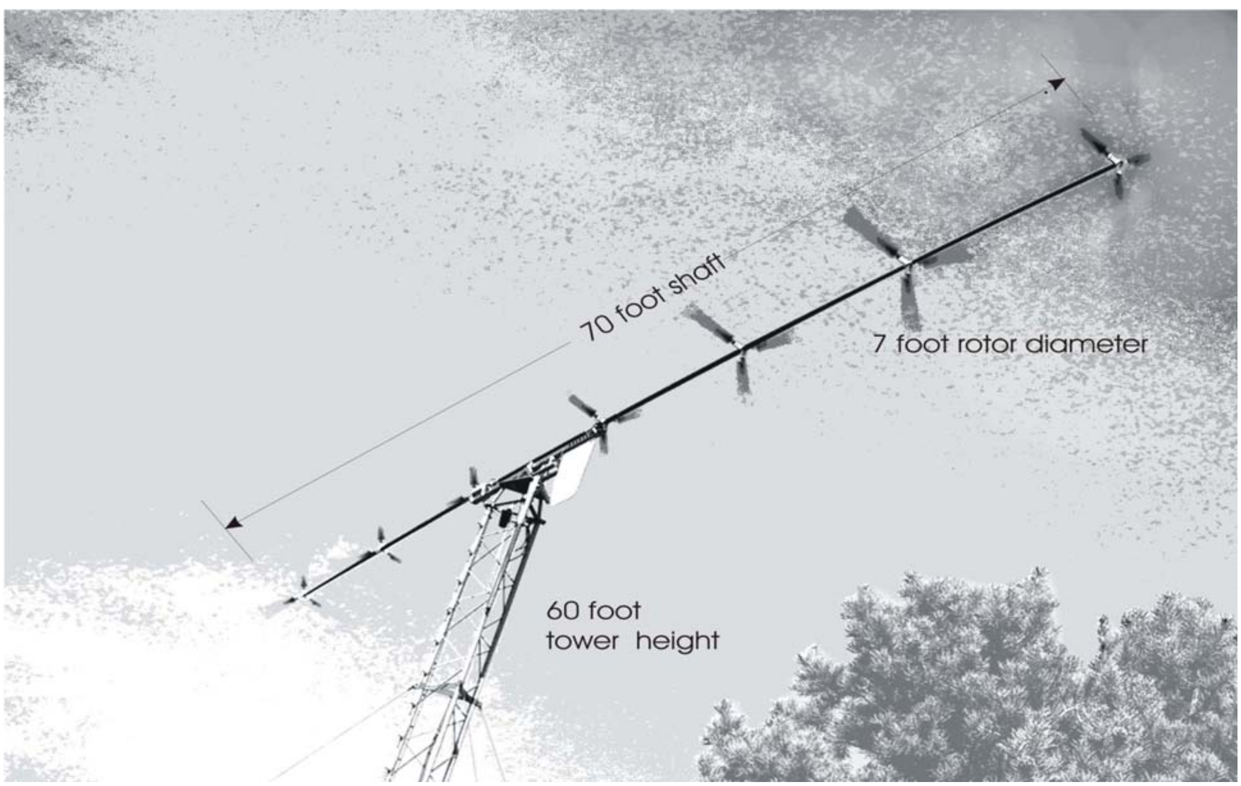

Figure 1: Prototype 3 kW Co-Axial, Multi Rotor Horizontal Axis Wind Turbine

Objectives

This project was to determine the feasibility of a new type of horizontal axis wind turbine, in a three kilowatt prototype. A co-axial, multi-rotor horizontal-axis turbine utilized an elongated driveshaft with seven rotors mounted coaxially at regular intervals, rather than a single rotor. A new type of furling mechanism allowed the shaft to be blown into a horizontal orientation for protection in high winds. The researchers established the following project objectives:

1. Fabricate a three kilowatt, co-axial, multi-rotor wind turbine (U.S. patent application number 09/997,499.)
2. Demonstrate an output of three kilowatts in a 27 mph wind from the prototype wind turbine.
3. Demonstrate full power generation at wind speeds of 27 mph to 45 mph.
4. Demonstrate power output that is at least three times higher at low and medium wind speeds (up to the rated wind speed of 27 mph) than a single-rotor turbine of the same diameter.
5. Demonstrate the capability of the design to protect the turbine against over-speed in winds up to 50 mph or if this speed is not reached, the highest wind speed measured during the testing period.
6. Demonstrate wind turbine durability by completing the 6-month testing period with at least 90 percent uptime.
7. Based on the data generated in this project, show that the projected life cycle cost of power of $.04/kWh for the proposed three kW design continues to be supported.
8.

Outcomes

1. The turbine was built with seven rotors, each seven feet in diameter, and mounted on a single, 70 foot long tubular carbon fiber driveshaft.
2. Output of the turbine was 4.5 kW (corrected to sea level) in the targeted 27 mph wind, well above the design target of 3 kW. With a conservative setting to begin furling at 16 mph, the turbine still met the targeted output of 3 kW in a 27 mph wind.
3. Turbine output was 5.5 kW at a 30 mph wind speed, increasing to 6 kW or more at wind speeds between 33 mph and 45 mph.
4. Output was 5 to 6 times the power of a single-rotor turbine of the same diameter at all tested wind speeds.
5. The turbine survived wind speeds up to 45 mph, the maximum speed encountered during the course of the study, with no damage, while maintaining full power output (between 5 and 6 kW at these speeds) and smooth operation. The tilting mounting mechanism (U.S. Patent 6692230) functioned as designed, allowing the shaft to rotate toward the horizontal from the default 25 degree upward tilt as wind speeds increased, thereby mitigating the amount of fresh wind striking all but the front rotor for overspeed protection.
6. The turbine operated during most times of sufficient wind during six months of testing over an eight month period. Overall the unit was fully deployed in operational mode for 90 percent of the six-month target duration. Other than adjustments to fine tune performance, there was no required maintenance or repair of the turbine.
7. Total cost for the prototype was not presented in the final report, nor was there information about the cost of a single-rotor unit of equivalent total capacity. The principal investigator

(PI) calculates that elimination of the gearbox in single-rotor machines would result in a 17 percent turbine cost reduction leading to a 10 percent life-cycle power cost savings, but does not show a supporting calculation of the life-cycle cost of power from the prototype design utilizing actual costs from the research.

Conclusions

1. The objective of fabricating a three kW unit was met.
2. Turbine output exceeded the objective by 50 percent, and met the objective even with a very conservative furling adjustment that began to reduce output at 16 mph wind speeds.
3. The turbine operated smoothly throughout a wide range of wind speeds, up to the highest encountered speed of 45 mph, meeting the objective for operation at high wind speeds.
4. Output of the seven blade unit was well above the targeted three times the output of a single-rotor turbine with the same diameter as the blades used in the tested unit, ranging between five and six times that of a single-rotor unit.
5. The patented tilting mechanism protected the turbine through wind speeds up to 45 mph (the highest encountered), and allowed smooth operation at higher wind speeds through its furling design, meeting the targeted objective.
6. The turbine met the objective for 90 percent operation during the six-month test period. There was no equipment failure or required corrective maintenance.
7. Without cost data for the tested unit and for a single-rotor unit of equivalent output, it is not possible to verify whether the costs of a production multi-rotor turbine would likely be sufficient to meet the targeted $0.4 / kWh life cycle target, or be less than a conventional single-rotor turbine of equivalent capacity. However, the research did provide useful cost insights. The PI states that the savings in rotor costs resulting from less required material than for a single rotor of equivalent capacity were roughly offset by the cost of the longer shaft required to support the multiple rotors. The most immediate savings opportunity is elimination of the gearbox (estimated at 17 percent of the cost of current systems), along with its associated maintenance and repair. Other cost savings should be possible through avoiding the need to transport very large single rotors to sites, especially those in remote locations.

This was a successful physical demonstration of the concept, design, and operation of a co-axial multi-rotor wind turbine. Output of the prototype exceeded the target; the innovative mount provided clearer wind for the downwind rotors during normal operation and protected them from overspeeding in high winds; and the unit operated successfully for six months under a range of conditions. Whether the life cycle cost of a production unit would compete effectively with existing single-rotor designs will depend on further testing and refinement of the various cost elements in this approach, and a comparison with comparable single-rotor machines.

Recommendations

1. Provide a follow-up report with details of the full cost of the equipment utilized, and a comparison to the cost of a single-rotor unit with equivalent output.

2. Conduct similar testing at a second location, with different wind regimes and topography (perhaps National Renewable Energy Laboratory in Colorado).
3. Extend the test duration beyond six months, to further evaluate operation and maintenance requirements of the design.
4. Conduct noise studies and compare results to a single-rotor design with equivalent output.

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 additional 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.

Benefits to California

Public benefits derived from PIER research and developments 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 its potential to increase the amount of wind-generated electricity available to California, thereby reducing environmental impacts of the California electricity supply. This potential can occur in several ways, assuming the positive indications from this research lead to successful development of commercial multi-rotor machines. For example, avoiding the need for ever-larger rotors to develop large amounts of power at a location could reduce the installation costs and overcome the potentially prohibitive access to some sites inherent in large rotor machines, fostering additional wind development. Additional sites could also become available due to the design’s mitigating the visual impacts of large, slow turning rotors.

Overall Technology Transition Assessment

As the basis for this assessment, the program administrator reviewed the researcher's 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 for cost effective, reliable, environmentally compatible alternative energy technologies is clearly booming. There is both a policy push (California's Renewable Portfolio Standard, California's Preferred Loading Order for new resource additions, various Tax Credits), and a demand pull resulting from ever-increasing costs of fossil generation, and consumer's awareness of the environmental impacts of such generation. There is considerable room for continued technological innovation in wind generation, as both traditional single-rotor designs and innovative alternate designs vie for a share of a very large international market.

Engineering/Technical

The principal investigator states that there are no remaining technical or engineering obstacles preventing product demonstration, and that a development path has been identified.

Legal/Contractual

The principal investigator states that a number of patents have been obtained, and that others are in progress relating to the tested design.

Environmental, Safety, Risk Assessments/ Quality Plans

No specific information was presented by the principal investigator related to further testing, reliability, cost, or manufacturing analysis. This appears to be an area where further research and funding would be appropriate.

Production Readiness/Commercialization

The principal investigator states that there are expressions of interest from major market players in helping commercialize the turbine, and that engineering specifications for the commercial product have been developed. He further describes ongoing expressions of interest in products, venture capital infusions, and buyouts from multiple entities.

Appendix A: Final Report (under separate cover)

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

Attachment A – Grantee Report

BUILD AND TEST A 3 KILOWATT PROTOTYPE OF A COAXIAL, MULTI-ROTOR WIND TURBINE

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Legal Notice

Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

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Abstract

Increasing the power of wind turbines, by increasing rotor diameter, results in engineering challenges of excessive blade weight, excessive torque, and low rotor RPM, requiring a gearbox. By combining seven separate rotors to spin a common driveshaft, this research demonstrates a new method to increase the swept area and power production of a wind turbine, without increasing diameter. The resulting high RPM shaft rotation directly drives the generator, needing no gearbox. Six months of testing at the facilities of Windtesting.com in Tehachapi, CA confirm reliable operation. Seven 7-foot (2.1 m) diameter rotors produced 4500 watts in winds of 27 mph (12 m/s), compared to 690 watts for one rotor. Spacing between rotors, and an offset angle from the wind direction, provide fresh wind to each rotor, for 5 to 6 times the power at all wind speeds. Winds up to 45 mph (20 m/s) produced continuous full power output and smooth operation, proving a new method of overspeed protection. Results exceeded targeted output goal, achieving a best-case scenario. Therefore, a new method to multiply the power output of a wind turbine, without increasing the diameter, is demonstrated, reducing the array turbine, with its known advantages, to a single moving part. The data generated from this research provides a scientific basis of comparison using industry-standard blades, to prove that multiple rotors mounted to a common driveshaft can effectively work together to generate vastly more power than a single rotor of the same diameter, validating a promising direction in wind turbine design.

Keywords: wind turbine, multi-rotor, array turbine, direct-drive generator, power, renewable energy, electricity, wind energy, offshore wind, RPS

Executive Summary

Introduction:

Wind-generated electricity, the fastest-growing segment of the energy industry, is mandated by legislation worldwide to form an increasing percentage of the energy mix in future years. The demand for more powerful turbines is currently being met by increasing rotor diameter. As diameter is increased, three major engineering challenges result:

First, larger blades produce less power for the amount of material used. Blade weight varies as the cube of diameter, power varies as the square of diameter, so with increasing diameter, blade weight grows faster than power output, making larger blades less economical. [10]

Secondly, as rotor diameter increases, RPM drops; larger rotors turn slower, requiring more gearing to drive a generator. With the largest rotors turning at less than 10 RPM, and generators requiring up to 1800 RPM, a multi-stage gearbox is normally required.

Third, drivetrain torque, like blade weight, is a cubic function in relation to diameter, and so torque also increases disproportionately, relative to power output, as diameter increases. For larger diameter turbines then, the gearbox, turning slower yet delivering more power, must be disproportionately more robust compared to the extra power produced. Wear on gear teeth and bearings is a major cause of expensive downtime and repair. Direct drive generators are one effective solution, prohibitively expensive due to the low RPM of large diameter rotors. [10]

The self-aiming design of this project with several rotors mounted on a common driveshaft, gathers more power, without the undesirable increase in diameter. Data generated in this research verify the most effective method of power augmentation yet found for a wind turbine of a given diameter, combining the greater power of a large turbine with the high RPM of a small turbine, to directly drive a generator of reasonable size, eliminating the gearbox. The result is a more reliable, economical turbine.

Project Objectives:

1. Fabricate 3-kilowatt wind turbine;
2. Demonstrate that the wind turbine generates 3 kilowatts in a 27 mph (12 m/s) wind;
3. Demonstrate that the proposed turbine continues to generate full power at wind speeds over the rated wind speed of 27 mph (12 m/s), up to 45 mph (20 m/s);
4. Demonstrate that the proposed turbine generates at least 3 times more power at low and medium wind speeds, up to the rated wind speed of 27 mph (12 m/s), than a single-rotor turbine of the same diameter;
5. Demonstrate that the proposed turbine mounting design is capable of protecting the turbine against overspeed in winds up to 50 mph (22.4 m/s) or if this speed is not reached, the highest wind speed measured during the testing period;
6. Demonstrate that the proposed prototype wind turbine will operate for the 6-month testing period with at least 90% uptime;
7. Based on the data generated in this project, show that the projected life cycle cost of energy of $.04/kWh for the proposed design continues to be supported;

Project Outcomes:

1. The turbine was built with 7 rotors, 7 feet (2.1 m) in diameter, on a single tubular carbon fiber driveshaft, with direct-drive generator, mounted on a tower at the facilities of Windtesting.com in Tehachapi, CA with full instrumentation, and run for 6 months, data taken.
2. The turbine generates 4500 watts at 27 mph (12 m/s) corrected to sea level (50% over target).

3. The turbine generates 5500 watts at wind speeds of 30 mph (13.4 m/s), and 6000 or more watts at all speeds from 33 mph (14.8 m/s) to 45 mph (20 m/s), maintaining full power in a gale.
4. The turbine generates 5 to 6 times the power of a single-rotor turbine of the same diameter, at all wind speeds, using industry standard blades for direct comparison to a known turbine model.
5. The turbine easily survived winds up to 45 mph (20 m/s), which were the highest encountered during the test period. A new tilt-back method of overspeed control functioned effectively.
6. The turbine operated effectively for the 6 month duration of the experiment, with 90% uptime, ending the study in operational condition.
7. The price of wind-generated electricity is now $.04/kWh. Eliminating the gearbox should lower the cost to $.036/kWh. The increased swept area and greater energy capture, of combined, multiple rotors, may extend the current price to regions with lower wind resources.
8. U.S. Patents 6616402 and 6692230 issued during this project, 3 more U.S. patents are pending, and International (PCT) patents are now pending around the world, all based on the general co-axial, multi-rotor wind turbine concept.

Conclusions:

1. By using industry-standard blades, allowing direct comparison to a known single-rotor turbine, this research has demonstrated that the co-axial multi-rotor configuration is an effective approach to generating electricity from the wind, by confirming that power output is multiplied generally in proportion to the number of rotors, with minimal losses.
2. For a 3000 watt version, at this 7 foot (2.1m) diameter, only five (5) rotors are necessary.
3. The co-axial multi-rotor configuration is now proven as by far the most effective method yet discovered, to increase the power output of a wind turbine of a given diameter.
4. The ability to passively increase the swept area in response to low wind speeds offers great potential to make wind energy viable in regions with a less-than-ideal wind resource.
5. The ability to passively decrease the swept area in response to high wind speeds has proven to be an effective method of overspeed protection.
6. The general design of the prototype saves costs by eliminating the need for a gearbox
7. Even more significant cost savings are possible with the next generation (patents issued and pending) of co-axial multi-rotor turbines specifically designed to maximize the benefits of the technology, while minimizing cost (See Appendix X – proprietary).

Recommendations:

With the power gathering ability of the co-axial multi-rotor configuration now proven, the concept should be implemented in its many further embodiments:
1. The floating, tilting, offshore version of U.S. patent 6616402, should be built. Comprising a single moving part, the design eliminates the rigid foundation, the heavy steel tower, the yaw bearing and yaw control mechanism, the gearbox, the gargantuan blades, and the requirement for a crane or large ship to deploy. Permitting is streamlined and range is expanded to deep water.
2. Atmospherically buoyant versions, as delineated in U.S. patent 6616402 should be explored with experienced blimp (LTA) manufacturers as part of a federally sponsored research program.
3. Next generation versions (patent pending – see Appendix X - proprietary), producing more power at lower cost, should be built and tested, based on the knowledge gained in this project.
4. International licensing should take place, based on the international (PCT) patents pending.
5. Further research and development of the co-axial multi-rotor turbine concept, including low wind speed performance, funded at the State and Federal level, and by private industry, is urged.

