Project Title:

Wind Fins: Novel Lower-Cost Wind Power System

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Executive Summary

This project evaluated the technical feasibility of converting energy from the wind with a novel “wind fin” approach. This patent-pending technology has three major components: (1) a mast, (2) a vertical, hinged wind structure or fin, and (3) a power takeoff system. The wing structure responds to the wind with an oscillating motion. The system is able to rotate freely around the mast and will automatically swing to orient itself downwind. It is self-starting. When the wind blows, the wing structure oscillates, and this oscillating motion is converted by the power takeoff system to unidirectional rotation, turning a generator and producing electricity. The wind fin technology was initially developed as a visually pleasing alternative to wind turbines. It allows for designs that are more compatible with existing architectural forms and that can blend more readily into the natural landscape. Furthermore, its basic structural design virtually eliminates lethality to birds and bats.

The overall project goal was to determine the basic technical feasibility of the wind fin technology. Specific objectives were the following: (1) to determine the wind energy-conversion performance of the wind fin and the degree to which its performance could be enhanced through basic design improvements; (2) to determine how best to design the wind fin system to survive extreme winds; (3) to determine the cost-effectiveness of the best wind fin designs compared to state-of-the-art wind turbines; and (4) to develop conclusions about the overall technical feasibility of the wind fin system. Project work involved extensive computer modeling, wind-tunnel testing with small models, and testing of bench-scale models in a wind tunnel and outdoors in the wind.

This project determined that the wind fin approach is technically feasible and likely to be commercially viable. An early initial design was substantially modified to enhance the system performance. Subsequent tests with models embodying this new design, both in wind tunnels and outdoors, concluded that the wind fin system is roughly equal in power output to state-of-the-art wind turbines of comparable size. Several cost effective methods of shutting down the system in high winds were developed. In addition, project tests confirmed that the wind fin system is subject to lower stresses than wind turbine systems, enhancing their survivability. Because of these lower stresses, less-expensive materials and manufacturing methods can be used to produce wind fin systems. This will significantly lower both the overall system cost and the cost of energy output. Project results suggest that this new technology has the potential to harvest wind energy at approximately *half the system cost* of wind turbines in the 10kW range. Overall, the project demonstrated that the wind fin technology has the potential to increase the economic viability of small wind-power generation. In addition, it has the potential to eliminate lethality to birds and bats, overcome public objections to the aesthetics of wind-power machines, and significantly expand wind-power’s contribution to the national energy supply.

Project Description

The overall goal of this project, titled "Wind Fins: Novel Lower-Cost Wind Power System," was to determine the basic technical feasibility of a radically new approach to wind-power generation involving an oscillating, vertically aligned, aerodynamic wing structure. Specific objectives, associated tasks, and project results follow:

***Objective # 1*:** Determine the general energy-conversion performance of the wind fin and the degree to which this performance can be enhanced through basic design improvements.

***Specific Tasks*:**

1) Undertake computer modeling to determine the estimated maximum conversion efficiency for specific wind fin sizes and configurations, and how this efficiency will vary with wind speed.
2) Undertake computer modeling and simulations to determine how different configurations of the wind fin will be affected by vertical wind-speed gradients and changes in wind direction.
3) Undertake computer modeling and simulations to determine how to enhance the energy-conversion performance of the wind fin through modifications of design, including geometry and addition of extra hinged panels to the oscillating fin.
4) Undertake bench-scale wind chamber experiments with small-scale models of the wind fin designs with the highest energy-conversion performance and select the best two candidates for wind tunnel testing.
5) Undertake wind tunnel tests with larger-scale models of the best two wind fin designs.

***Major Results*:**

Approximately 60 percent of the total effort during this year-long project focused on this objective. During the First Quarter, project work involved computer modeling wind-tunnel experiments with small (7-inch tall) models of varying designs to determine those with the highest energy-conversion efficiency. Following this initial work, the research team decided to undertake wind tunnel tests at the facilities at the Massachusetts Institute of Technology (MIT) to develop preliminary conclusions about the performance of a larger bench-scale model of the leading wind fin design. A model measuring 6 ft. tall by 1 ft. wide was constructed and tested at MIT. These tests occurred at the end of the First Quarter.

