Cover Page

A Simple Self Feathering
Wind Turbine
for Light Winds

A Proposal in response to

DOE: Low Wind Speed Technology for Small Turbine Development RFP
SOLICITATION NUMBER DE-PS36-03GO93005

Technical Area 2

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A. PROJECT OVERVIEW

A Greater Energy Harvest per Tower: An effective wind turbine efficiently harvests wind energy from a large area, yet is able to let high winds slip by harmlessly, skimming off just the power that the generator will tolerate and no more. Given a tower of limited strength and a generator of limited capacity, one wants to use the largest turbine possible without overloading the tower or generator. The important issue, then, is control of the turbine. This proposal offers a turbine design that is expected to provide near-optimum control with just one moving and one flexing part per blade. It is a robust, inexpensive blade-feathering mechanism that should match or outperform the best computer servo controls, letting sudden gusts and violent eddies pass harmlessly through its blades. The bottom line is that a larger turbine of this type can operate safely with a given generator, tower, and related parts, thus substantially increasing the energy harvest at little or no added cost.

For cost reasons, active pitch controls are nearly absent from modern small wind turbines. The two passive control forces available in a wind turbine are centrifugal force and wind pressure, while the result of these control forces is always a reduction in aerodynamic efficiency, eventually involving either blade stall or blade feathering. Blade feathering is preferred in this proposal, avoiding the noise and vibration of blade stall and the inherent difficulty of making stall develop at just the correct rate to keep a constant governing power. Of the two available control forces, both are employed in the proposed design: wind pressure to maintain blade pitch in a constant and unstalled relationship to the wind, and centrifugal force to bias that blade pitch relationship. This dynamic interplay of two control forces provides more complete control than has been achieved using either force alone. As will be seen, the aerodynamic pitch control mode is very quick, operating at all windspeeds to keep the blades unstalled and operating at low stress, while the centrifugal mode of reducing the equilibrium lift angle operates in the slower time frame of significant change in angular momentum of the rotor.

Program Goals, and Objectives

This project sets out to demonstrate an inexpensive wind turbine accomplishing passive centrifugal and aerodynamic blade pitch control without hub linkages. A first goal is to show that this turbine develops significantly lower maximum tower forces, lower blade stress and fatigue, and better power governing, than competing designs of comparable power-gathering ability. Following from this, a second goal is to demonstrate that an existing design of tower, bearings, generator, and inverter can reliably and safely be mated with a significantly larger turbine of the proposed design, yielding significant increases in average power for little or no increase in cost. While bushings or bearings must be added to permit blade feathering, rigid blade construction will be simpler and less fatigue-prone than many flexing and bend-twist blades. Based on indications that this design will self-orient upwind in a two-blade configuration and not suffer the yaw vibrations of other upwind two-bladers, a third goal is to realize the economy of just two rather than three blades.

To maximize the advantages of its passive blade pitch control, the new turbine will be operated with programmed control of electronic inversion, creating an optimum torque load match for efficient low-wind operation and constant-power high-wind operation. The blades, modified from constant cross-section by warping the thin trailing edges, will be compatible with inexpensive composite fabrication.

Pre-Program Status

Several basic concepts for the proposed design were successfully tested in the past. The design has since been improved, reduced to a solid model, and analyzed for inertial, stress, and aerodynamic properties. Further analysis has explored steady-dynamic and transient responses to wind. Design constraints for stable operation have been identified and predict adequate stability margins consistent with good performance. Though further computer studies are proposed, including dynamic simulation in turbulent winds, the concept is already developed, sufficiently for specifying and fabricating a first scale model, followed quickly by longer-term work toward an intermediate-scale model. The state of research is therefore considered to justify this proposal under Technical Area 2, “Component Development.”

Program Sequence

Completed analyses of dynamic and transient performance will be refined using commercial software[1], while concurrent fabrication and testing of a model-scale turbine will complete a preliminary concept validation. Contingent on positive results, an intermediate-scale turbine will be fabricated, heavily instrumented for wind, motion, and strain, and operated under steady and turbulent wind conditions. The turbine will ride above the bed of a moving truck while baffles are lowered, raised, and dropped abruptly, generating turbulence and sudden gusts, which will hit the turbine from all angles. Test results will be compared statistically to simulation results. Contingent again on a positive evaluation, and on acquisition of a manufacturing partner, a full-scale small turbine will be designed and fabricated using techniques adaptable to economic volume production methods, for testing with the partner’s tower and generator system.