Public Benefits to California:

Meeting RPS Goals: The co-axial multi-rotor configuration shows potential to lower costs and expand the range of wind-generated electricity, helping the state to meet its recently-enacted Renewables Portfolio Standard (RPS) goal of 20% non-hydro renewable generation by 2010.

Lowering the cost of electricity provides an economic benefit to California.
The co-axial, multi-rotor wind turbine, sufficiently deployed to meet RPS goals, can provide savings ranging between $5.7 billion and $17.1 billion per decade for California, based on generation at or below $.04/kWh and conservative, published estimates of the avoided future cost of energy. Greater savings would result from higher fuel prices and/or wider deployment.

Facilitating clean electricity generation provides aesthetic and health benefits to California.

Confirmation of the power gathering ability of the land-based version is a first step toward development of California's huge offshore wind potential, since the floating, tilting, offshore version lowers costs, and expands the range to deeper waters, typical of California's coast.

Improved Low Wind Speed Performance: California's high wind areas are remote, while lighter winds prevail near cities. Using multiple rotors enhances energy capture in low winds, expanding the number of viable sites near cities, reducing demand for more transmission lines.

Improvements in wind turbine technology allow generation of abundant power while producing no CO_2, helping California conform to the Kyoto Protocol, and generating income for the state from carbon emissions trading schemes such as Green Tags.

Hydrogen Economy for California and the *California Hydrogen Highway Network* : Abundant electricity to make inexpensive hydrogen fuel is limited only by installed wind energy capacity. Multi-rotor wind turbines, by lowering costs and expanding the number of sites, help to make such a transition possible.

Self-Sufficiency for California: The abundant energy in the wind can make California self-sufficient, eliminating the expense in lives and capital of defending foreign oil.

Cash Influx to California through Worldwide Licensing and Sales: International (PCT) patent protection, covering 95% of the wind energy market, is generating strong licensing interest from around the world. Local manufacture would generate jobs and capital infusion.

Introduction

Power output of a wind turbine is proportional to the area swept by the blades. Traditionally this swept area was increased, by increasing the rotor diameter. This resulted in disproportionately heavy blades and lowered rotational speed (low RPM), which then required more gearing to drive a high-speed generator.[10] The co-axial multi-rotor turbine of this research project multiplied output six fold by adding six extra rotors to a single very long driveshaft. The light weight and high RPM of smaller rotors is combined with the increased swept area, and higher power output, of a larger diameter rotor, essentially achieving the best of both worlds, using only a single moving part. The higher RPM can be used to directly drive a generator, bypassing the need for a gearbox. The self-aiming driveshaft with its attached rotors is oriented at a slight angle to the wind direction, to bring fresh wind to each rotor, so all rotors gather full power. In very strong winds the driveshaft is blown parallel to the wind, placing all rotors within the protective zone of the wake generated by the first rotor, to prevent damage.

This project has verified the most effective way yet to increase the power output of a wind turbine without increasing the diameter, by using industry-standard blades for the sake of comparison to the known output of a single-rotor turbine of the same diameter. It represents scientific validation of a new principle in wind turbine design, opening a new door into the third dimension, and a new chapter in the science of aerodynamics and fluid mechanics in general. Continued exploration down this design path of co-axial, multi-rotor technology can be expected to produce from one to several orders of magnitude more power than today's single-rotor designs, yielding a lower cost of energy.

Problems with the Present State-of-the-Art, Addressed or Solved by this Research:

Current single-rotor wind turbines are a refined version of a 1000 year-old design, and suffer from the following challenges as ever-larger and more powerful versions are attempted:
(See also: Appendix VIII: Prior Art – Approaches by Others)

- Disproportionately Heavy Blade Weight:

Larger blades capture less energy per unit mass than small blades due to the cube/square law, leading to clearly diminishing economic returns for the largest blades. [10, 12]

- Low RPM of Larger Rotors:

The larger a rotor, the slower its rate of rotation (RPM). A gearbox is currently needed to translate the slow rotation of the rotor to the fast rotation required by the generator.

- Disproportionately High Torque of Larger Rotors, Due to Increased Power at Lower RPM:

Torque, being proportional to diameter cubed, grows faster than power output with increasing blade length, causing stress on drivetrain components, especially gear teeth and bearings. [16]

- Gearbox Failure:

The gearbox is therefore the most wear-prone, maintenance-intensive component of existing large wind turbines, most responsible for expensive downtime and repairs. [10, 16]

- The Direct-Drive Generator Solution:

One approach to eliminate the gearbox uses a specially built, large diameter, low RPM, direct-drive, permanent-magnet ring generator, as currently utilized by turbine-maker *Enercon*. [17]

- Low RPM Makes Direct-Drive Generators Too Costly:

Large diameter rotors turn slowly, requiring direct-drive generators to be prohibitively large. [10]

- Difficulty Manufacturing and Transporting Larger Blades:

Tooling for larger blades is more expensive, and requires a larger facility. Blades as long as 60 meters (200 feet) are cumbersome, requiring special equipment, roads, and trucks to transport.

- Tower Strikes by Blades:

Current single-rotor upwind turbines encounter issues with blades hitting the tower. Longer blades in close proximity to the tower must be made stiff enough to avoid tower strikes.

- Yaw Control Mechanism Required:

Current turbines constantly measure wind direction and then actively aim the entire nacelle by a gear drive. The mechanisms are expensive to design, install, support, and maintain.

- Performance in Low Wind Speeds:

Communities with low wind resources nevertheless desire to participate in wind energy. The only answer from current technology is to increase blade length, lowering RPM, raising costs.

- Aesthetics:

Visual clutter often associated with the unconnected movements of many single-rotor turbines is objectionable, but may be reduced with the simultaneous, uniform movement of multiple rotors.

- Safety: Habitable buildings must be located many diameters from today's larger turbines. A large blade, if thrown, can travel long distances and damage buildings and people.

This research effort was carried out under the Renewable Energy Technologies subject area of the PIER program of the California Energy Commission.

Project Objectives

The following objectives were specifically targeted:

Objective 1: Fabricate 3 kilowatt wind turbine;

Objective 2: Demonstrate that the proposed prototype wind turbine will generate 3 kilowatts in a 27 mph wind;

Objective 3: Demonstrate that the proposed turbine is capable of continuing to generate full power at windspeeds over the full-power rated wind speed of 27 mph, up to 45 mph;

Objective 4: Demonstrate that the proposed turbine generates at least 3 times more power at low and medium wind speeds, up to the rated wind speed of 27 mph than a single-rotor turbine of the same diameter;

Objective 5: Demonstrate that the proposed turbine mounting design is capable of protecting the turbine against overspeed in winds up to 50 mph or if this speed is not reached, the highest windspeed measured during the testing period;

Objective 6: Demonstrate that the proposed prototype wind turbine will operate for the 6-month testing period with at least 90% uptime;

Objective 7: Based on the data generated in this project, show that the projected life cycle cost of energy of $.04/kWh for the proposed design continues to be supported;

Project Approach

Task 1: Build 3 Kilowatt, Co-Axial, Multi-Rotor Turbine:

Subtask 1.1: Obtain Components:

Driveshaft:
Filament-wound carbon fiber/epoxy tubes were obtained as driveshaft material, based on strength, fatigue resistance, light weight, straightness, structural integrity, dimensional accuracy, and a uniform bending response.

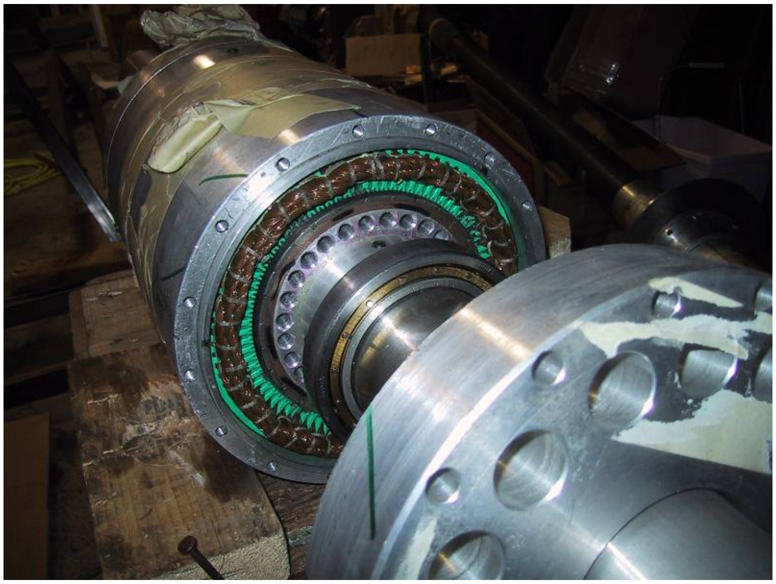
Frame:
Structural steel, bearings, shock absorbers and gas springs were obtained for the frame.

Tower:
A surplus wind turbine tower was obtained – height: 60 feet (18 m).

Blades:
Blades from the popular model Whisper H-40 (now renamed Whisper 100) were obtained from the manufacturer, Southwest Windpower of Flagstaff, AZ. The rotor diameter using these blades is 7 feet (2.13 meters). Rotational speed for these blades is ~800 RPM in a 27 mph (12 m/s) wind. Twenty-one of these blades were procured.

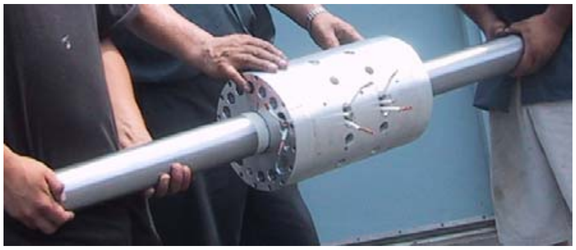
Generator:
Matched sets of rotors and stators, each set designed for 2000 watts per set at 800 rpm, were obtained. The stators each have 28 poles wound into 84 slots. The rotors each have 28 neodymium magnets on a steel drum within a carbon fiber sleeve.

Subtask 1.2: Fabricate Prototype;



Fabricating the Generator:
An aluminum generator enclosure that could hold 1, 2, or 3 of the rotor/stator pairs, was fabricated. After lathe-testing for power output, and testing for cogging torque using a balance, only 2 rotor/stator pairs out of the 3 were used. The expected electrical output of 4000 watts at 800 RPM gave a safety margin of 33% to meet the power output goal of 3000 watts at 27 mph (12 m/s).

Seven Rotors: To produce 4000 watts at 800 rpm, 7 rotors having a combined total of 21 blades were used. Each rotor was 7 feet (2.13 meters) in diameter. Production of 600 watts per rotor would produce more than enough power to match the generator.   Average spacing between rotors would be just under 12 feet (3.7 m).



Aluminum Hubs:
Hubs were computer-designed by the Principal Investigator and CNC machined from aircraft-grade 7075 aluminum plate. Care was taken to match the original *Whisper H-40* blade spacing and diameter to insure a meaningful comparison.   The hubs feature webbing for added strength, and a pattern of holes was drilled in each hub to reduce weight.

Carbon Fiber Driveshaft:
The driveshaft was assembled from filament-wound carbon fiber tubes. The middle section of the driveshaft was thickest, assembled from 3 inch (7.6 cm) diameter tubes. The wall thickness was about 1/8 inch (3 mm). This middle section was 36 feet (11m) long, and would support a total of four (4) rotors. Extending another 12 feet (3.7 m) forward and aft were tapered tubes, transitioning from a 3” (7.6 cm) diameter to a 2” (5.1 cm) diameter. At the end of these two sections were mounted two (2) more rotors. Finally, one more 12-foot (3.7 m) long section was added to the aft end, to support a seventh rotor. This last section was a 2-inch (5.1 cm) diameter carbon fiber tube. The total length of the driveshaft when fully assembled was 70 feet (21 m).

Tower: As part of this research project, Brent Scheibel, founder of Windtesting.com in Tehachapi, California fabricated and erected a 60 foot guyed steel lattice tower, with yaw bearing and attached hoist, from existing surplus tower parts.

Hoist: A folding hoist assembly integral to the tower was used to lift the turbine to the top for installation.

Yaw Bearing: The Heavy-duty turntable-type bearing on top of the tower was designed for a 50 kW downwind turbine. The yaw bearing allows free rotation in the horizontal plane, so that the turbine can change directional aim, to face the wind at all times.

Aiming: The turbine is a predominantly downwind machine, with 4 rotors downwind and 3 rotors upwind, of the yaw bearing. Nonetheless, for this prototype a conventional tail fin was added to the downwind end of the tilting chassis to insure proper tracking of the wind direction. The yaw bearing atop the tower allows free rotation in the horizontal plane.

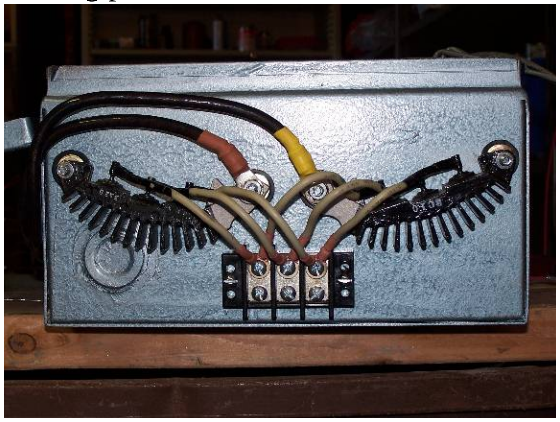
Tilting Chassis Pivots on Fulcrum, Adjusts Swept Area, Protects from Overspeed: For overspeed protection, a new, patented method of furling was implemented. In normal winds the aft end of the turbine is raised by gas springs to a 25-degree angle from horizontal. This offset angle α exposes all rotors to fresh wind and maximize power output. In high winds the aft end is pressed down by the thrust force of the wind, compressing the gas springs and placing the column of rotors directly in line with the wind, so that only the first rotor is exposed to fresh wind, and the others are protected within its wake. This horizontal alignment reduces power capture in high winds for protection from overspeed. U.S. Patent 6692230.

Central A-Frame with Fulcrum: A central A-frame fulcrum mounts to the yaw bearing plate atop the tower. The tilting chassis pivots fore-and-aft about this fulcrum like a teeter-totter. The A-frame section includes a forward stop/rest for the chassis to define the angle of forward tilt at 25 degrees from horizontal during normal operation. Aft of the fulcrum is a horizontal extension that supports a stop/rest to define the angle of backward tilt to zero degrees (horizontal) in high winds. The result is 360 degrees of directional freedom in the horizontal plane, and 25 degrees in the vertical plane. The central A-frame with attachment points for the gas springs and shock absorbers was welded from mild steel and painted for protection from the weather by the Principal Investigator. U.S. Patent 6692230.

Tilting Chassis: The tilting chassis, including bearing mount points, central fore-and-aft pivot, generator mounting points, shock absorber and gas spring mount points, disk brake mount points, and mount points for the tail fin, was welded from mild steel and painted for protection from the weather, by the Principal Investigator. The tilting chassis varies in attitude from being tilted 25 degrees forward for normal operation, to a horizontal orientation for protection in high winds. U.S. Patent 6692230.

Hydraulic Disk Brake System: The prototype is also equipped with a hydraulic disk brake system. The brake disc was mounted to an aluminum hub on the rotating cylindrical aluminum sleeve that connected the driveshaft to the generator. The brake caliper assembly was mounted to attachment points on fixtures welded to the steel tilting chassis, aft of the generator. A high-pressure nylon brake line connects to a master cylinder actuated by a lever at ground level. As with utility-scale commercial turbines, this brake may be applied for positive shutdown to protect from storm winds, for maintenance, or when power is not needed. Therefore, the combination of the furling mechanism and the hydraulic disk brake system insure that the turbine is never in danger of damage from overspeed.

Rectification of 3-phase AC Output to DC Current: Diode bridge rectifiers, designed for heavy-duty truck alternators, rectified each 3-phase output to DC. The resulting two DC outputs were combined in parallel, then measured for voltage and current, before being fed to a charge controller and battery bank. The diode sets with finned heat sinks were mounted on the steel instrumentation box located within the lattice structure at the tower top, depending from the yaw bearing plate. This convenient method of rectification does result in some power lost to heat.



Each diode has a characteristic voltage drop of .7 volts, which, when multiplied by 2 diodes per phase, indicates a voltage drop of 1.4 volts during rectification. At low power levels this represents a 10% power loss. At the higher voltages generated in stronger winds this drops to about a 4% losses. Data is measured after rectification, meaning that the actual AC electrical power generated before rectification is between 4% and 10 % higher than the recorded measurements show.

Task 2: Preliminary Testing:

Before building the actual final prototype, two smaller configurations using 5 foot (1.5 m) diameter rotors were built to test the new tilt-back furling concept, which was shown to work. The main prototype of this study was then built and run mounted on a test stand just above ground level to determine balance and general operability. Observation of smooth operation at ground level confirmed readiness of the prototype to be mounted onto the tower.

Subtask 2.1: Mount on tower with instrumentation;

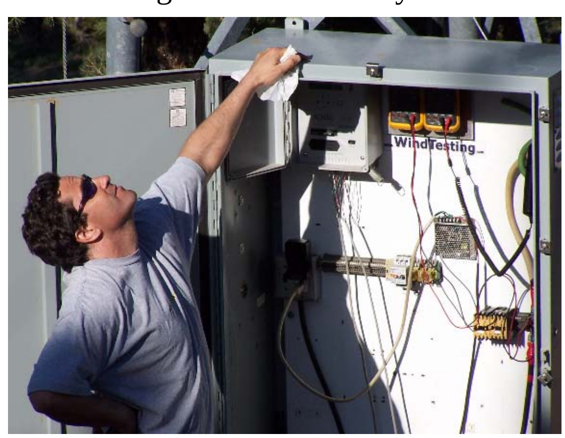
Mounting The Turbine onto the Tower: A folding hoist assembly integral to the tower was used to lift the turbine to the top for installation. Ropes were used to stabilize the turbine during the ascent. The base of the A-frame fulcrum was bolted securely to the circular steel mounting plate of the yaw bearing. This operation was managed by Brent Scheibel of Windtesting.com.