The MIT experiment produced some valuable results. (1) First, it confirmed that the wind fin approach is theoretically sound. Power measurements taken from the bench-scale model in the MIT wind tunnel indicated that the wind fin is capable of harvesting economically significant amounts of wind energy. (2) The MIT experiment resulted in observations and insights that suggested ways to improve the wind energy-conversion performance of the wind fin. In particular, it was determined that performance could be improved by increasing the exposure of the wind fin surface in the wind stream. This led to a decision to focus on an alternative wind fin design (covered by one of the patent applications) that employs stand-off arms. Fig. 1 provides a sketch of this design. The stand-off arms position the wind fin at a greater distance from the tower, increasing its sweep and exposure to the wind stream.

During the Second Quarter, most of the research involved analysis of the results from the MIT wind tunnel experiment, design and construction of small models using the stand-off arm design, and testing of these models in the wind tunnel at DCM Studios. Major elements of this work included: (1) Comparisons between the old and the new approach; (2) design of a new power measurement mechanism; and (3) a series of iterative tests with a succession of models, to try to maximize the wind energy conversion performance of the system. These models employed not only different structural designs but different construction materials as well. The research team was able to achieve progressively larger energy-conversion values through this research. These values were plugged into a scaling equation, developed by the head of the MIT wind tunnel facility, in order to predict how a full-scale wind fin product would behave. By the end of the Second Quarter, the research team concluded that the new stand-off arm design was the most promising. It has since been the major project focus.

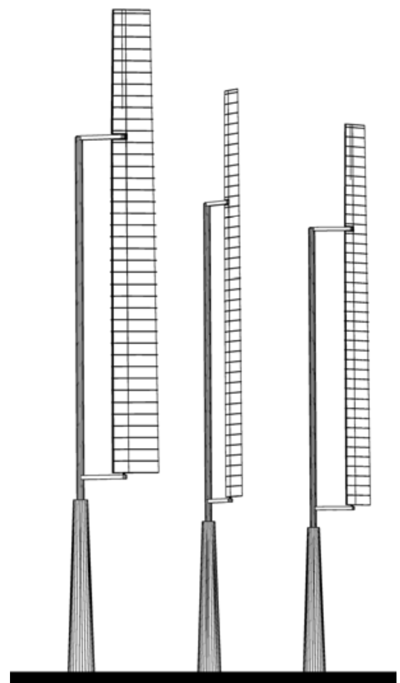

Fig. 1. Wind fin design with stand-off arms

During the Third Quarter, work consisted primarily of preparations for a second stage of bench-scale model testing. Preparations consisted of conducting additional wind tunnel tests with small bench-scale models, to determine the most promising airfoil shapes for best results. These models were continuously refined using both airfoil modeling as well as basic kinematic mechanical modeling to optimize power output. Power output was assessed by measurements of the work performed by each of the different models. In addition, during the Third Quarter, calculation tools for use in Excel were developed, refined, and used on a regular basis. These tools have allowed for easy comparison and contrasting of wind fin shape attributes. In addition, project researchers designed an improved power measurement device, to ensure accurate determination of power performance of the bench-scale models and projection of this performance to full-sized units.

During the Fourth Quarter, work focused primarily on (1) construction of the power measurement device, and (2) construction and testing of two different bench-scale wind fin models with slightly different airfoil shapes. This testing was conducted near Bend, Oregon, from in late June and early July 2007. The wing structures on the bench-scale wind fins measured 6 ft. tall by 2 ft. wide. They were attached to a mast by two 2-ft. standoff arms. The mast was mounted on a completely instrumented testing apparatus, with a torque sensor to measure torque output, a potentiometer to measure the angular velocity of the wing structures, and an anemometer to measure wind speed—all feeding data directly into a computer.