Technical Concept

Each blade rotates passively, or feathers, about a pitch change axis, responding to a balance of inertial and aerodynamic forces generated in an inherently pitch-stable airfoil. Below governing RPM, each blade is inertially balanced, responding almost solely to aerodynamic forces and independently seeking a constant average lift angle. That lift angle equilibrates quickly in response to wind and RPM changes. In the governing RPM range, a weight on each blade, moving centrifugally on a flexible steel strip, breaks the low-speed inertia symmetry, creating a twisting centrifugal force that competes with aerodynamic forces to reduce the lift angle, thus limiting torque and RPM. This approach avoids noise-producing aerodynamic stall, an identified problem area for many small wind turbines. Unlike designs for centrifugal blade feathering (e.g., Jacobs), gusts always feather the blades, in and below the governing RPM range. Rotor thrust depends almost entirely on RPM, while rotor torque varies with windspeed.

A tail orients the stopped rotor upwind, while the spinning rotor gently self-orients upwind with the tail furling in response to side gusts, minimizing gyroscopic forces and vibrations. It is believed that this design can be configured successfully as a two-bladed upwind turbine, though three blades is a backup option.

An “intelligent” inverter provides a low-wind torque curve that optimizes efficiency. In higher winds, the inverter fine-tunes governing at constant maximum power by controlling the rotor load and resultant RPM, effectively regulating the action of the passive centrifugal movement of the governing blade weights. The transition from optimum-efficiency to constant-power operation is made via the low-thrust side of optimum performance, so that peak rotor thrust is kept to an absolute minimum.

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[1] Elliott, Andrew S. & Depauw, Todd R., “ADAMS/WT Advanced Development – Version 1.4 and Beyond”, http://www.adams.com/news/events/userconf/na/1996/UC960024.PDF .

B. DOE IMPACT ON VIABILITY OF THE PROJECT

The proposed design by TDC is backed by careers of experience in dynamic systems analysis, simulation, instrumentation, industrial and energy system development. Specific experiences have included wind energy, hydropower, fluid controls, electronic controls, combustion power generation, and composite fabrication. A stint by one in the helicopter industry, developing simulations in aeromechanics, provided key knowledge for this design. Yet for all this background, it was two DOE RFPs that gave the impetus to re-examine past designs in light of recent experience and discover a new synthesis. A continuing study of both patent and technical literature fails to reveal highly similar past work, indicating the probability of a valuable design of novel inventorship. There is ample motivation to pursue development to commercialization. The prospects for near-term commercial funding are poor, however, on account of the risks inherent in such a comparatively radical design concept, and also on account of a continuing economic slump. If this and a recent smaller and more limited DOE proposal both fail, TDC is likely to continue with other federal and state proposals. Significant progress will probably have to await some form of grant funding.

C. DESCRIPTION OF THE PROPOSED CONCEPT DESIGN

Early Work

The project is rooted in a design concept that was empirically validated in 1980[2], and which has now emerged with renewed interest stemming from major design improvements by TDC. A description of the simpler 1980 design is provided here as an intermediate step toward understanding the simpler but more subtle proposal design. That 5 foot diameter, two-bladed turbine (Fig. 1, Attachment 1) resembled two airplanes flying in circles (view A), each one free to feather (rotate in pitch) on a bushing sleeve about its radial pitch-change axis and independently seek a stable pitch angle relative to the wind through the rotor disk. A high-lift, pitch-unstable airfoil (Wortmann FX63-137[3]) was stabilized by a smaller elevator control airfoil developing negative lift, overcoming the pitch-down moment of the main airfoil and establishing a stable positive angle of attack. Since the relative wind velocity past a blade was predominantly tangential (see labeling of view F), and since each blade self-regulated for a constant lift coefficient, the total aerodynamic force on each blade was mostly dependent on rotor RPM and nearly independent of windspeed. At constant RPM, an increased windspeed rotated the blade lift vector to give higher torque (comparing views E and F).