Instrumentation: (See also Appendix III)
Instrumentation consisted of anemometers, current and voltage sensors, and a data logger. Wind direction data was also recorded, and included in the data sets, but was not used in this study. All instrumentation was selected, procured, mounted, connected, and monitored solely by Brent Scheibel, founder of *Windtesting.com* and former Head of Anemometry at G.E. Wind.

Mount Anemometers for Wind Speed Measurement:
Two *NRG* #40 Anemometers were used. The first was put on a meteorological (met) tower, about 50 feet from the turbine, at the same elevation. The second was placed on the tower where the turbine would later be mounted, for general site calibration.
Calibration Certificates included in Appendix III
Towers measured for correlation 9/3/03 to 12/10/03.
Correlation file available, See appendix VII

Mount Current and Voltage Sensors for Electrical Power Output Measurement:
The *CR Magnetics* CR5210 DC Current transducer, and CR5310 DC Voltage transducer were mounted inside an enclosed steel electrical equipment box with a door. (Manufacturer's signed certificates of calibration included in Appendix III) This steel enclosure was bolted to the bottom of the steel yaw bearing plate, located just below the turbine, centered within the lattice structure of the tower, and rotated with the yaw plate and the turbine itself during aiming. The rectifying diode sets with finned aluminum heat sinks were mounted to either side of the box, one complete set per side. The 3-phase AC output was carried to these diode sets from each of the two 3-phase alternators comprising the generator, by a total of six (6) 4-gauge insulated, stranded copper cables (3 cables for each 3-phase alternator). The 3-phase AC current was rectified to DC current by the diode sets, then passed into the interior of the box, where it was combined in parallel, routed through the aperture of the *CR5210* current transducer, and connected to the leads of the *CR5310* voltage transducer. These transducers that measure current and voltage are connected by shielded cables to a *Nomad* data logger located in a large steel utility cabinet, located at the base of the tower.

DC Output to Battery Bank: The DC output of the turbine was then routed to a large diameter drop cable that led down the tower and connected through thick copper cables to a battery bank.



Subtask 2.2: Observe, record data, log output data vs. wind speed;

This was done first for the preliminary prototypes. Experience gained from these preliminary models provided valuable insights that guided the design of the full-scale prototype.

Task 3: Fine-tune Prototype for Long Term Testing;

When the full-scale prototype turbine was mounted on the test stand at ground level, rotation was observed upon brake release. After mounting the prototype on the tower with instrumentation, the turbine was seen to perform in the expected manner, producing power in the target range.

Task 4: Long Term Testing:

The prototype was mounted on top of the 60 foot tall steel lattice tower, on March 3, 2004, at the facilities of *Windtesting.com* in Tehachapi, CA. Upon startup, the turbine performed well, and long term testing commenced. Brent Scheibel, Chief of Operations at *Windtesting.com* tested the machine through October 28, 2004, generating data sets and power curves. (See Appendix V - Testing Timeline.)

Initially, the chosen furling speed was low, between 16 mph (7 m/s) and 24 mph (10.7 m/s), to keep the turbine within a safe operating regime as overall performance was assessed. Rated power of 3000 watts at 27 mph (12 m/s) was achieved, recorded and noted. Corrected for sea level air density, this equates to over 3400 watts. At this power level, the generator remained cool, and the driveshaft did not seem in danger of breakage. It was also apparent that the prototype turbine was capable of producing significantly more power.

Gas shock absorbers and gas springs regulate fore-and-aft tilt for overspeed protection.

Improving Performance:

During the course of long-term testing, the performance envelope was explored.

Raising Furling Speed:

The furling speed was raised by adding higher-force gas springs (right), increasing power output at higher wind speeds, while allowing operation at wind speeds up to 45 mph without damage.

Raising Voltage:

The operational charging voltage was raised slightly, to optimize RPM and power output. A solid 4000 watts at 27 mph (12 m/s), and 5000 watts at 30.5 mph (13.6 m/s) were generated, peaking at 6000 watts as winds approached 40 mph (18 m/s). Adjusted to sea level air density, this translated to well over 4500 watts at 27 mph (12 m/s), 5500 watts at 30 mph (13.4 m/s), and 6000 watts at 33 mph (14.8 m/s) and above.

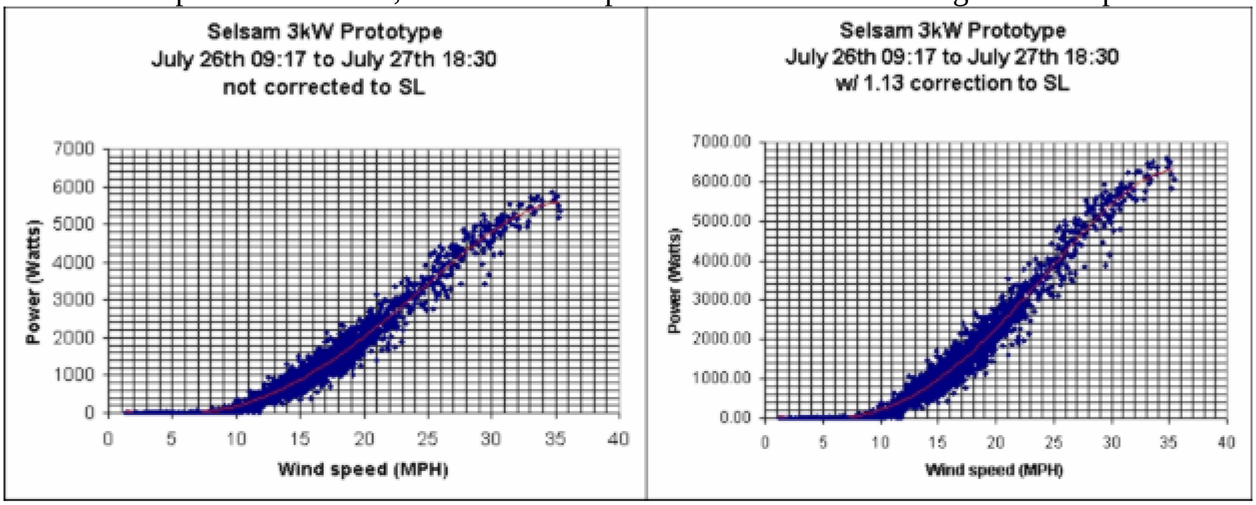
Project Outcomes

Objective 1: Fabricate 3 kilowatt wind turbine:

Fabrication of the prototype was completed in February 2004. With a 70-foot (21.3 m) long carbon fiber driveshaft, and seven 7-foot (2.13 m) diameter rotors, the turbine produces up to 6 kilowatts. Therefore the fabrication effort for this project was a success.

Objective 2: Demonstrate that the proposed prototype wind turbine will generate 3 kilowatts in a 27 mph (12 m/s) wind: (See Appendix II - Scatter Plots and Power Curves)

Corrected to sea level, power output is over 4500 watts at 27 mph (12 m/s), exceeding target output of 3000 watts by 50% (see chart below). Actual measured output at 27 mph (12 m/s) is 4000 watts at the testing site altitude of 5000 feet (1524 m). At 30.5 mph (13.6 m/s) actual measured output is 5000 watts, with measured peaks near 6000 watts at higher wind speeds.



The chart to the left shows raw data. The chart to the right shows output corrected to sea-level air density, by adding 13%, a conservative correction since sea level air is actually 16% more dense. It is customary to correct wind turbine power measurements for altitude, to a "standard atmosphere" of sea level air density. Test site elevation is 5000 feet (1524 m).[9] Corrected to sea level air density, power output exceeds 4500 watts at 27 mph (12 m/s), 5500 watts at 30 mph (13.4 m/s), and 6500 watts at higher wind speed. DC output, after rectification losses, is about 643 watts per rotor at 27 mph (12 m/s). Rectification losses at low voltage can be as high as 10%, indicating that the twin alternators are actually generating significantly more raw 3-phase AC power than the DC measurements after rectification show.

Even when adjusted so that furling begins taking place at 16 mph (7.15 m/s), the prototype generates more than the target 3000 watts in winds averaging 27 mph (12 m/s), a reasonable value representing a significant contribution of power from each rotor. As testing progressed, the configuration was fine-tuned to give the highest power output. Comparing this prototype against a turbine in mass production suggests that with further development, a turbine based on this prototype could be refined to harness even somewhat more power from each rotor.

All measurements were taken and compiled based on ten-minute, and one-minute averages by Brent Scheibel, founder of *Windtesting.com* and former Head of Anemometry at G.E. Wind, using calibrated, certified, industry-standard instrumentation and recording practices. Scatter plots and power curves included in Appendix II, data in separate Excel file Appendix VI.

Objective 3: Demonstrate that the proposed turbine is capable of continuing to generate full power at windspeeds over the full-power rated wind speed of 27 mph (12 m/s), up to 45 mph (20 m/s):

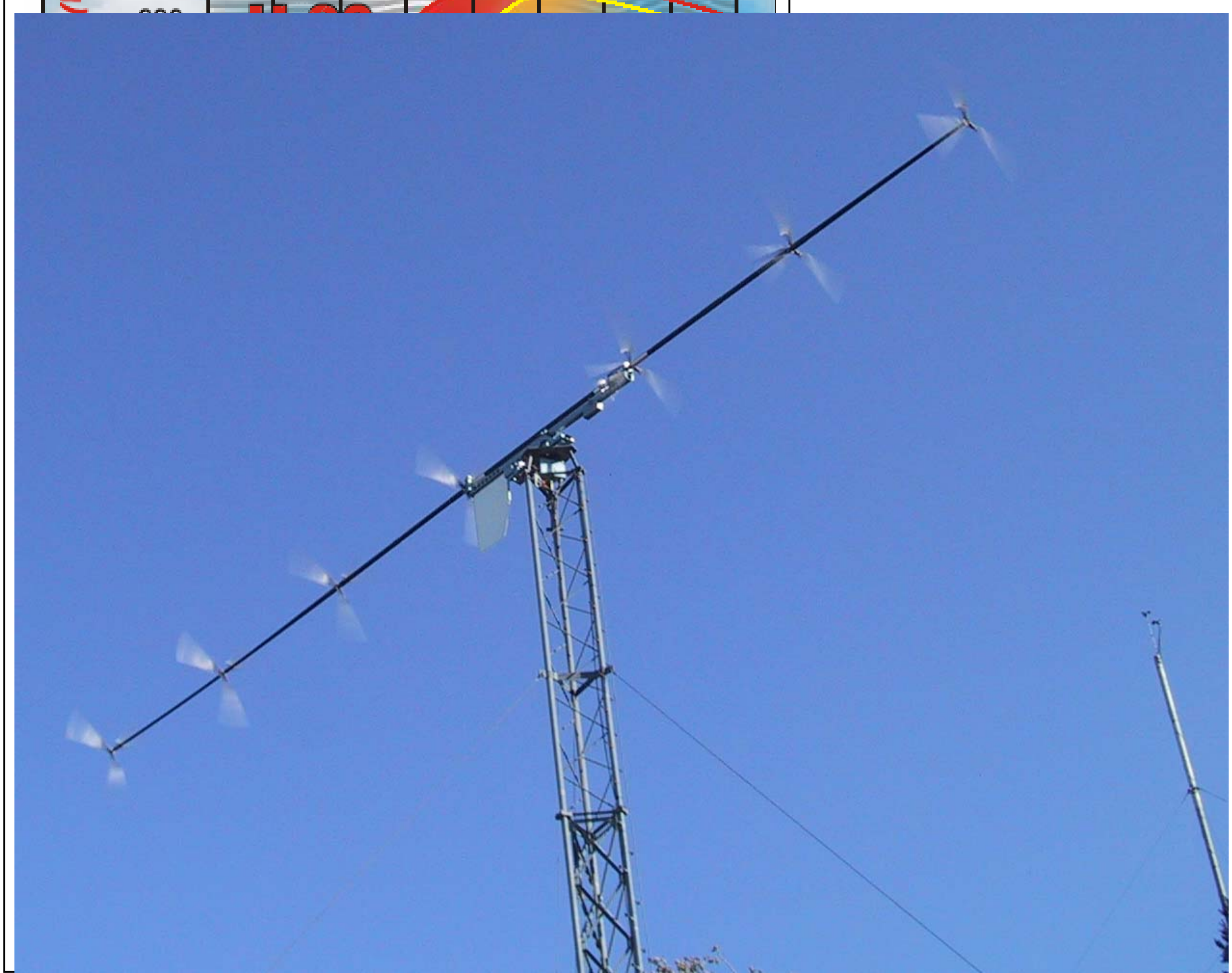
During the course of this effort, the prototype turbine was observed to maintain full power in recorded wind speeds of up to 45 mph (20 m/s). The novel tilt-back method of furling yields no point above rated speed at which output declines, unlike other small turbines that use the side-furling method of overspeed protection. This is verified by the shape of the power curves, as seen on the previous page and next page, which ascend with increasing wind speed then level off, but do not decline at higher wind speeds.

Objective 4: Demonstrate that the proposed turbine generates at least 3 times more power at low and medium wind speeds, up to the rated wind speed of 27 mph (12 m/s) than a single-rotor turbine of the same diameter:

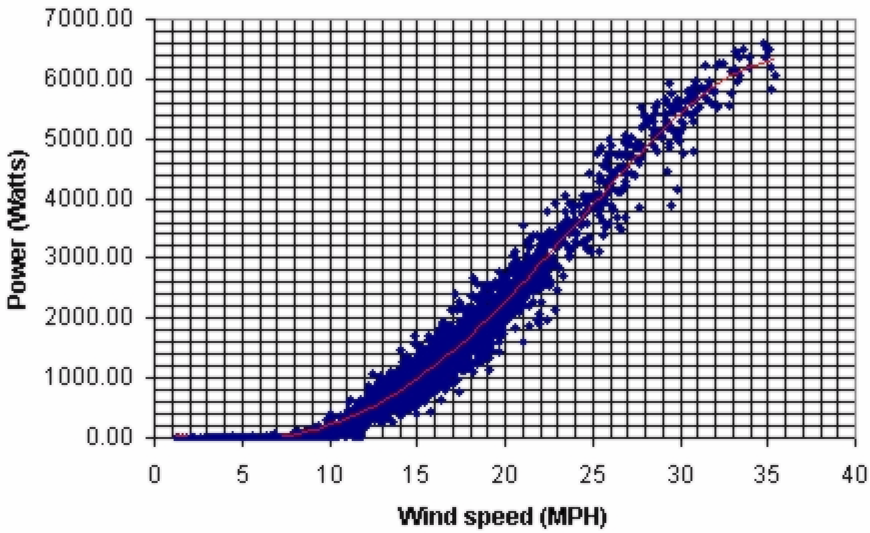
Comparing the power curve chart of the prototype to the published power curves of a single-rotor turbine of the same diameter (next page), verifies that the prototype of this research project in fact generates between 5 and 6 times the power of the Whisper H-40 turbine with a single 7-foot diameter rotor that uses the same blades, at all wind speeds, low, medium, and high.

Manufacturer's power curve (left) shows 800 watts at 27 mph (12 m/s) at sea level, for a single rotor. 13.8% thinner air at 5000 feet elevation should reduce this to 690 watts per rotor. [9]
Note: The Whisper H-40 has now been renamed as the Whisper H-100. Link:
http://www.windenergy.com/Whisper_100_200_Spec_Sheet.pdf

The U.S. National Renewable



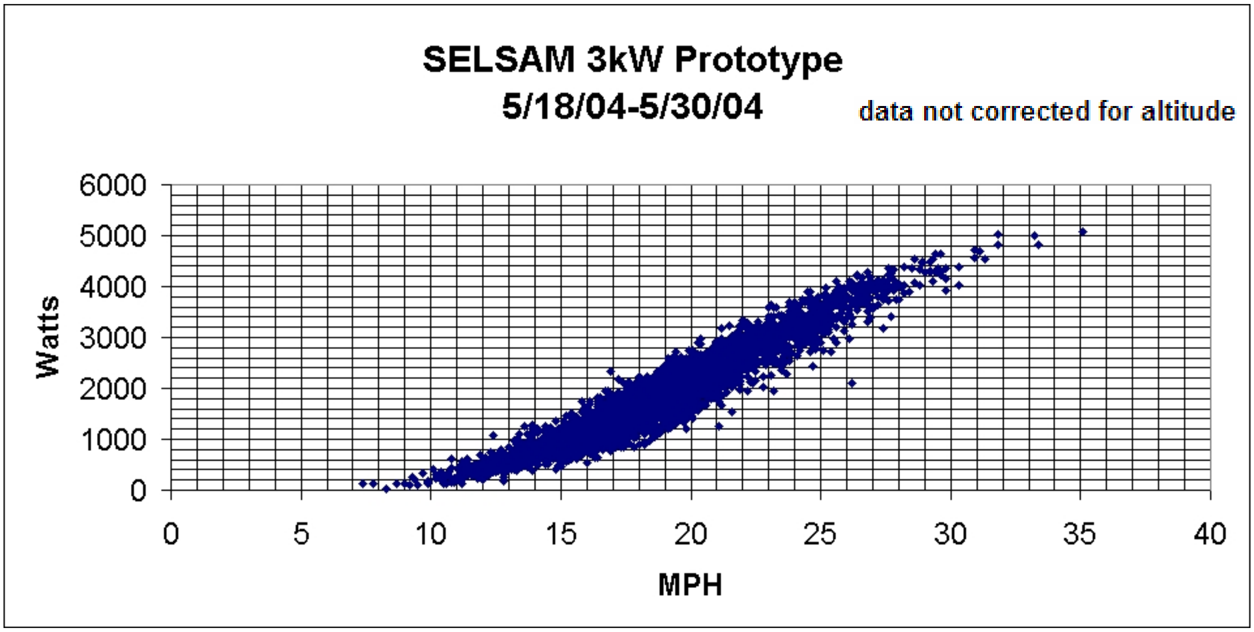
Energy Labs (NREL) report the rated power output of these same rotors at around 525 watts per rotor at 27 mph (12 m/s). [7] (left)
http://www.nrel.gov/wind/pdfs/32748.pdf



The prototype of this research effort generated an actual measured average 4000 watts at 27 mph (12 m/s), at 5000 feet (1524 m) altitude. Conservatively corrected to sea level (left), this equates to well over 4500 watts, or 643 watts per rotor, which is within the range of full power from each rotor. Output was multiplied 5 to 6 times at low, medium, and high wind speeds

Objective 5: Demonstrate that the proposed turbine mounting design is capable of protecting the turbine against overspeed in winds up to 50 mph or if this speed is not reached, the highest wind speed measured during the testing period:

The turbine survived wind speeds up to 45 mph (20 m/s), the maximum wind speed encountered during the course of the study, with no damage, while maintaining full power output between 5000 and 6000 watts, and smooth operation. The chassis that carries the driveshaft smoothly tilted fore-and-aft in response to the wind speed. The default position of being tilted forward by 25 degrees exposed each rotor to its own supply of fresh wind, allowing each rotor to produce full power. Stronger winds pressed downward on the aft end of the driveshaft with its attached rotors, compressing the gas springs, with the motion smoothed by the shock absorbers. The result is that only the first rotor produces full power – the other rotors are shielded from the wind, located within the wake of the first rotor. This novel method for overspeed protection, now proven to work smoothly and effectively, is protected by U.S. Patent 6692230, which issued during the course of this project. As part of an entirely new type of wind turbine, it is also an entirely new method for handling excessively strong winds, which any turbine must have. So, in addition to introducing the first way to increase swept area without increasing diameter, this prototype also introduced a way to reduce that swept area in response to high winds for overspeed protection.