The original test design called for the bench-scale models to be mounted on top of a vehicle, with the field test to be conducted by driving the wind fin down an airport runway in the early morning hours, when the airport was closed to traffic and when there was little or no wind. The idea was that the moving vehicle would create wind flow and allow power-output measurements to be taken at different speeds. However, this protocol proved to be unworkable: slight imperfections in the road and lateral movement of the vehicle interrupted the smooth functioning of the wind fin, introducing unacceptable perturbations. Instead, the research team parked the vehicle between two long hangars. Wind in the afternoon funneled through the space between the hangars, creating a large natural wind tunnel.

Data from the torque sensor and the potentiometer were collected at a frequency of approximately 425 samples per minute. From the torque and angular velocity, mechanical power consumed by a disk brake operating on a disk attached to the bottom of the rotating mast was calculated. Bench-scale Model A was tested for a total of 34 minutes and Model B was tested for a total of 50 minutes, both at wind speeds that ranged from 4 to 11 miles per hour. Bench-scale Model B performed almost twice as well as Model A. It achieved an average power output of 6 Watts at 6.9 mph wind speed. From the measurements, a power curve of Model B's projected power output performance was calculated using well proven scaling formulas.

Results from these tests were very encouraging. The Model B power curve revealed that at 25 mph wind speed, the Model B wind fin would generate 285 watts. This means that, according to well-established scaling formulas, a wind fin measuring 15 ft. tall by 3 ft. wide would generate 1,070 watts. This compares well to the power performance of the world's largest selling 1kW wind turbine, the Bergey XL.1 Wind Turbine, which has a rotor measuring 8.2 feet and which generates 1,000 watts at 25 mph wind speed. The Model B results also compare well to the power performance of the world's best-selling 10kW wind turbine, the Bergey Excel, which has a 22 ft. rotor diameter and which generates 10,000 watts at 31 mph. A wind fin with the Model B airfoil configuration measuring 44 ft. by 5 ft. would generate 10,066 watts at 31 mph, the Bergey Excel's rated wind speed. These results, combined with the economic analysis presented below under Objective 3, indicate that the wind fin approach has the potential to significantly lower the cost and cost-effectiveness of small wind-generation systems, particularly in larger sizes.

***Objective # 2*:** Determine how best to design the wind fin system to survive extreme wind conditions.

***Specific Tasks*:**

1) Undertake computer modeling and bench-scale wind chamber experiments to determine the best ways to lock the oscillating panels in alignment with the wind stream
2) Undertake computer modeling and simulations to determine when guy lines are needed for a wind fin design of a given height, to enable the system to successfully withstand extreme winds.
3) Undertake computer modeling and simulations to determine how well immobilized wind fins will survive maximum possible wind loads.
4) Select the best "survivability" features and integrate them into scale-model constructions of the wind fin designs selected for testing in bench-scale wind chambers and wind tunnels, as described in Objective #1 above.

***Major Results*:**

Approximately 10 percent of the total project effort focused on this objective. The MIT wind-tunnel experiment with the early bench-scale model, conducted during the First Quarter, demonstrated that the basic wind fin design is able to survive high wind speeds. No structural deficiency was observed in the bench-scale model following extensive testing in the MIT wind tunnel at 42 mph wind speed. This experience confirmed the belief of the project team that the wind fin system is subject to lower stresses than wind turbine systems, enhancing their survivability. The team conceived of several mechanical ways to enable the wind fin system to automatically shut itself down at certain pre-specified high wind speeds to prevent damage to the system. However, none of these were developed or tested because it was observed in wind tunnel tests that, with the stand-off arm design, a wind fin of a given size and weight would stall out at a specific high wind speed, at which point it would automatically orient itself downwind and "wind vane." In the stand-off arm design, with a single symmetrical wind fin, weight needs to be added to the trailing edge of the fin or wing

Fig. 2. Wind Fins on California Coastline *(Simulation)*

structure to initiate its oscillation, or back and forth rotation, in the wind. The project team observed that the amount of weight added to the trailing edge could be used as a mechanism to control the wind speed at which the wind fin would stall. Therefore, a wind fin could be designed to stall and wind vane at a pre-selected high-wind speed, such as 30 or 35 mph. These various experiments and observations led the research team to conclude that guy lines were not needed. The system will be designed with a supporting lower tower structure, as represented in Figs. 1 and 2, with the mast above serving as a drive shaft. These systems will be designed using the extensive body of knowledge pertaining to flag poles, which are designed to withstand extremely high wind conditions.