For governing in the early prototype, the elevator airfoil was mounted on flat spring steel spring strips (views A, D, E, F). Increasing winds bent the springs (comparing views D and E), allowing the main airfoil to pitch down and operate at reduced lift force. Section view D shows an unbent spring and a high blade angle of attack. View E shows a bent spring and reduced blade angle of attack, responding response to the greater resultant wind vector, which includes an increased axial wind component and a proportionately increased tangential rotation component. View F shows and a more bent spring, a blade angle near zero lift, a nearly unchanged tangential rotation velocity component, and a much-increased axial wind velocity component, causing the blade to feather to a highly pitched-down angle. Tested on a truck-mounted tower without shaft load, the unloaded rotor approached maximum rotation speed in a 10 mph windspeed, stayed at nearly constant RPM up to 50 mph, then slowed progressively in winds up to 70 mph (the highest tested). Thus, the prototype proved capable of two distinct types of self-protective adjustments:

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[2] Experimental turbine designed by J. Seale, fabricated by J. Baldwin, at the New Alchemy Institute, 1980. This and related designs have been maintained in confidence up until a recent provisional U.S. Patent application.

[3] Althaus, D., Wortmann, F.X.,'Stuttgarter Profilkatalog 1', F. Vieweg, Braunschweig, 1981.

1. rapid maintenance of a fixed aerodynamic blade angle of attack in changing winds minimized force variations in gusts; and,
2. high-wind reduction of the blade angle of attack resulted in aerodynamic self-governing.

In order for aerodynamic forces to control pitch, it was necessary to provide balance weights near the hub, above and below the blade roots along the direction of the rotor axis, as labeled in view D of Fig. 1. These weights, colored red on orange stalks, functioned like the balance weights used on helicopter rotors, for example, the Model 47 Bell helicopter illustrated in the inset photo, view C, with the counterweights highlighted by white ellipses. In both wind turbines and helicopters, the weights counter the inertial tendency of the blades to flatten into the plane of rotation. Without counterweights, the elevator airfoils in the experimental turbine could not pitch the blades down in high winds, and the turbine would not feather to self-govern.

Despite its success at governing, the turbine design just described was not deemed worthy of pursuing to manufacture. The particularly high and unsymmetric rotational inertia of the blades called for sensitive counterbalancing with the helicopter-style inertia symmetry weights. The steel spring strips for the elevator required limit stops (not shown in Fig. 1) to keep the turbine from reversing in high winds. Sensitive pitch control hardware out in the elements invited runaway malfunction from ice formation and imbalance promoting runaway rotation. The design was kept confidential, in case it might be taken up again later by one of the development partners. Circumstances, and significant ideas for improvement, have finally brought about a setting for that continued development.

D. TECHNICAL AND DEVELOPMENT STATUS

Recent Completed Work

In this proposal, Figs. 2 and 3 illustrate a new design that emerged from the 1980 turbine concept. Fig. 2 looks from the blade root out toward the tip, which appears smaller only because of perspective – the blade is untapered. A constant blade cross-section is modified by warping to give positive camber at the root and negative camber at the tip, notably in the outer triangular area labeled “trim tab region” near the trailing edge[4]. The separate reverse-camber elevator airfoil of the 1980 design has been integrated into an unbroken blade section profile. By using a narrower airfoil, and by further reducing polar inertia of the airfoil through use of a thin, light trailing edge region, the airfoil is able to respond far more quickly in pitch change than the older airfoil. The lifting region of the new blade is effectively tapered from root to tip, with the entire root chord width contributing lift and only the leading half of the tip chordwidth contributing lift. The extra wetted area of the trim tab region, developing neutral local lift, causes relatively little increase in profile drag (compared to a tapered airfoil that eliminates this non-lifting area), since the wind velocity over this trailing section is lower than over the forward lifting surface. To put this efficiency tradeoff in perspective, many commercial small wind turbine designs make the same compromise of untapered blades, looking simply to the economic advantages of extrusion and pultrusion[5] methods of fabrication.

To balance the pitch-up aerodynamic moment of the outer airfoil, the blade is swept so that the pitch change axis emerges well ahead of the 25% chord – at about the 13% chord in

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[4] The pictured airfoil is a rough approximation, constructed from a NACA 0021 airfoil over the leading 50%, blended and tapered into a thin trailing airfoil, then bent using NACA midline formulas for the desired pitching moment distribution. Boundary layer codes will be used to develop better contours. The solid section c.g., currently falling at the 25% chord, must be brought further forward by a leading edge weight insert near the blade tip.