As one can see from the above power curve scatter plot, power output levels off at high wind speeds. This particular data set was taken early in the testing regimen, during the spring season, operating in a relatively low voltage and low furling speed regime, resulting in lower than maximum power output. While higher power output levels were achieved later in the testing, this early-stage power curve is a good illustration that with furling set to a low speed, this power curve levels off at the top as it ideally should, and does not decrease, which is desirable. Other power curves also verify that the turbine was protected from high winds.

Objective 6: Demonstrate that the proposed prototype wind turbine will operate for the 6-month testing period with at least 90% uptime:

The turbine operated during most times of sufficient wind, during six months of rigorous testing, taking place over a total span of eight months. For the duration of testing, the turbine performed normally and exceeded the original power output target. Aside from periods of adjustment, including a two month hiatus in late summer during low winds, the turbine remained generally in proper working order, ready and able to produce power at all times. Reflecting normal operation of a small wind turbine, during certain periods when Windtesting.com personnel were not physically present to monitor performance, the hydraulic disc brake system was utilized to shut the turbine down. These periods included short out-of-town trips, or sometimes overnight if the wind was excessively strong, with batteries charged and personnel sleeping. Testing Timeline: Appendix V; Raw Data: Appendix VI. Overall, the turbine was fully deployed in an operational mode for 90% of the 6 month duration of active testing, meeting the project goal. The prototype turbine today, after completion of the study, remains in full working order.

Objective 7: Based on the data generated in this project, show that the projected life cycle cost of energy of $.04/kWh for the proposed design continues to be supported:

1. Current single-rotor technology at utility scale, has now reached the targeted $.04/kWh price.

2. The rotor represents about 18% of installed costs of current systems.
3. Multiple co-axial rotors weigh less for the power produced, using less material, saving cost.
4. This cost savings of reduced blade material in this prototype was generally offset by the additional cost of the projecting, cantilevered driveshaft to support the multiple rotors.
5. The resulting higher RPM of a multi-rotor machine, however, allows the use of a direct-drive generator, eliminating the gearbox, and all costs associated with the gearbox.
6. Gearboxes represent about 17% of the installed cost of current systems.
7. By eliminating the gearbox, the general design of the prototype of this project, using a cantilevered driveshaft, could therefore lower the cost of utility-scale turbines by 17%.
8. Since turbines represent 64% of the cost of wind energy, (Source: British Wind Energy Association – link: http://www.bwea.com/ref/econ.html) this 17% reduction in turbine cost should therefore lower the cost of utility-scale wind energy by about 10%, from today's $.04/kWh to $.036/kWh.
9. Gearbox failure is the leading cause of downtime and repair costs, and gearbox maintenance represents a large portion of O&M costs.
10. Further cost reductions should logically result by eliminating gearbox maintenance and repair costs, and the downtime costs of gearbox failure.
11. Other cost savings include lower blade tooling costs, easier blade transport to less accessible areas, and increased swept area to capture more energy at low wind speeds, expanding the range of usable sites, reducing the need for new transmission lines.

Further Outcomes:

The power gathering capability of the co-axial multi-rotor configuration in general has now been verified, validating a new direction in turbine design. During this project, patent protection was filed for a "next generation" of co-axial multi-rotor turbines, that maximize and amplify the inherent advantages of the concept, while further reducing costs. (See Appendix X, Proprietary)

Conclusions:

1. By using industry-standard blades, allowing direct comparison to a known single-rotor turbine, this research has demonstrated that the co-axial multi-rotor configuration is an effective approach to generating electricity from the wind, confirming that power output is multiplied generally in proportion to the number of rotors, with minimal losses.
2. For a 3000 watt version, at this 7 foot (2.1m) diameter, only five (5) rotors are necessary.
3. The co-axial multi-rotor configuration is now proven as the most effective method yet discovered, to increase the power output of a wind turbine of a given diameter.
4. The increased swept area and energy capture, provided by multiple rotors, offers great potential to make wind energy viable in regions with a less-than-ideal wind resource.
5. The ability to passively decrease the swept area in response to the wind speed has proven to be an effective method of overspeed protection.
6. The general design of the prototype saves costs by eliminating the need for a gearbox.
7. Even more significant cost savings are possible with the next generation (patents issued and pending) of co-axial multi-rotor turbines specifically designed to maximize the benefits of the technology, by requiring less material (Appendix X – proprietary).
8. Confirmation of the co-axial, multi-rotor concept in general, weighs in favor of the potential viability of related co-axial multi-rotor designs, such as the floating, tilting offshore turbine, and atmospherically buoyant turbine of U.S. Patent 6616402, etc.

Therefore in general:

Power output far exceeding target, verification of expected performance modes, proven reliability, and demonstrated survivability, in view of the specific cost-saving drivers for the design, combine to support the goal of providing energy at $.04/kWh. Reduced blade weight, and elimination of the gearbox, the most wear-prone component of a wind turbine, by effectively placing the gearing into the air itself, can be expected to further lower the cost of energy (COE) for utility-scale wind-generated electricity to below the current price of 4 cents per kilowatt-hour. The advantage of high RPM means that standard, off-the-shelf components can be used to build suitable direct-drive permanent magnet alternators, taking advantage of economies of scale of items already in mass production. Established single-rotor turbine companies such as *Enercon* implement direct-drive ring generators for simplicity and low maintenance, but their low RPM mandates an excessively large diameter for these generators, resulting in excessive cost.[10, 17] Multiple rotors allow direct-drive generators that are much smaller for the same power output, due to higher RPM.

Ample clearance between rotors and tower allow greater blade flexibility without tower strikes, and full height guy wires, lowering the cost of both blades and tower. Passive yaw control provides a further cost reduction at this scale, although active yaw may be implemented in larger versions. These factors, combined with verified performance at this new, larger scale, support the outlook for this general multi-rotor design, and other multi-rotor designs to lower the cost of wind energy, based on the facts and data generated by this research effort.

The most significant cost savings, however, may be realized in "next generation" co-axial, multi-rotor turbines, for which patent protection was applied during this project. Taking further advantage of the favorable economic design drivers of the co-axial, multi-rotor concept, while eliminating unnecessary high-cost aspects, this "next generation" of designs, as revealed in Appendix X (proprietary), lowers the cost of wind-generated electricity, while expanding its useful range.

Recommendations:

1. Since the power gathering ability of the co-axial multi-rotor configuration has now been proven, the concept should be implemented in its many further embodiments.
2. Offshore is the next frontier for wind energy, predicted to eclipse land-based wind. The floating, tilting offshore version of U.S. patent 6616402 should be built. Major developers see this minimalist design, with a single moving part, as the ideal solution for offshore wind, especially for deep waters, which typify coastal California. The driveshaft, also acting as the tower, elevates a series of rotors while driving a generator at surface level, solving major challenges by eliminating the rigid foundation, the heavy steel tower, the yaw mechanism, the gearbox, the gargantuan blades, and the requirement for a crane or large ship to deploy. Self-deploying, GPS guided, and registered as vessels, rather than permanent marine edifices, these floating turbines can drop anchor, plug in, and start making power. (See Appendix IX)
3. Atmospherically buoyant versions as delineated in U.S. patent 6616402 should be explored with an experienced blimp (LTA) manufacturer such as Lockheed Martin Akron Division and ILC Dover, as part of the NIST ATP research program. (See Appendix IX)
4. Future "next generation" land-based versions (See Appendix X - Proprietary), patented and patent pending, further maximizing the advantages of the co-axial multi-rotor concept, while eliminating the remaining high-cost aspects, to generate more power at comparatively lower cost, should be built and tested, based on the favorable outcome of this project.
5. International licensing should take place, based on the international (PCT) patents pending.
6. Low Wind Speed Turbine: Producing full power at half the wind speed for the same diameter, with swept area passively adjusted to wind speed, a multi-rotor "Low Wind Speed Turbine", of 50 kilowatt output should be funded by DOE / NREL as part of their LWST effort.

7. Computational Fluid Dynamics (CFD) modeling and smoke studies of the airflow through co-axial multi-rotor arrays should be conducted, emphasizing optimal rotor placement and spacing, and recaptured energy in the wake vorticity (swirl) of upwind rotors, by downwind rotors.
8. Finite Element Analysis (FEA) computer studies of the driveshaft with attached rotors should be conducted to optimize the configuration, and to explore larger scale versions.
9. Further research into the co-axial, multi-rotor concept, funded at both the State and Federal level, and by private industry, is urged.

Public Benefits to California

Meeting RPS Goals: Co-axial multi-rotor wind turbines can increase the 10.6% non-hydro renewable portion, of nearly 300,000 gigawatt-hours of annual generation by California's investor-owned utilities, to 20% by 2010. An additional 9.4% of total generation, or 28,500 gigawatt-hours, 6.3 times the present 1.5%, or 4500 gigawatt-hour contribution from wind, would meet this goal.   (data: http://www.energy.ca.gov)
Every cent of avoided cost per kWh, of this added 28,500 gigawatt-hours of annual generation, yields $285 million in annual savings, to the State of California. Since existing class 6 windfarm areas are largely exploited, a technology that expands the number of viable sites, such as the co-axial multi-rotor concept of this research, will be required to meet the RPS goals using wind energy. The co-axial multi-rotor technology, with performance now proven by this research, expands the potential range of wind energy in two ways:
1. High wind sites not accessible to existing single-rotor turbines, may be exploited using "next generation" (Appendix X - proprietary) versions of the technology.
2. Lower wind sites, closer to power lines and cities, may be more economically developed due to the lower cost and increased output derived from co-axial, multi-rotor technology.

Low Cost Electricity for California: By eliminating the gearbox, the general design of the prototype of this project could lower the cost of utility-scale turbines by 17%. Since turbines represent 64% of the cost of wind energy, this general design should therefore be able to lower the cost of utility-scale wind energy by about 10%, from today's $.04/kWh, to $.036/kWh. Recent hikes in commodity prices, however, are now causing utility-scale turbine prices to rise, reversing the previous 20-year trend of steadily lower prices. The improved economics of the turbine design of this project may therefore serve to maintain the existing price of $.04/kWh, rather than actually lowering it, while the cost of electricity from newly manufactured single-rotor turbines continues to rise.

More significantly, using the "next generation" multi-rotor turbine technology (patent pending), as delineated in Appendix X (proprietary), costs at windfarm sites and other high wind areas should logically be brought significantly lower than even today's $.04/kWh, despite generally rising costs. Allowing more powerful turbines, using comparatively less material, this technology makes generation at $.030/kWh, or less, conceivable at windfarm sites and other sites with a similar wind resource. Areas with lower winds may be able to match today's $.04/kWh class 6 windfarm price, using these "next generation" multi-rotor systems.

The California Public Utilities Commission (CPUC) has published a Market Price Referent (MPR) for comparison of various generating technologies with regard to meeting the Renewables Portfolio Standard (RPS) goals. Source: CPUC Resolution E-3942 July 21, 2005 link: http://www.cpuc.ca.gov/word_pdf/AGENDA_RESOLUTION/47797.pdf In 2005, the 2004 MPR was revised upward in response to rising fuel prices, to $.0605/kWh for baseload MPR and $.1142/kWh for peaking MPR. (table below, link above, page 3 of draft resolution)

February 11, 2005 ACR - Revised 2004 Market Price Referents At Specified Zonal Delivery Points (e.g., NP15 or SP15) **(cents/kWh)**			
Resource Type	**10-Year**	**15-Year**	**20-Year**
Baseload MPR	6.05	6.05	6.05
Peaking MPR	11.41	11.42	11.42

The CPUC states that the remainder of the MPR matrix for projects started in years 2005 to 2010 (table below) will be similarly revised upward, from the currently published estimated future baseload MPR averaging about $.06/kWh, and peaker MPR averaging about $.115/kWh. (Source: Appendix A on page 10 of the draft resolution, available on the web at the link above.)

2004 Baseload MPR Matrix
Based on Project Start Date (Nominal $/kWh)

	Contract Term	10 year	15 year	20 year
2005	MPR All-in	0.0578	0.0588	0.0599
2006	MPR All-in	0.0574	0.0587	0.0600
2007	MPR All-in	0.0575	0.0591	0.0605
2008	MPR All-in	0.0582	0.0600	0.0615
2009	MPR All-in	0.0594	0.0614	0.0629
2010	MPR All-in	0.0608	0.0628	0.0644

2004 Peaker MPR Matrix
Based on Project Start Date (Nominal $/kWh)

	Contract Term	10 year	15 year	20 year
2005	MPR All-in	0.1102	0.1117	0.1133
2006	MPR All-in	0.1103	0.1123	0.1142
2007	MPR All-in	0.1111	0.1135	0.1155
2008	MPR All-in	0.1127	0.1154	0.1175
2009	MPR All-in	0.1151	0.1179	0.1201
2010	MPR All-in	0.1177	0.1206	0.1228

Therefore an avoided price of $.06/kWh is a reasonable and conservative minimum estimate for electricity replaced by future added wind capacity. Rising fuel prices and the high cost of generation from inefficient "peaker plants", could easily bring this avoided price to $.08/kWh. Assuming the current price of $.04/kWh for the added 28,500 gigawatt-hours of annual wind generating capacity, and a conservative avoided price of $.06/kWh, yielding a cost aversion of $.02/kWh, the annual savings to California would be $570 million, or $5.7 billion per decade. The table below summarizes the savings to California if RPS goal is met by added wind energy.

Savings per Decade to California, from meeting RPS goal by adding 28,500 gigawatt-hours of annual wind generating capacity (nominal dollars)

Avoided Price Of Electricity (Nominal $/kWh)	Price of Wind Generated Electricity (Nominal $/kWh)				
	.02	.03	.04	.05	.06
.06	$11.4 billion	$8.5 billion	$5.7 billion	$2.85 billion	0
.07	$14.25 billion	$11.4 billion	$8.5 billion	$5.7 billion	$2.85 billion
.08	$17.1 billion	$14.25 billion	$11.4 billion	$8.5 billion	$5.7 billion
.09	$19.95 billion	$17.1 billion	$14.25 billion	$11.4 billion	$8.5 billion
.10	$22.8 billion	$19.95 billion	$17.1 billion	$14.25 billion	$11.4 billion
.11	$25.65 billion	$22.8 billion	$19.95 billion	$17.1 billion	$14.25 billion
.12	$28.5 billion	$25.65 billion	$22.8 billion	$19.95 billion	$17.1 billion

It is obvious that a further increase in avoided price, further cost reductions for wind energy, and/or wider deployment, could result in savings of over $20 billion per decade for California. Still higher fuel prices, combined with wider specific wind energy deployment than existing RPS standards require, to 20% of total generation, could push savings to over $40 billion per decade for the Golden State. The co-axial, multi-rotor wind turbine can therefore provide savings ranging between $5.7 billion and $40 billion per decade for California, possibly more, depending on fuel prices and the extent to which multi-rotor wind turbine technology is deployed.

Clean Electricity Generation for California: Facilitating clean electricity generation provides aesthetic and health benefits to California, which translate to further economic benefits.

Offshore Wind Energy for California: California has a huge offshore wind resource that is not utilized because of deep waters, with no shallow continental shelf, upon which to mount rigid foundation platforms. The floating, tilting, offshore version of the co-axial, multi-rotor wind turbine solves major cost challenges of offshore wind, needs no rigid foundation, and reduces the entire installation to a single moving part. Verification of the power-gathering ability of this land-based version has been a pivotal first step toward development of California's vast, powerful, offshore wind potential. See P.I. website at http://www.offshoreturbine.com

Low Wind Speed Performance for California: California's high wind areas are remote, while lighter winds prevail near cities. Automatically adjusting swept area in response to wind speed, with no diameter increase, the turbine of this project fills the role of a "Low Wind Speed Turbine", producing the same output as a single-rotor turbine of the same diameter, at about half the wind speed. Based on diameter, the prototype of this project achieved class 6 performance from class 1 wind speeds. Such low wind speed performance, never even contemplated until this research, greatly expands the number of viable windfarm sites, including sites near cities, reducing demand for more transmission lines.

CO2 and California's Contribution to "Global Warming": Improved wind turbines generate electricity, green tags, but no CO2, helping California conform to the Kyoto Protocol.