***Objective # 3*:** Determine the estimated cost-effectiveness of the best wind fin designs.

***Specific Tasks*:**

1) Undertake computer-based spread-sheet calculations to determine the estimated *manufacturing cost* of wind fins of different sizes, configurations, and construction materials.
2) Undertake computer-based calculations of the anticipated average annual output of energy produced *per unit of system cost* for different wind fin sizes, configurations, and construction materials in order to determine the most cost-effective designs.
3) Undertake computer-based calculations of the benefit-to-cost ratios of various modifications to the wind fin—including changes to its geometry and the addition of extra oscillating panels—to enhance its energy-conversion efficiency.
4) Determine the design features and construction materials that can be expected to produce the greatest benefit-to-cost ratio.
5) Select the best designs for testing in the bench-scale wind chambers and wind tunnels described in Objective #1 above.

***Major Results*:**

Approximately 15 percent of the total project effort focused on this objective. The project's extensive wind tunnel testing with different designs confirmed that the wind fin system's wing structures are not subject to the enormous, alternating, bending stresses and centrifugal forces of wind turbine blades, enabling them to be constructed with less-expensive materials and lower-cost manufacturing methods. The project team determined that durable wing structures can be constructed in a number of different relatively inexpensive ways. For example, they can be constructed like an aircraft wing with a skin that conforms to symmetrical wing ribs or a molded foam core. This skin can be made of fiber reinforced plastic (such as glass fiber reinforced plastic or carbon fiber reinforced plastic), an aircraft fabric covering product (such as Ceconite®), aluminum, or even ripstop nylon. In addition, wing structures can be constructed of a rigid material within a frame or be designed to be a self-inflating airfoil, like a parafoil, comprising rows of cells that are open at the front and joined together side by side such that the wind keeps the cells inflated.

The project team estimated the manufacturing cost of a wind fin system using a mid-priced approach involving a wing structure constructed of fiberglass skin over a molded foam core and a mast and support tower of structural galvanized steel. For a 1kW wind fin measuring 15 ft. tall by 3 ft. wide on an 80 ft. pole, the estimated labor and material costs for construction are as follows: *labor*, $650; *materials*, mast, $620; support tower, $860; wing structure, $474; bearings, $38; power takeoff system, $435; and miscellaneous parts, $75, for a total cost of $3,152. For a 10kW wind fin measuring 44 ft. tall by 5 ft. wide on an 90 ft. pole, the estimated labor and material costs for construction are as follows: *labor*, $2,450; *materials*, mast, $2,125; support tower, $4,850; wing structure, $2,691; bearings, $195; power takeoff system, $1,730; and miscellaneous parts, $335, for a total cost of $14,376. If overhead and profit of 45 percent are added to the manufacturing costs, the factory price of a 1kW wind fin would be $4,570 and the factory price of a 10kW wind fin would be $20,845.

***Objective # 4*:** Develop conclusions about the technical feasibility of the wind fin system.

***Specific Tasks*:**

1) Analyze all results from the computer modeling, simulations, wind chamber, and wind tunnel testing described above.
2) Determine the general cost-effectiveness of the wind fin system compared to other state-of-the-art horizontal-axis and vertical-axis wind turbine designs.
3) Develop plans for further development and commercialization of the wind fin technology—should the proposed project indicate its technical feasibility.
4) Prepare and submit a final comprehensive report to the DOE EERE Inventions and Innovations Program on the technical feasibility of the wind fin technology.