[5] It remains to be seen whether a pultrusion can be twisted in the manner described, perhaps using a slightly thermoplastic formulation for deforming the trailing surface while hot after pultrusion.

the illustrated example. When there is inertia symmetry, then the combination of blade aerodynamics and sweep controls the equilibrium angle of attack. To achieve a highly stable blade and allow variable blade coning without blade twist, the blade center of mass is designed to coincide roughly with the blade elastic axis. This coincidence calls for some modification of the leading edge vicinity of the blade, adding both stiffness and weight. The stability margin of the blade will be quantified, leading to an informed judgment concerning necessary blade modifications. If needed, inclusion of heavy metal threads along with glass fibers near the leading edge might provide the needed stiffening and weight shift. Alternatively, a simple solid airfoil with a thinner trailing half might offer an economic solution with adequate aerodynamic performance. These are questions to be addressed and quantified in the first phase of proposed work.

Fig. 4 illustrates, among other things, the primary pitch change components of one blade. A stylized pair of circular sleeve bushings surround the tubular pitch-change axis, allowing free rotation of the shaft, clamp, and blade, as indicated. A cable is attached at the center of the hub and at the outer end of the pitch-change axis tube, operating in tension to retain the blade against high centrifugal forces while allowing limited pitch change and resisting multiple revolutions of pitch change. Not shown is a thrust bushing, preloaded with a wavy spring washer, to push the blade out and maintain some cable tension against gravity even when the blade comes to rest pointed straight up.

Both Figs. 3 and 4 show moving balance weights, one on each blade. Note that the turbine operates upwind of the tower and is coned slightly downwind, toward the tower. Thus, the wind travels from right to left in view A of Fig. 3. The weights resemble, and function like, the helicopter blade weights in the photograph insert of Fig. 1, and also like the pair of weights for each blade of the self-governing turbine drawn in Fig. 1. Comparing these balance weights to the helicopter balance weights in the Fig. 1 photo inset, one sees that each weight-supporting flat spring is attached to the blade clamp at a relatively large radius (compared to the helicopter weights). From its attachment point, the spring strip slopes away from the pitch change axis and inward toward the hub. At low rotor speeds, with a strip negligibly bent, the weight approximates an exact symmetry balance, allowing the trim tab region of the rotor blade to exert complete aerodynamic control. With increasing rotor speed, the strips bend and the weights move out, as shown by comparison of views A and C of Fig. 3, progressively breaking the inertia symmetry and creating a centrifugal torque that causes the blade to feather, as in view C. The strip is also shown bent in the lower-left inset view of Fig. 4. Though the weight movement may appear small, recall that the polar inertia of each weight about the pitch change axis matches the in-plane polar of an entire blade, and the weight inertia moment increases as the square of the distance from the pitch change axis. Thus, a 41% increase in distance from the pitch change axis causes a 100% increase in polar inertia, profoundly influencing the aerodynamic balance.

Observe the weight on the upper blade in view B, seen at the inner end of the flat spring, which appears flat in this view, edge-on in other views, and in perspective in the lower-left inset view of Fig. 4, where it is centrifugally bent. The blade in view B is flat in the plane of the diagram, and the flat spring is angled slightly toward the trailing edge of the blade, going from the attachment point to the weight. Adjustment of this angle permits control of the onset of governing, and the stability of that process, which can be varied from gradual to abrupt by a controllable regenerative “feedback” relating pitch change to aerodynamic pitch equilibrium. Use of this angle, and the spring angle relative to the pitch change axis seen in view A, is discussed in the following optional technical discussion.

Optional Technical Discussion: Preliminary Dynamics Calculations

Part 1: Pitch Change Response Speed

The proportions in Figs. 2, 3, and 4 are realistic, based on pultrusion fiberglass blades and steel weights on flexing flat steel spring bands. Preliminary analysis of the diagrammed system yields the following results. The turbine is proportioned for an optimum tipspeed ratio of approximately 8. At low rotor speeds, the weights provide approximate inertia symmetry as drawn. The blades are swept so that the pitch-change axis emerges from the blade tip at about 13% chord. The illustrated blade tip camber is roughly correct to achieve a lift coefficient of about 0.35 at the tip, increasing to about 1.0 at the root. Since only the front half of the tip airfoil is effective at developing “positive” lift (due to the negative camber of the trailing section), the “working” portion of the tip airfoil acts as if it were developing a lift coefficient of 0.7 to 0.8, i.e., less than a factor-of-two away from stall, which is desirable to limit forces if local wind eddies should bring about a maximum possible lift in a given region. The pitch change axis follows, approximately, the static center-of-lift, giving balance, while the dynamic center of lift follows the 25% chord, which falls behind the pitch change axis in the region where high tangential windspeed gives the greatest aerodynamic “purchase.” The fast-moving and pitch-stable tip region thus dominates the pitch control situation, providing positive dynamic stability.