The *California Hydrogen Highway Network*: Rapid transition to clean hydrogen fuel can power existing cars and trucks with minimal modifications. Abundant electricity to make inexpensive hydrogen fuel is limited only by installed wind energy capacity. Production during off-peak hours, and storage, at the point of distribution (fueling station), buffers the intermittency of wind while eliminating transport issues. Multi-rotor wind turbines, by expanding the useful wind resource, can make economical hydrogen fuel a reality for California. Liquid hydrocarbon fuels can also be made from H2.

Self-Sufficiency for California: Improvements in wind energy technology save the cost in lives and capital of defending foreign oil sources.

Cash Influx to California: International (PCT) patent protection, covering 95% of the wind energy market worldwide, can bring cash to California through licensing. Local manufacture would generate jobs and further capital influx.

References

[1] Principal Investigator's Website: http://www.Selsam.com http://www.Superturbine.net http://www.Offshoreturbine.com

[2] U.S. Patent Number 6616402 "*Serpentine Wind Turbine*"

Issued to Principle Investigator September 9, 2003   http://www.USPTO.gov

[3] U.S. Patent Number 6692230 "*Balanced, High Output, Rapid Rotation Wind Turbine*"
Issued to Principle Investigator September 9, 2003   http://www.USPTO.gov

[4] U.S. Patent Application "*Side-Furling Co-Axial Multi-Rotor Wind Turbine* "
Application Publication Number 20040219018   Filing date November 4, 2004

[5] (PCT) International Patent Application "*COAXIAL MULTI-ROTOR WIND TURBINE*"
World Intellectual Property Organization (WIPO) International Patent Cooperation Treaty
Application Serial Numbers   WO 2002/103200   PCT/US02/19181   Filing date 14 June 2002
Publication date 20 February, 2003   http://www.wipo.int/ipdl/en/search/pct/search-adv.jsp

[6] Blade Manufacturer's Website Page featuring published power curve for
Whisper H-40 Wind Turbine by *Southwest Windpower*, Flagstaff, AZ, USA
The Whisper H-40 model has now been renamed Whisper 100 for marketing purposes.
http://www.windenergy.com/Whisper_100_200_Spec_Sheet.pdf

[7] *NREL* (*National Renewable Energy Laboratories*, USA) – study featuring power curve for Whisper H-40 Turbine, published December, 2001. http://www.nrel.gov/wind/pdfs/32748.pdf

[8] Independently measured power curve for the Whisper H-40 by Paul Gipe, noted wind author.   http://www.wind-works.org/articles/H40Whisper.html

[9] *Standard Atmosphere Calculator* Convenient online calculator gives air density when altitude is input. http://aero.stanford.edu/StdAtm.html

[10] *Wind Energy – The Facts: Volume I – Technology*   (Highly Recommended)
A pivotal study by the *European Wind Energy Association (EWEA)* and the *European Commission's Directorate General for Transport and Energy* (DG TREN) citing the following FACTS on pages 1-39:
1. The fact that a point of diminishing returns exists for single-rotor turbines over 1.5 megawatts
2. The fact that multi-rotor turbines with "a number of rotors on a single support structure" may be the best answer for the next generation of more powerful turbines of 5 to 10 MW capacity.
3. The fact that smaller blades gather vastly more power per unit weight - blade weight is proportional to diameter cubed, while power only grows with diameter squared. (page 35)
4. The fact that direct-drive, permanent magnet generators have low maintenance and high reliability, as a solution to low rotational speeds and high torques, reducing tower-head mass and overall costs, while increasing efficiency by omission of the gearbox. (page 13)
5. The fact that while direct-drive generators are the wave of the future, a source of higher RPM is desired to keep generator size in a reasonable range. (pages 23-25)
6.   The fact that "The next great leap for the wind energy industry" will be offshore.
7. The fact that floating turbines will be necessary for the vast wind resource over deep waters.
8. The fact that a simplified design with low operation and maintenance costs will be essential to utilize this vast offshore resource.
9. The fact that the greatest impact of structural flexibility in wind turbine design is yet to come.

10. The fact that current offshore wind energy technology is in its infancy, a temporary make-do marriage of land-based turbines with offshore oil rig technology.
11. The fact that new technologies are needed specifically addressing the needs of offshore wind energy to lower excessive installation, operations, and maintenance costs.
12. The fact that sufficient wind resource exists offshore to provide ALL of Europe's electricity.
http://www.ewea.org/documents/ewea.pdf
http://www.agores.org/Publications/Wind%20Energy%20-%20The%20Facts/VOL1vfinal.pdf
http://www.ewea.org/documents/Facts_Volume%201.pdf

[11] *Floating Offshore Wind Turbines for Shallow Waters*
A study by The Netherlands Agency for Energy and the Environment (NOVEM) Floating, multi-rotor wind turbines are in our future. http://www.ecn.nl/docs/library/report/2003/rx03039.pdf

[12] *Wind Turbine Technology Offshore* by JRC Armstrong discusses benefits of direct drive generators, multi-rotor turbine designs of the future, including kite turbines.
http://www.owen.eru.rl.ac.uk/documents/bwea20_44a.pdf

[13] *A Turn for the Better? Innovative Concepts for Wind Turbines* by Eize DeVries - World authority on wind energy discusses future turbine designs, including floating offshore turbines, multi-rotor turbines, direct-drive permanent magnet generators, and diffuser-augmentation to increase power output. http://www.jxj.com/magsandj/rew/2001_02/turn_better.html

[14] *Windship* – floating, tilting, multi-rotor array turbine design by naval architect *Heronemus*
http://www.phoenixproject.net/windship.htm (We reduce this concept to a single moving part)

[15] *Concentrating Windsystems - Sense or Nonsense?* An authoritative discussion of other methods – ducts, shrouds, concentrators, and diffusers, to increase the power output of a wind turbine without increasing the diameter. Source: University of Stuttgart, Germany
http://www.ifb.uni-stuttgart.de/~doerner/diffuser.html

[16] *Clipper Wind D-GEN Multiple Generator Technology Webpage* Technology that addresses exponentially increasing torque and disproportionate drivetrain stresses in today's largest turbines, with explanation of its necessity. http://www.clipperwind.com/dgd.htm

[17] *Enercon Website* Manufacturer of utility-scale turbines using large-diameter, direct-drive rare-earth, permanent-magnet, ring generators for maintenance-free operation, with no gearbox. http://www.enercon.de (This clearly superior, yet expensive solution is made more affordable by high RPM, multi-rotor technology, which allows the generator to be more reasonable in size.)

[18] *Vari-Blade Website* Telescoping blade technology to increase swept area in low winds is expected to increase production by 20-33%. http://www.variblade.com

California Energy Commission Energy Innovations Small Grant (EISG) Program **PROJECT DEVELOPMENT STATUS**	**Questionnaire**

Answer each question below and provide brief comments where appropriate to clarify status. If you are filling out this form in MS Word the comment block will expand to accommodate inserted text.

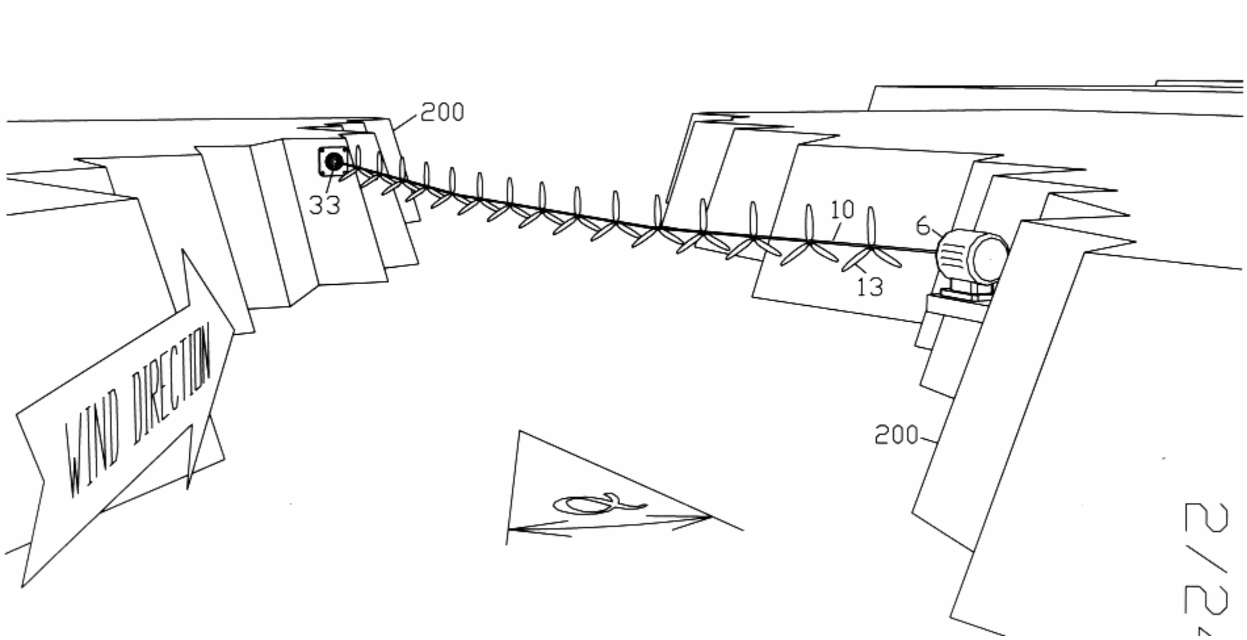
Please Identify yourself, and your project: **PI Name** _Douglas Selsam__**Grant** # 02-18______	
Overall Status	
Questions	**Comments:**
1) Do you consider that this research project proved the feasibility of your concept? **YES**	*Briefly state why.* **It produced the hard numbers to compare to a single-rotor turbine. The results were even better than expected. The configuration worked well. The furling method is now proven to be very effective and smooth. The driveshaft is shown to withstand the cyclic stress.**
2) Do you intend to continue this development effort towards commercialization? **YES**	*If NO, indicate why and answer only those questions below that are still relevant.*
Engineering/Technical	
3) What are the key remaining technical or engineering obstacles that prevent product demonstration?	**None**
4) Have you defined a development path from where you are to product demonstration?	**Yes**
5) How many years are required to complete product development and demonstration?	**A few months at most if I could ever get to it. Most of the work has already been done.**
6) How much money is required to complete engineering development and demonstration?	*Do not include commercialization costs such as tooling.* **$20,000 or less using off-the-shelf components. More for larger and other advanced versions now patented.**
7) Do you have an engineering requirements specification for your potential product?	*This specification details engineering and manufacturing needs such as tolerances, materials, cost, stress etc. If NO indicate when you expect to have it completed.* **YES**
Marketing	
8) What market does your concept serve?	*Residential, commercial, industrial, other.* **ALL**
9) What is the market need?	*Summarize the market need and identify any sources you referenced.* **Energy needs increase as peak oil looms.**

10) Have you surveyed potential customers for interest in your product?	*If YES, the results of the survey should be discussed in the Final Report.* **I have requests for 1 to literally hundreds of turbines every day. Visitors come from around the world to discuss licensing. The entire wind energy industry is following my progress and eagerly awaiting the next step. Requests for quotes and licensing are coming in from developers in many nations. A major wind energy developer is now convinced that my offshore design solves most engineering and cost challenges faced by offshore wind energy. Technology incubators, venture capitalists, and entrepreneurs have offered to buy the company, or take it over. Wind is the future of energy.**
11) Have you performed a market analysis that takes external factors into consideration?	*External factors include potential actions by competitors, other new technologies, or changes in regulations or laws that can impact market acceptance of your product?* **Renewables Portfolio Standards (RPS) increasingly mandated by legislation worldwide insure a rapidly increasing market for wind energy, already the fastest-growing segment of the energy industry.**
12) Have you identified any regulatory, institutional or legal barriers to product acceptance?	*If YES, how do you plan to overcome these barriers?* **CEC ban on offshore energy research. Get it lifted.**
13) What is the size of the potential market in California for your proposed technology?	*Identify the sources used to assess market size and any assumptions related to anticipated market penetration.* **The entire wind energy industry, which is growing extremely fast. You can do the math.**
14) Have you clearly identified the technology that can be patented?	*If NO, how do you propose to protect your intellectual property?* **Yes. Also U.S. Trademark "Superturbine"**
15) Have you performed a patent search? **I have more types of wind turbine patented than anyone on the world. The patent system is my playground.**	*If YES, was it a self-search or professional search and did you determine if your product infringes or appears to infringe on any other active or expired patent?* **Let's worry about others infringing on me, not me on them. No infringers yet, but give it time.**
16) Have you applied for patents? **Yes and I have the best patent attorneys.**	*If YES, provide the number of applications.* **Please see the "references" section of this report, or look them up on the web – I have an entire portfolio of wind energy patents pending worldwide.** (PCT) International Patent Application "***COAXIAL MULTI-ROTOR WIND TURBINE***" World Intellectual Property Organization (WIPO) International Patent Cooperation Treaty Application Serial Numbers WO 2002/103200 PCT/US02/19181 Filing date 14 June 2002 Publication date 20 February, 2003 **U.S. Patent Application Number 10/ 781213** **"Side-Furling Co-Axial Multi-Rotor Wind Turbine"** Filing Date February 17, 2004 Publication Number 20040219018 Publication Date: November 4, 2004 And others.

17) Have you secured any patents?	*If YES, provide the patent numbers assigned and indicate if they are generic or application patents.* **U.S. Patents 6616402, 6692230, more pending plus PCT filings in the national stage around the world.**
18) Have you published any paper or publicly disclosed your concept in any way that would limit your ability to seek patent protection?	*If YES, is it your intent to put the intellectual property into the public domain?* **No. I have patents issued with more pending worldwide - more types of wind turbine patented than any other entity in the world.**
Commercialization Path	
19) Can your organization commercialize your product without partnering with another organization?	*If YES, indicate how you would accomplish that.* **Yes, we start selling small turbines, work our way up. A model for market is mostly developed including sources for all parts.** *If NO, indicate who would be the logical partners for development and manufacture of the product.* **We will also work with other companies. Licensing remains an option, with offers being made regularly.**
20) Has an industrial or commercial company expressed interest in helping you take your technology to the market?	*If YES, are they a major player in the marketplace for your product?* **Yes and yes.**
21) Have you developed a commercialization plan?	*If yes, has it been updated since completing your grant work?* **Yes, informally, and it is continually updated. We have registered "Superturbine" as a trademark.**
22) What are the commercialization risks?	*Risks are those factors particular to your concept that may delay or block commercialization.* **Lack of funding, excessive paperwork, lack of time to even meet with investors and potential partners or to read and respond to contracts being offered.**
Financial Plan	
23) If you plan to continue development of your concept, do you have a plan for the required funding?	**Selling Turbines, further research, and licensing. Every day brings another potential investor, customer, etc. The plan is to start Superturbine Inc. and possibly sell shares.**
24) Have you identified funding requirements for each of the development and commercialization phases?	**To a certain extent. This new technology has many implications with limitless possibilities. Many steps are outlined but the overall effort is vast, with many applications, including offshore. I will start producing small turbines to prove the concept. Similar funding with no strings attached would have resulted in a turbine on the market long ago. Abundant grant funding exists, in the millions of dollars, from many sources, including NREL/DOE, NIST, and many state programs. There is a need for additional personnel to secure this funding, and administrate the research.**
25) Have you received any follow-on funding or commitments to fund the follow-on work to this grant? **Haven't had time, too busy doing paperwork for this project, and filing patents. Interested parties have offered to help write grant proposals but none has actually done so.**	*If YES, indicate the sources and the amount.* *If NO, indicate any potential sources of follow-on funding.* **NREL /DOE Low Wind Speed Turbine effort. NYSERDA Programs, and other state programs. NIST- ATP Grant for $2 million – Lockheed Martin Akron eager to collaborate on version using a blimp.**
26) What are the go/no-go milestones in your commercialization plan?	**Making and selling turbines rather than doing paperwork would be a good milestone. It is all "Go".**
27) How would you assess the financial risk of bringing this product/service to the market?	**ZERO – it works, people love them.**

28) Have you developed a comprehensive business plan that incorporates the information requested in this questionnaire? **Producing and selling turbines is paramount at this point. Jim Robbins and the EBC may help produce a formal business plan at some point in the future.**	*If YES, can you attach a non-proprietary version of that plan to your final report?* **The business plan is to stop doing paperwork and start building turbines. As it is I don't even have time to read the many proposed international licensing agreements received. Daily requests for turbines and licensing will result in a brisk business. Selling a product and establishing a research facility in a high wind area of the desert are priorities. A product in the marketplace is the only complete test of any design. The many versions, offshore, building-mounted, and blimp-supported, will revolutionize the industry. Development can be assisted by funding through further grants.**
Public Benefits	
29) What sectors will receive the greatest benefits as a result of your concept?	*Residential, commercial, industrial, the environment, other.* **ALL**
30) Identify the relevant savings to California in terms of kWh, cost, reliability, safety, environment etc.	*Show all assumptions used in calculations.* **Projected to lower the cost of wind-generated electricity to 3 cents per kWh in high wind areas, and bring the current price of 4 cents per kWh to lower wind areas, mitigating the need for more power lines. Zero emissions and abundant electricity to produce hydrogen fuel eliminates smog, and makes California self-sufficient, with no need to defend foreign oil. SEE FINAL REPORT. SEE EXECUTIVE SUMMARY.**
31) Does the proposed technology reduce emissions from power generation?	*If YES, calculate the quantity in total tons per year or tons per year per relevant unit. Show all assumptions used in calculations.* **OUR TURBINES PRODUCE ZERO EMISSIONS, reducing overall emissions in direct proportion to the extent they are deployed.**
32) Are there any potential negative effects from the application of this technology with regard to public safety, environment etc.?	*If YES, please specify.* **NO, only positive as long as you keep your hands and pets out of the blades.**
Competitive Analysis	
33) What are the comparative advantages of your product (compared to your competition) and how relevant are they to your customers?	*Identify top 3.* **Lighter Total Rotor Weight, Higher RPM, Direct-Drive Generator, passive yaw control, easier transport – the main challenges of turbine design. Major developers are convinced. Further, related versions are patented, and ready for development.**
34) What are the comparative disadvantages of your product (compared to your competition) and how relevant are they to your customers?	*Identify top 3.* **We need a longer, stronger driveshaft than the competition. Customers want them anyway.**
Development Assistance	
The EISG Program may in the future provide follow-on services to selected Awardees that would assist them in obtaining follow-on funding from the full range of funding sources (i.e. Partners, PIER, NSF, SBIR, DOE etc.). The types of services offered could include: (1) intellectual property assessment; (2) market assessment; (3) business plan development etc.	
35) If selected, would you be interested in receiving development assistance? **YES**	*If YES, indicate the type of assistance that you believe would be most useful in attracting follow-on funding.* **$20,000 with no strings attached and minimal to no paperwork. Bureaucratic requirements can restrict design creativity, and redundant documentation slows progress. Unrestricted funds of the same amount would have a product on the market by now.**