***Major Results*:**

Approximately 15 percent of the total project effort focused on this objective. The research team compared the cost-effectiveness of the wind fin system to the Bergey XL.1 and the Bergey Excel, which are the best-selling 1kW and 10kW wind turbines in the world. Table 1 shows this comparison. The table shows that, based on this project's test results, the wind fin competes very favorably in both performance and cost categories. According to the Bergey Windpower Company's published technical data sheet, the Bergey XL.1 generates approximately 1,000 watts at its rated wind speed of 25 mph wind speed. By comparison, according to project results, a wind fin in the 1kW class, with a wing structure measuring 15 ft. tall by 3 ft. wide, would generate 1,070 watts at 25 mph wind speed. The Bergey Excel generates 10,000 watts at its rated wind speed of 31 mph. By comparison, a wind fin in the 10kW class, with a wing structure measuring 44 ft. tall by 5 ft. wide, would generate 10,066 watts at 31 mph wind speed.

TABLE 1. Performance and Cost Comparison of 1kW and 10kW Wind Fins to the Bergey XL.1 and Bergey Excel

	Bergey Windpower Company XL.1 (1kW)	1kW Wind Fin	Bergey Windpower Company Excel (10kW)	10kW Wind Fin
Size of system	• 8.2-foot rotor diameter • 80-foot tilt-up tubular tower	• 15-foot tall, 3-foot wide fiberglass wing • 80-foot mast and supporting tower	• 22-foot rotor diameter • 90-foot self-supporting lattice tower	• 44-foot tall, 5-foot wide fiberglass wing • 90-foot mast and supporting tower
Power output in watts at 25 mph wind speed (*the BWC XL.1's rated wind speed*)	1,000 watts	1,070 watts	--	--
Power output in watts at 31 mph wind speed (*the BWC Excel's rated wind speed*)	--	--	10,000 watts	10,066 watts
Price of system *(uninstalled)*	$4,640	$4,570	$39,700	$20,845
System cost per watt output at rated wind speed *(1kW or 10kW)*	$4.64	$4.25	$3.97	$2.07

SOURCES: Bergey Windpower Company's product technical specifications sheet and Wind Fin research results

The manufacturer's factory price for the Bergey XL.1 with an 80-foot tilt-up tubular tower, is $4,640. In comparison, the estimated manufacturer's price for a 1kW wind fin on an 80-foot mast with a wing structure of fiberglass skin over a molded foam core, would be $4,570. This means that the system cost per watt output at the 1kW rated wind speed is $4.64 for the Bergey XL.1 and $4.25 for the wind fin.

Because a relatively large portion of the total wind fin cost is accounted for by the mast and support tower, and because significant economies of scale are realized on the wing structure with scale up, the most significant cost-comparison difference between the wind fin and a state-of-the-art wind turbine is realized at the 10kW class level. The manufacturer's factory price for a Bergey Excel with a 90 foot self-supporting lattice tower is $39,700. By contrast, the manufacturer's factory price for a 10kW wind fin with a fiberglass skin over a molded foam core would be only $20,845. This means that the system cost per watt output at the rated wind speed is $3.97 for the Bergey Excel and only $2.07 for the wind fin. If the Bergey Excel was equipped with a 90-foot self-supporting tubular tower, to improve its aesthetics and to compare more closely to the wind fin's mast and lower supporting tower structure, the system cost would jump to $49,949 and the system cost per watt output would increase to $4.99.

These performance and cost advantages, particularly at the 10kW class level, should enable the Wind Fin to readily penetrate the marketplace for small wind turbines. Results from the DOE EERE project need to be confirmed and expanded with additional research, particularly wind tunnel testing with a larger bench-scale model to establish a power curve of energy output performance at wind speeds ranging from approximately 5 mph to 32 mph. Research started with this DOE EERE project is continuing with a just-initiated SBIR Phase I grant from the US Department of Agriculture. This new project's purpose is to demonstrate that it is technically feasible to develop a wind fin system, optimized for use on individual farms and ranches (incorporating input from end-users), that is significantly less expensive than current state-of-the-art wind turbines of equivalent power output, without sacrificing performance. Our target goal is half the cost of the current leading state-of-the-art wind turbines.