Appendix X (Proprietary) – Next Generation Designs – Patent Pending:

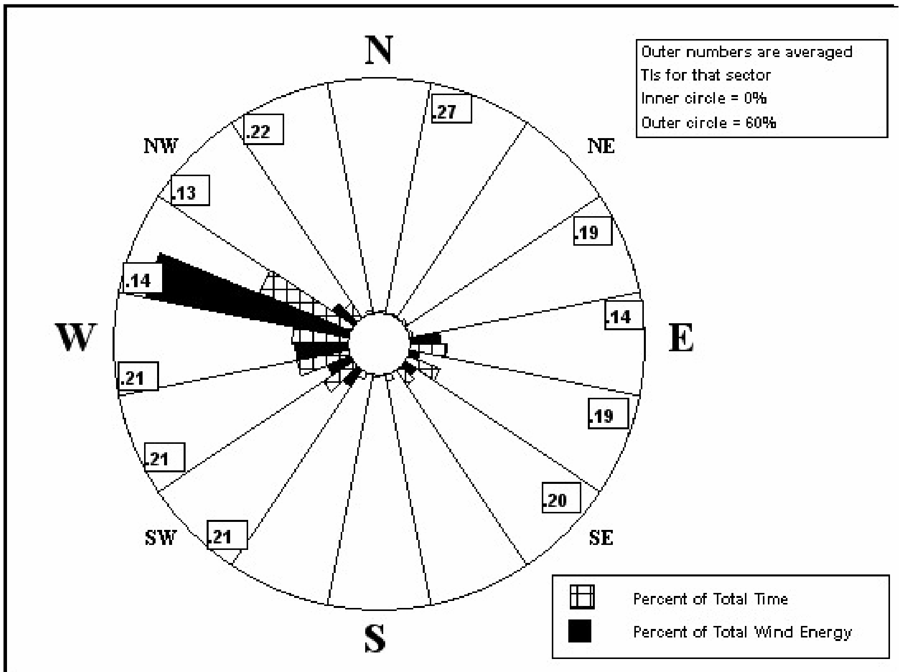


All images and descriptions in this appendix from U.S. patent application number 60/712792, filing date 08/30/2005

Five significant observations from this research effort resulted in the next generation of designs for which patent protection has now been filed: (These designs are still confidential at this time.
U.S. patent application number 60/712792, filing date 08/30/2005)

1. **Power** was proportional to the number of rotors that could be supported at sufficiently spaced intervals by the cantilevered driveshaft. The number of rotors was **limited by driveshaft length**.
2. **Driveshaft length**, in turn, **was determined** by the cost of providing sufficient stiffness, straightness, and light weight demanded **by a cantilevered configuration**.
3. The **cantilevered** method of supporting the driveshaft was implemented mainly to allow free directional rotation of the entire turbine about a central yaw bearing, **to maintain exact aim into the wind**.
4. **Exact aim** of the driveshaft, however, **was not essential** for useful power output. (In fact, the very nature of the co-axial, multi-rotor design prefers a slight misalignment from the wind direction.) Performance was satisfactory over a range of offset angles to the wind direction.
5. The predominant **wind** resource in many regions, including the test site of this research project in Tehachapi, CA, **prevails** from within **a narrow directional range**. Such a relatively unidirectional wind resource is common to most high wind locations.

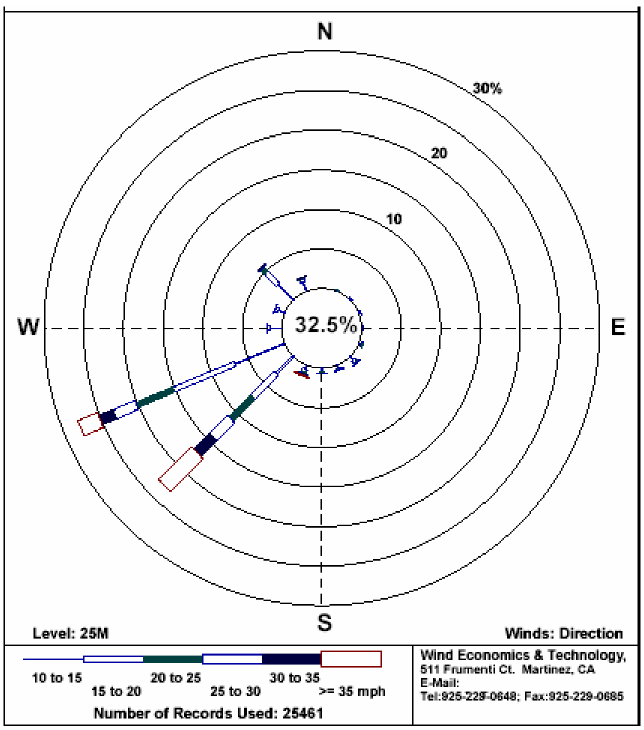
Given these facts, in such unidirectional winds, the next generation of co-axial, multi-rotor turbines advantageously trades the ability to aim the driveshaft, for the freedom to reduce its stiffness, and hence its cost, while extending its length, by supporting it from at least two fixed points. Placing the driveshaft under tension then allows greater spans between supports, while raising resonant frequencies and critical speeds, which adds stability in lieu of stiffness. The earth or underlying substrate is thereby placed in compression, becoming in effect part of the turbine structure. The number of additional rotors that such a longer driveshaft can support overcomes any losses from aiming inaccuracy. The result is a far more powerful turbine that still runs at high RPM to directly drive a generator, which can be located proximate one end.



Wind Power Rose for Tehachapi, CA, the project testing location, showing the strongly unidirectional nature of the wind resource.

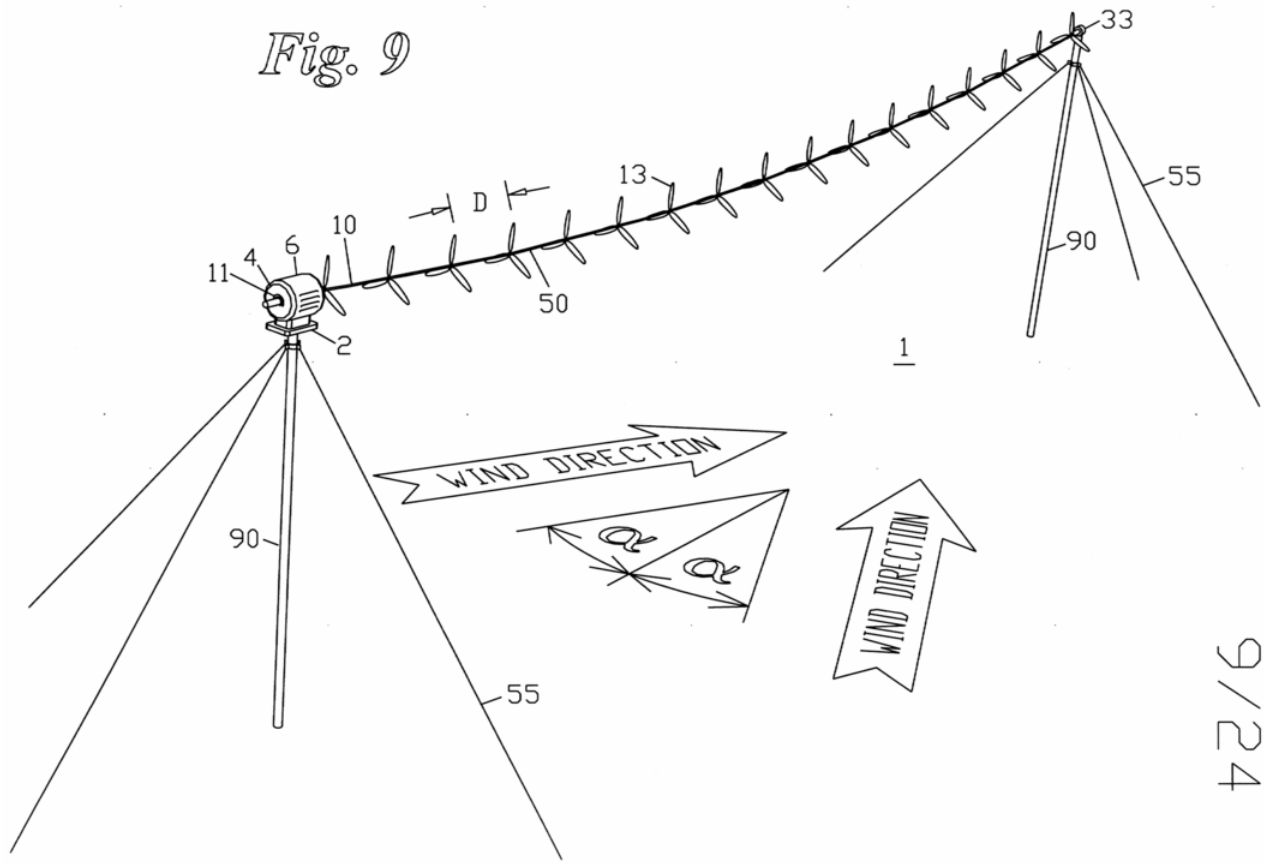
Why Aim What Doesn't Need Aiming?

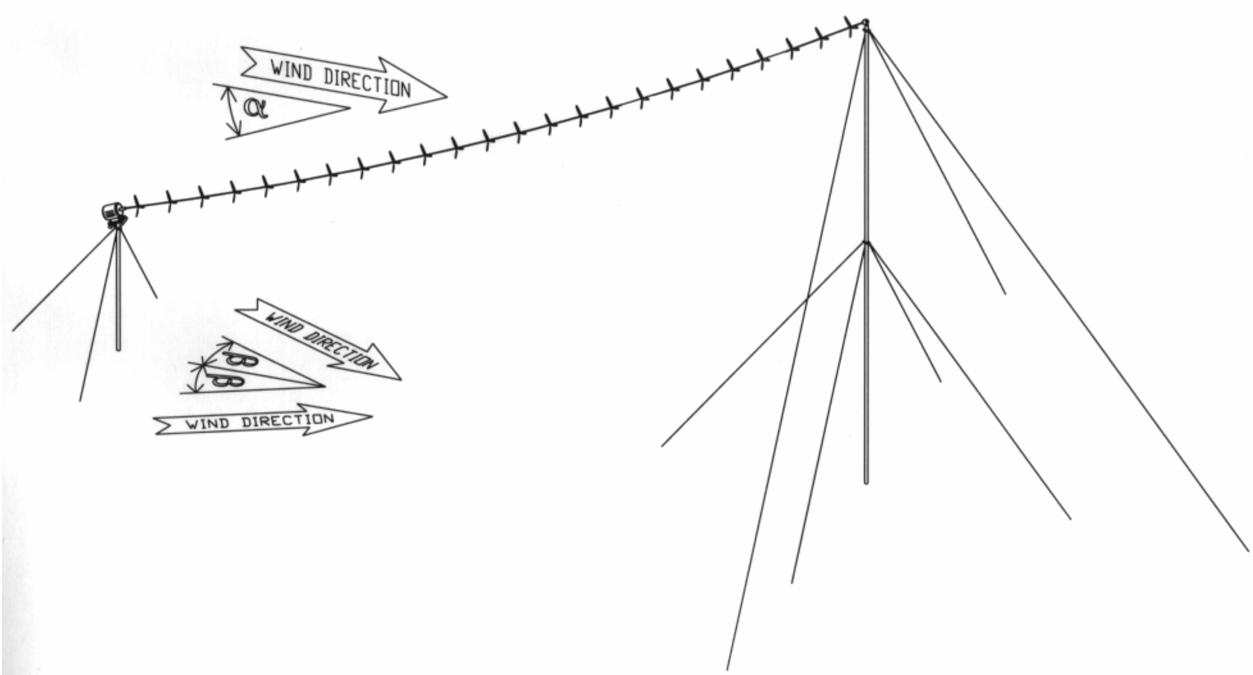
The co-axial, multi-rotor configuration does not require exact aim, nor is the ability to change aim particularly important given the unidirectional nature of the resource in many areas, including most windfarm locations. With the main factor limiting power output, and preventing further cost reduction, being in providing the ability to aim, a logical conclusion is that non-aiming versions, that can support many more rotors, can thereby generate far more total energy, at lower cost.



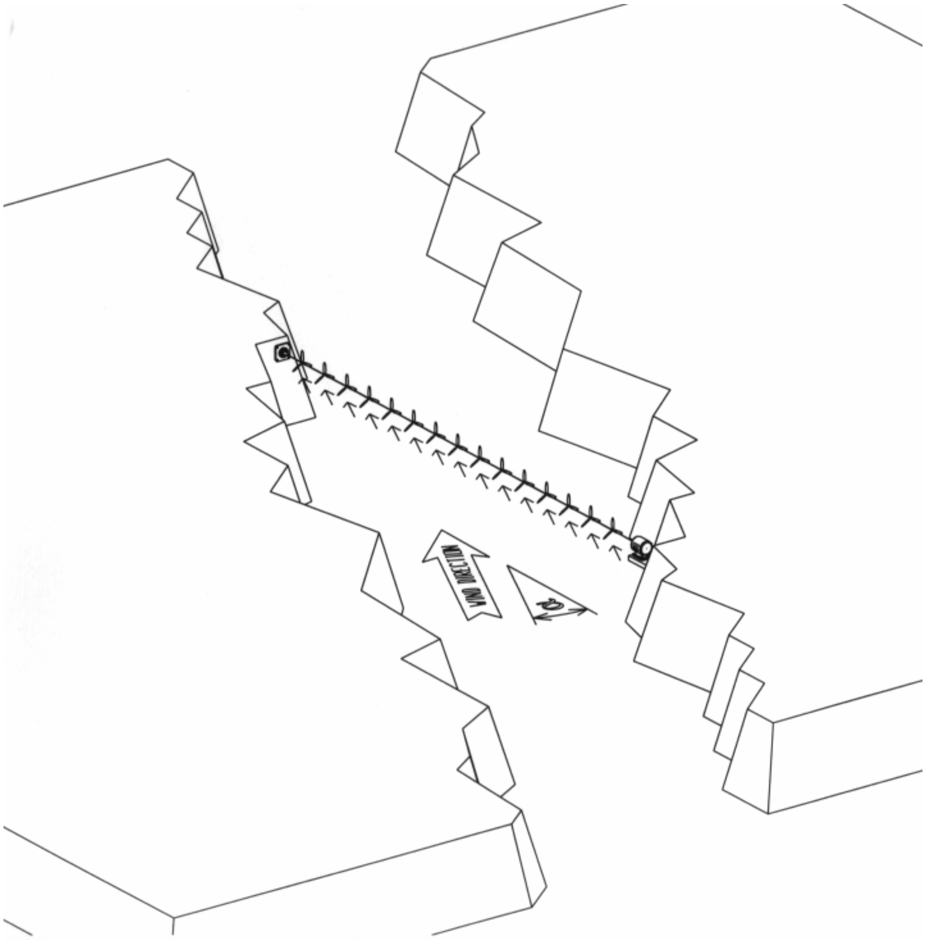
Two sample wind rose examples showing unidirectional nature of the resource typical at wIndfarms – Wind power rose for the San Gorgonio Pass near Palm Springs (left) and the Altamont Pass (right)

Figure 3-1
Typical Annual Wind Rose at Altamont Pass





Suspended catenary co-axial multi-rotor wind turbines (pat. pend.) place the driveshaft in tension, and the Earth or underlying substrate in compression, making the substrate part of the structure. Elimination of most conventional components lowers the number of moving parts to one.



Suspension across a canyon, providing both a unidirectional wind resource and elevated support points, greatly lowers costs. A single such turbine might have output equal to an entire wind farm of conventional turbines, delivering energy at much lower cost. (left) (pat. pend.)

In a similar manner, strategically placed buildings in a uni-directional wind resource serve as an upwind concentrator, a downwind diffuser, and as means of support for a planar array. (below)
(pat. pend.)

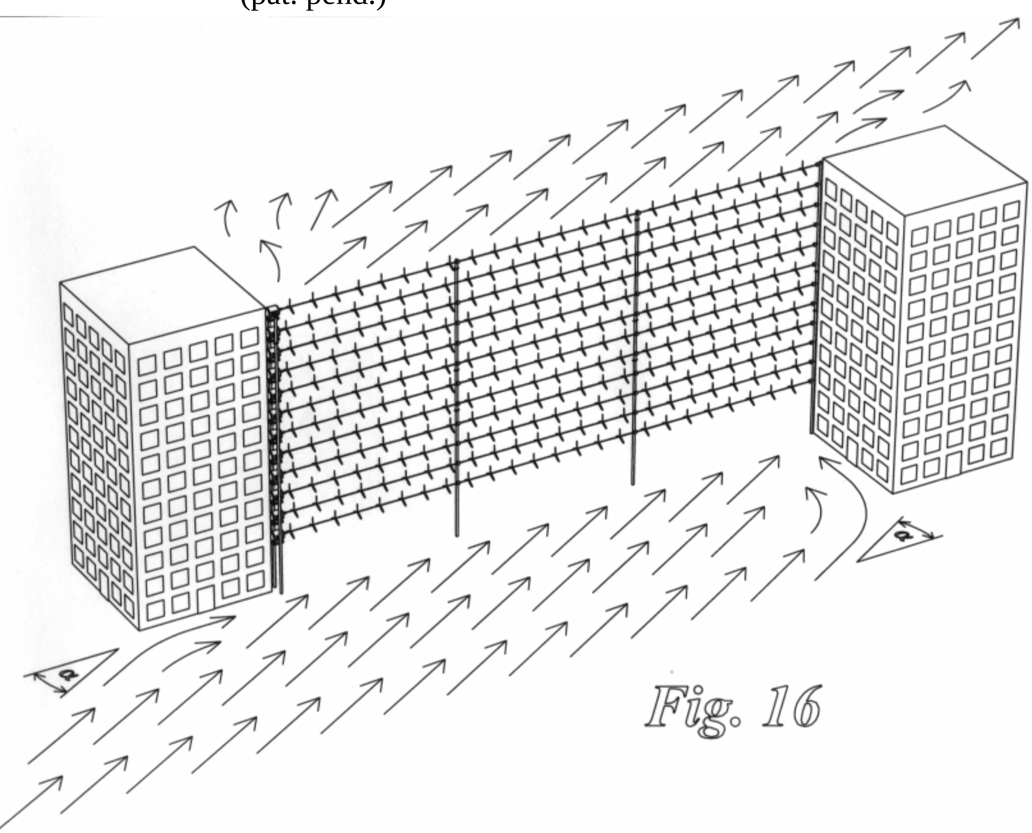


Fig. 16

A building, landform, or other structure elevates one end of multiple, parallel, suspended, catenary co-axial, multi-rotor, wind turbines. (right)
The generators are located at ground level.
Offset angle α (alpha) is in the vertical plane.
(pat. pend.)

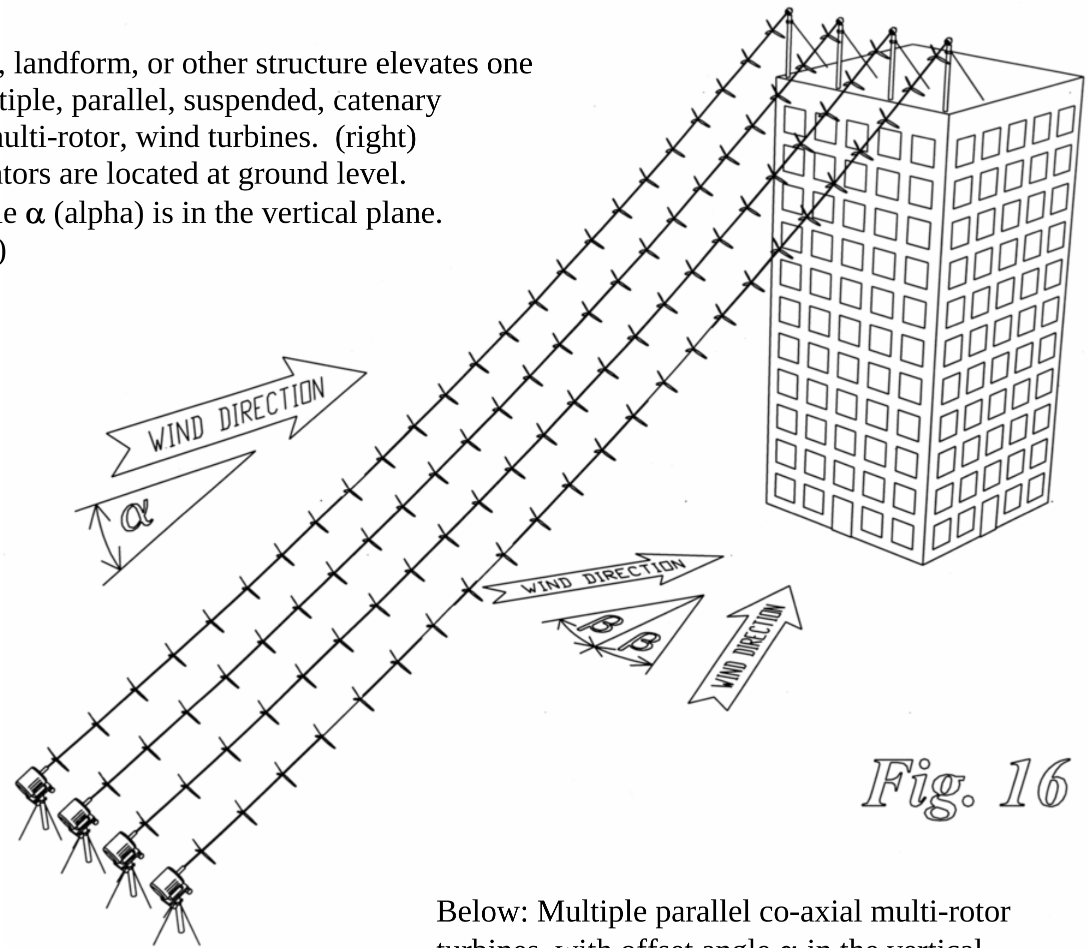


Fig. 16

Below: Multiple parallel co-axial multi-rotor turbines, with offset angle α in the vertical plane, project in a cantilevered manner past the ridgeline of a sloping gable roof, that acts as both an upwind concentrator and a downwind diffuser. (pat. pend.)

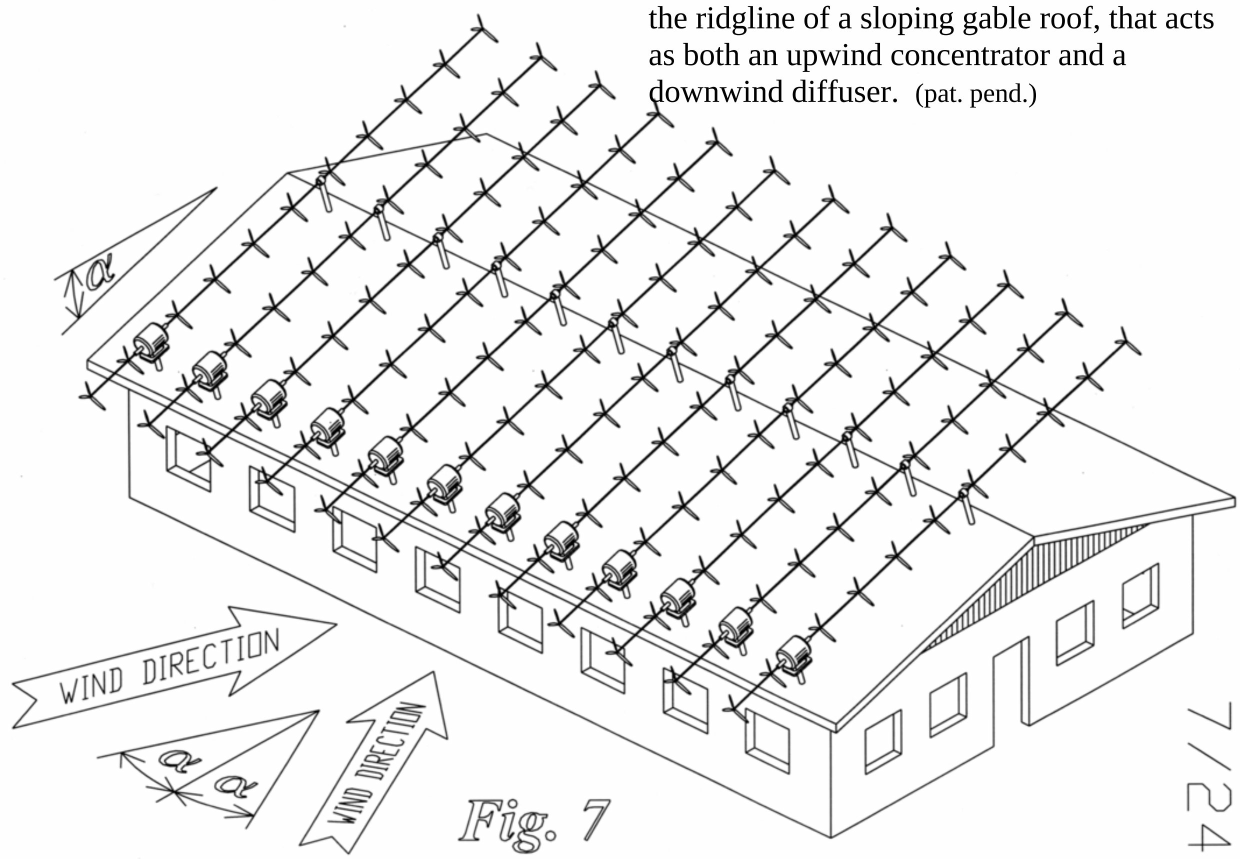
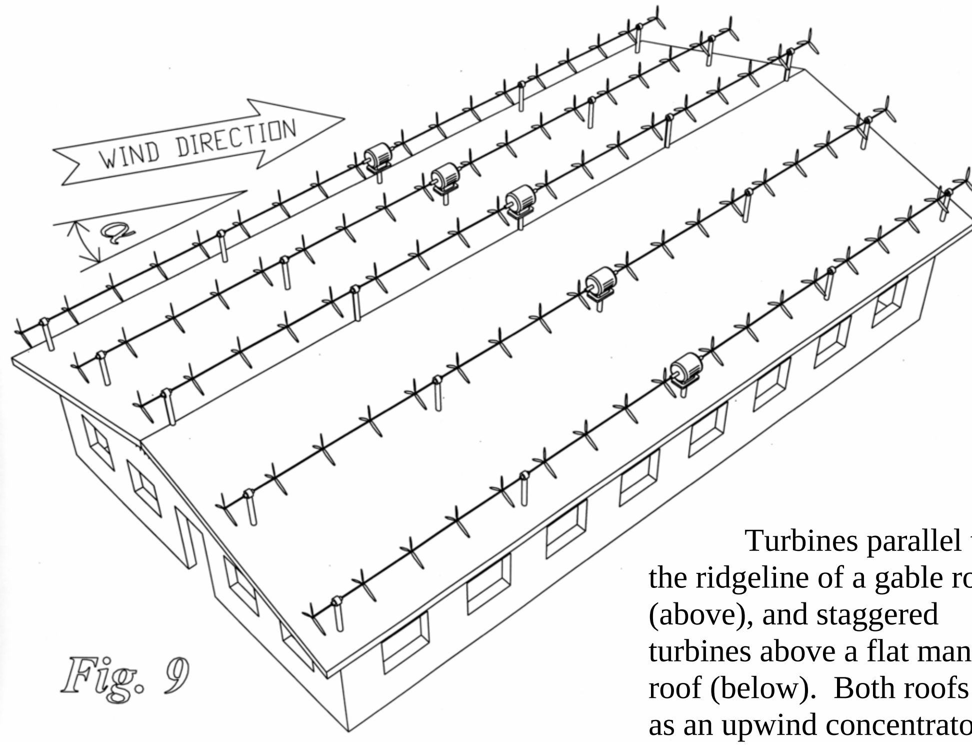


Fig. 7



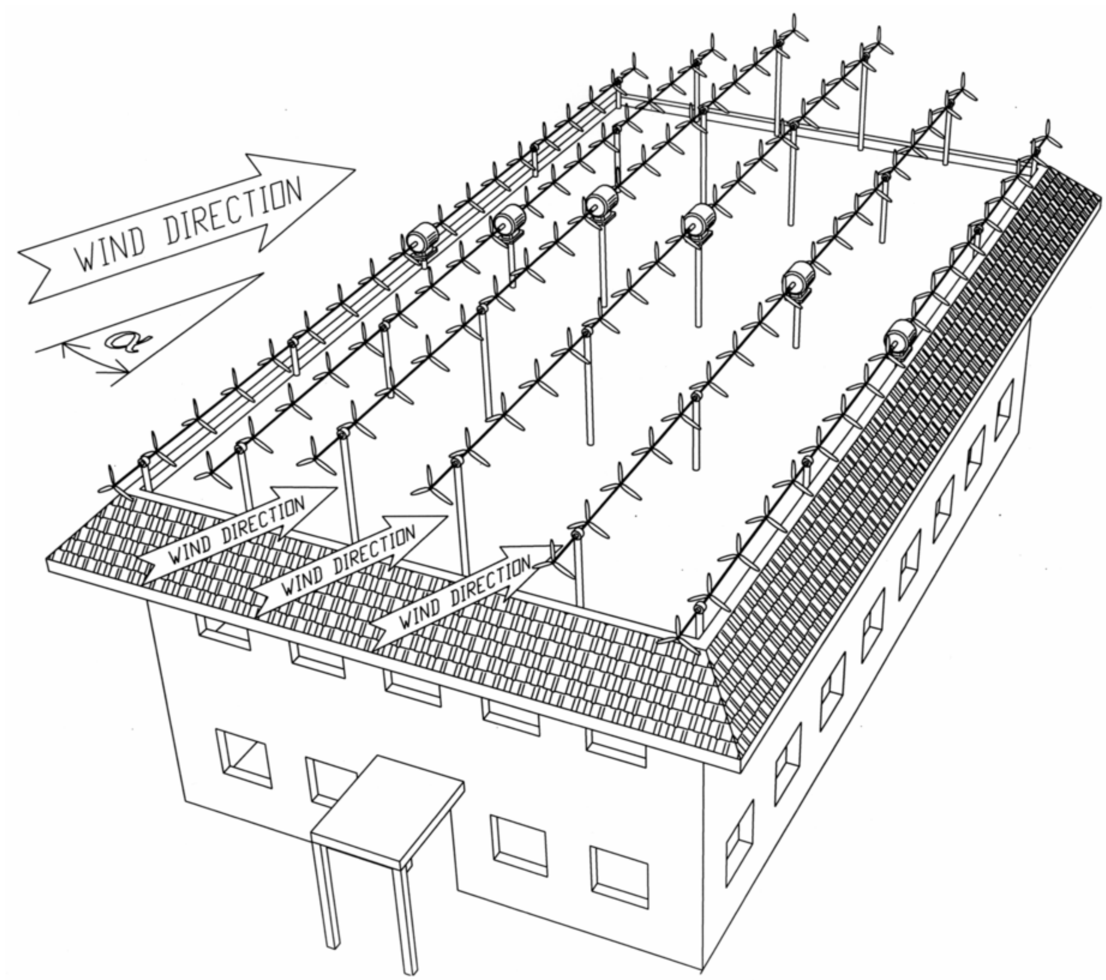
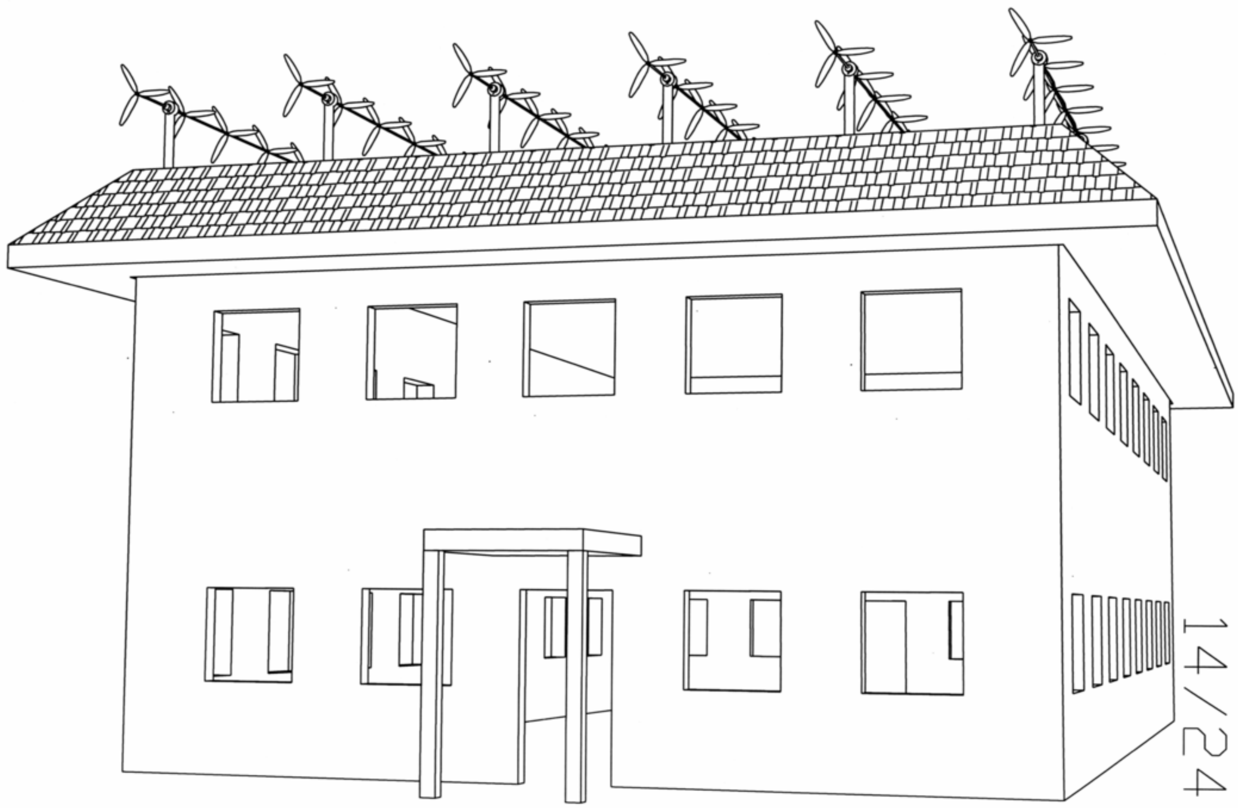


Fig. 9

Turbines parallel to the ridgeline of a gable roof (above), and staggered turbines above a flat mansard roof (below). Both roofs act as an upwind concentrator

and as a downwind vacuum
diffuser. (pat. pend.)



Such rooftop arrays in areas with a good wind resource can easily zero out a building's electric bill, with minimal visual intrusion. (pat. pend.)

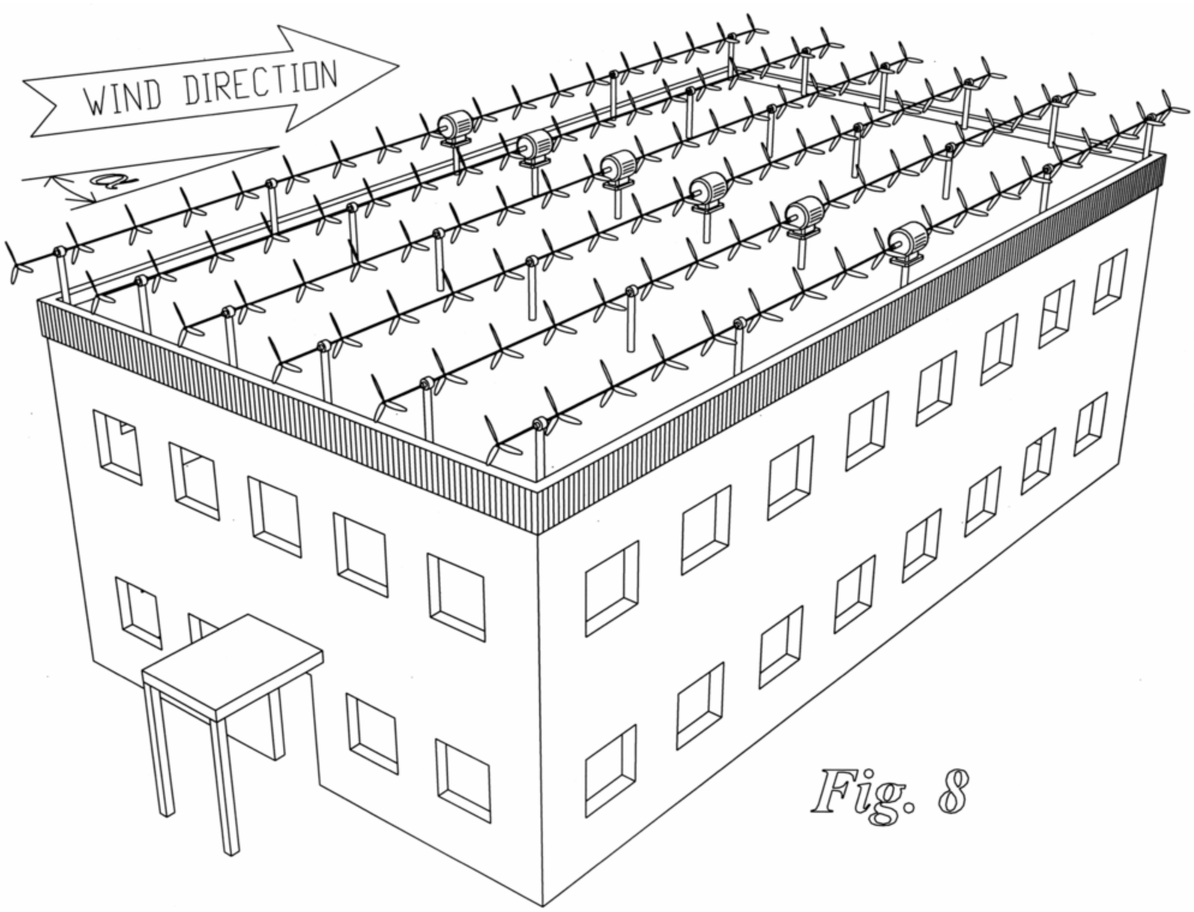


Fig. 8

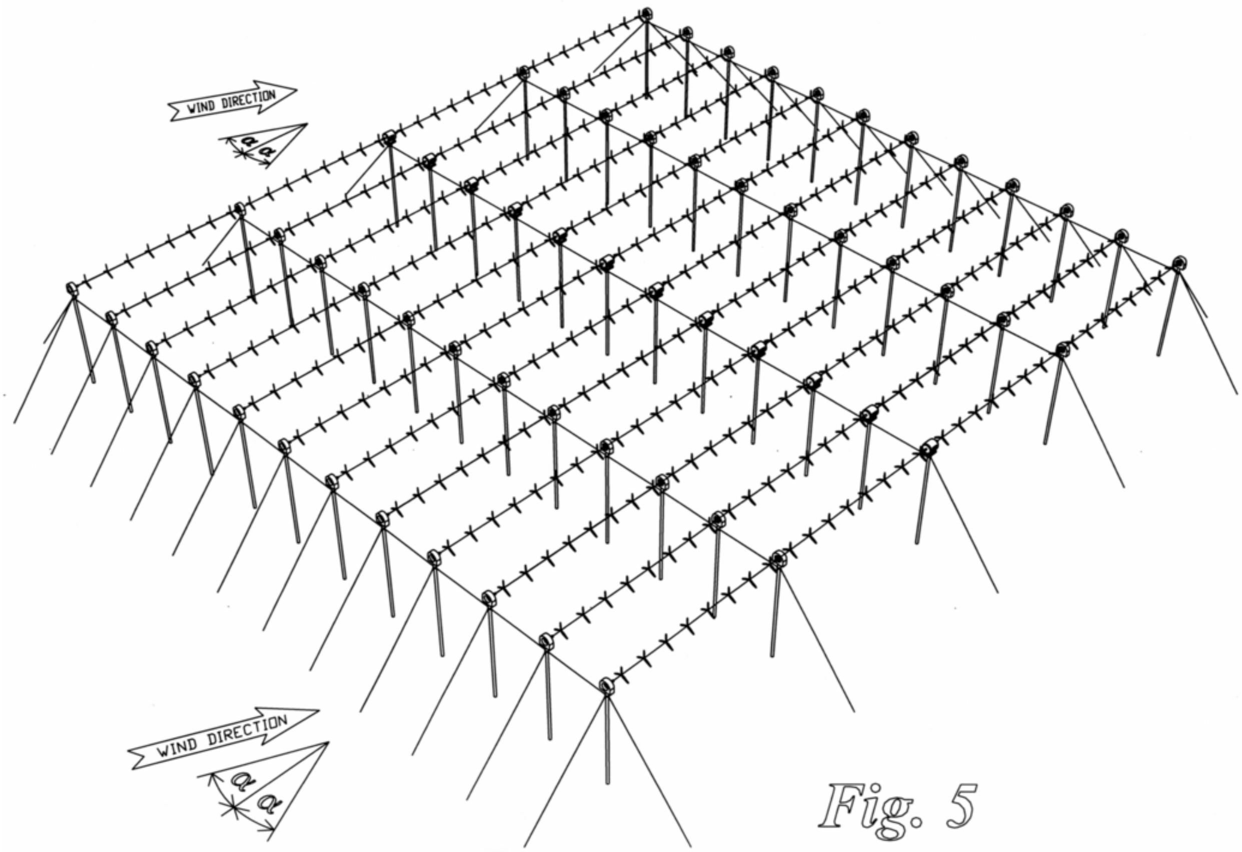


Fig. 5

Arrays, both horizontal and vertical, of co-axial multi-rotor turbines (pat. pend.), can extract electricity windy areas, leaving the land still usable for agriculture, grazing, parking, railroads, highways, power line corridors, storage and municipal yards, solar

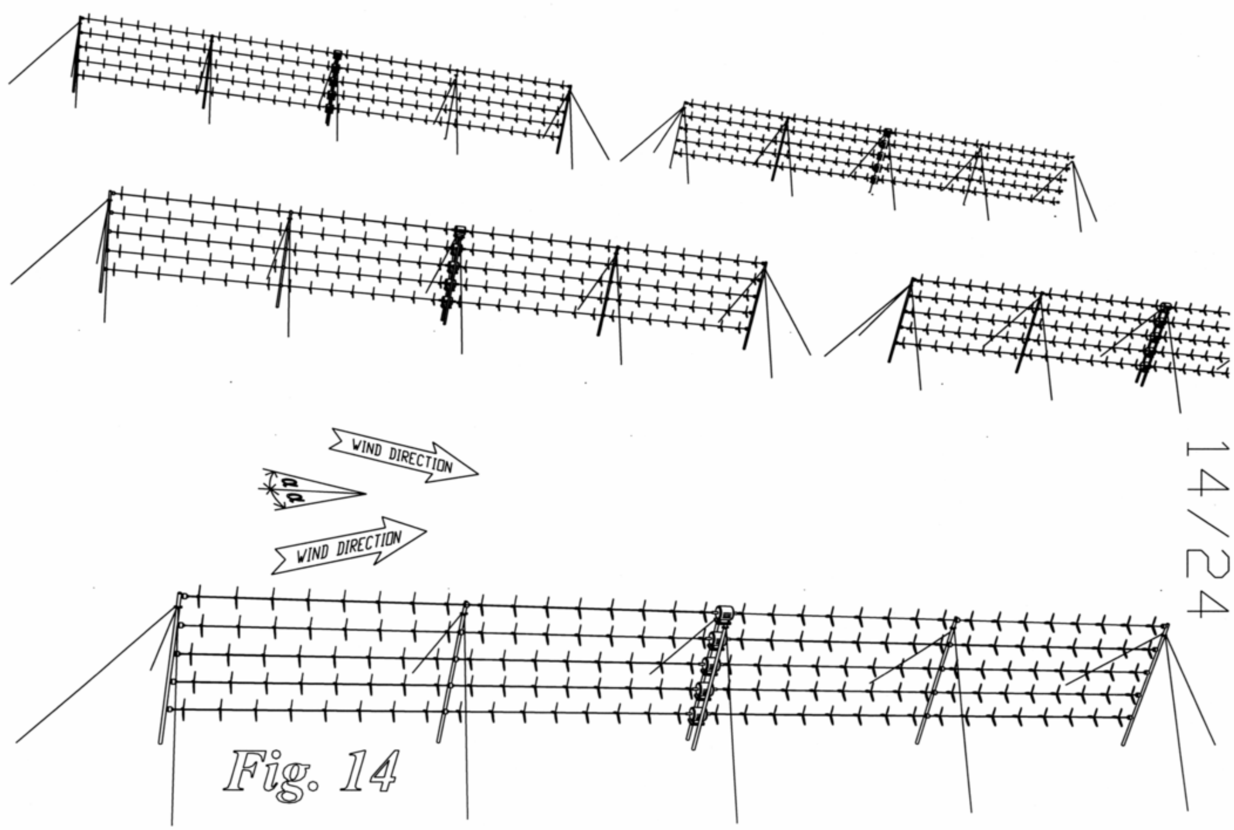
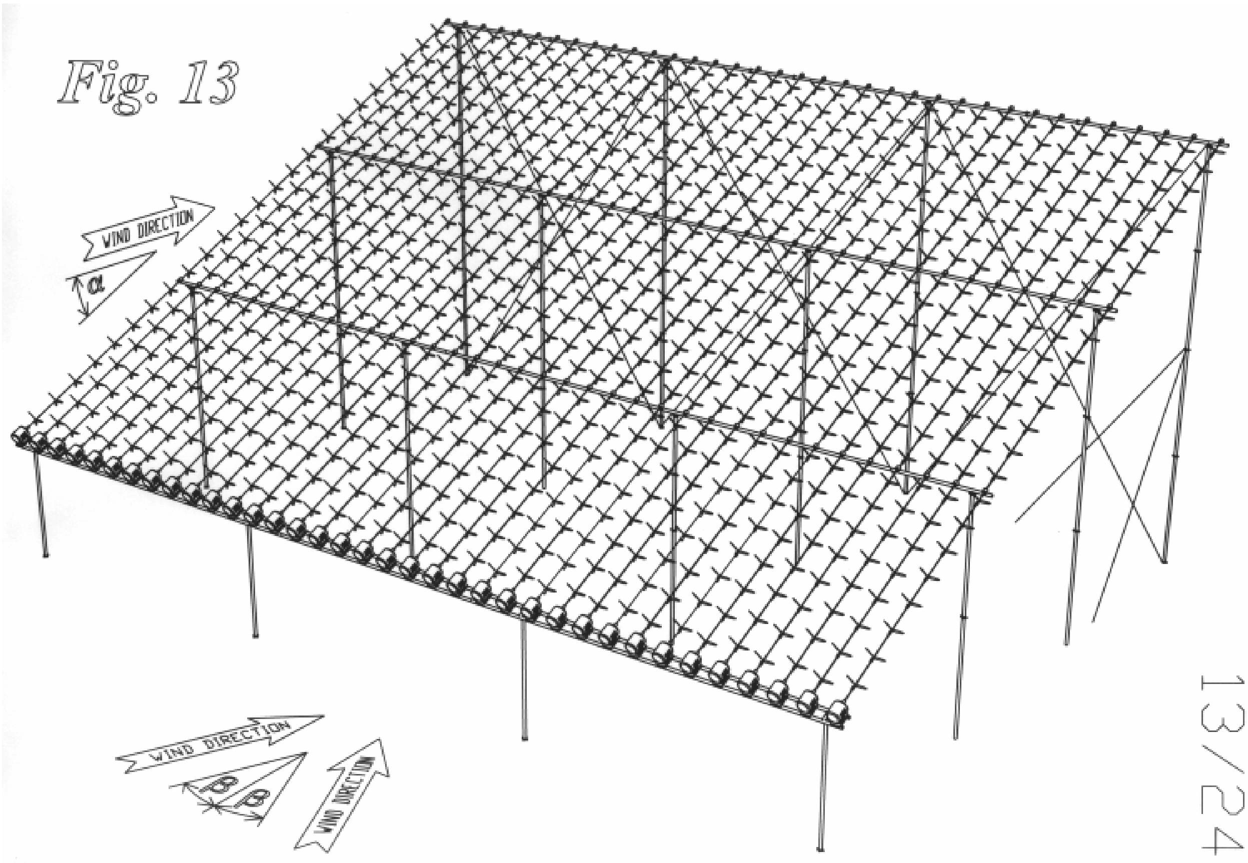


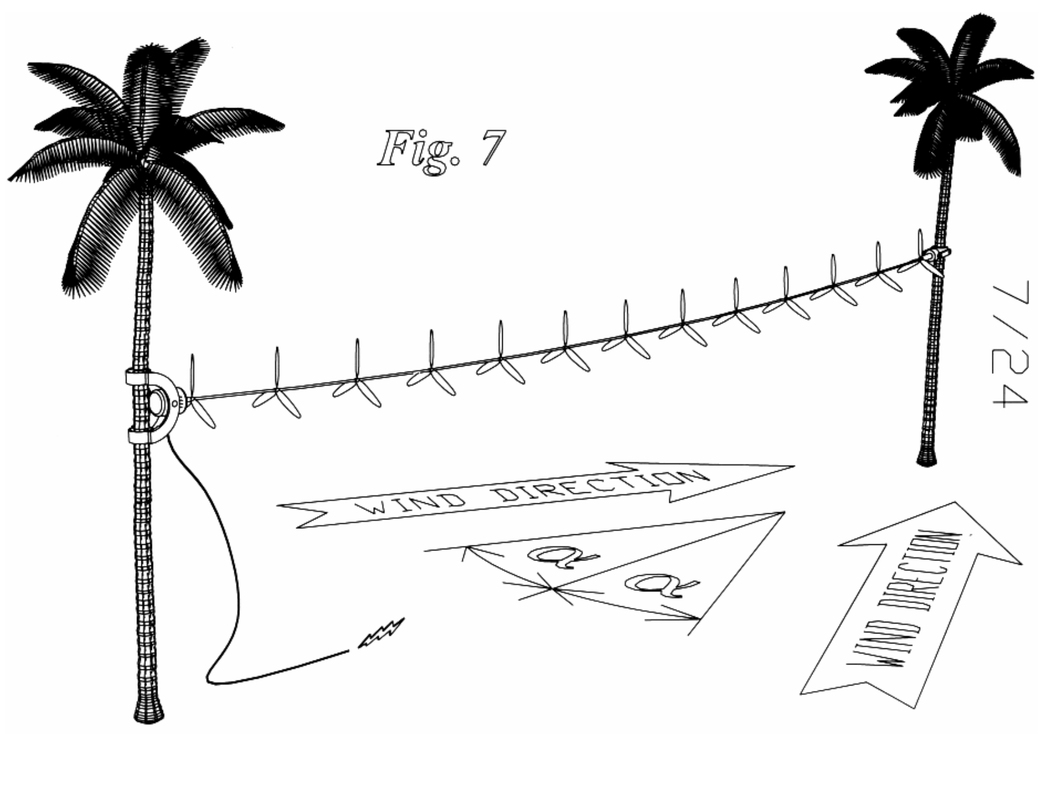
Fig. 14



energy installations, etc.

1.5 Megawatt array (above) uses 5-foot (1.5 m) blades, steel tubing, bearings, hubs, alternators, and guy wires, comprising 36 rows of 24 rotors. Projected cost: $300,000 installed. (pat. pend.)

Below: Ideal for camping and remote locations, suspended catenary turbines of relatively small size may use almost any object, tree, or structure for support. (pat. pend.)



The principal Investigator has formed a California corporation, Superturbine Inc. Based on the findings of this research, the American Twin™, a side-furling, dual rotor machine, captures almost twice the power of a single rotor, at about the same cost. Two rotors, are easy to support by a cantilevered driveshaft at offset angle α to the wind, without the use of exotic materials. Priced at about one dollar per watt of rated output, this machine cuts the cost of small wind turbines in half. This is just the first step in making wind energy far more affordable, using multiple, co-axial rotors. U.S. pat. 6692230

interchangeable driveshafts provide an alternative configuration having four smaller rotors. And a 5-rotor machine, similar to the prototype of this research, that tilts back to furl, is almost fully developed for mass production. U.S. pat. 6692230