If the blade balance weights were absent, there would be two competing torsional restoring forces acting on the blade: an inertial “spring rate” pulling the blade toward a flat in-plane alignment; and an aerodynamic “spring rate” pulling the blade toward a preferred pitch angle. The inertial “spring rate” would give the blade a small-perturbation natural rocking frequency of one cycle per blade revolution – the revolution and rocking rates naturally follow each other in what is described in helicopter lore as the “tennis racket effect[6].” The aerodynamic spring rate in this example is about 5 times as large as the inertial rate without balance weights. Thus, one would expect a natural torsional frequency, from aerodynamic effects alone, of about SQRT(5) oscillations per rotor revolution. An important observation here is that the inertia balance is not highly critical, since aerodynamics are already dominant (5-to-1) over inertia in a reasonable example.

When the counterweight is added in the above scenario, neutralizing the inertia asymmetry and doubling the pitch-change inertia, the aerodynamic natural frequency drops to about SQRT(5/2) oscillations per rotor revolution – the “2” in the square-root denominator comes from the doubling of inertia when the counterweight is added. With aerodynamic damping caused by cast-off vortices during the pitch oscillation, the oscillation becomes fairly strongly damped (a confident damping figure has not been determined). The tentative conclusion is that the pitch change exponential settling time, falling somewhere between one and two radians at the undamped natural frequency, corresponds to somewhere between 35 and 70 degrees of turbine rotation, while the immediate pitch change response (not counting the time for overshoot and ringing) is more than half completed (one radian of sinusoidal response time) after just 35 degrees of turbine rotation. Air moving through the turbine at the 75% radius, and slowed slightly by the turbine in efficient operation, travels only about 5% of the turbine diameter during that 35 degrees of rotation – an air movement of about one blade chordwidth. A gust, which is actually an eddy carried along by other moving air, can envelop the turbine in not much less time than is required for prevailing air movement to carry an eddy through one turbine diameter. The preliminary conclusion, then, is that a turbine blade is unlikely to be

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[6] Hold a tennis racket horizontal in front, racket face horizontal, and attempt to toss it so that it revolves in the air about a horizontal line across the long axis of the racket, completes one turn, and lands flat on the floor in the same orientation that it was tossed. It won’t work. The tennis racket does a half-twist in the air and lands with the opposite flat face turned up. This is the “large perturbation” outcome whose small-perturbation counterpart would cause the tennis racket, or a flat rotor blade, to do a full back-and-forth twist oscillation about the minor inertia axis during one rotation about the semi-major inertia axis.

pushed into complete aerodynamic stall by a gust when the blades are operating relatively flat, up to moderately high winds. In extreme winds, on the order of eight times the governing windspeed (for an 8-to-1 tipspeed ratio), the blades are at a large feathering angle, are developing higher aerodynamic forces, and are therefore responding more quickly in torsion except when they might be caught in a wind-reversing gust. To analyze farther at this time is to speculate. Given the preliminary figures just presented, it is believed that only highly improbable, extreme combinations of high windspeed and high turbulence, on a scale matching the rotor size, would be capable of pushing the proposed turbine far from pitch equilibrium and cause peak loads much higher than normal loads on the blades and tower. It appears unlikely that a blade would ever be pushed into high-speed stall over its entire length. Measurements and simulations should provide better insight, and quantitative guidelines, for equipping a wind turbine of this design to handle peak stresses. Conclusions are summarized below.

Part 2: Resonance of the Centrifugal Weight

Preliminary results are as follows. For the geometry illustrated, comparing natural frequencies (and not damping or settling times), the natural frequency of the counterweights "wagging" on their spring strips is about 1.5 periods per torsional oscillation of a turbine blade at the governing rotation speed. The turbine blade oscillation is, in turn, faster than the blade rotation period. These results describe dimensionless ratios arising out of the proportions of the design. The frequencies tend to track one another in constant proportions for similar geometries. If the counterweight is angled to a shallower angle than 30 degrees from alignment to the pitch change axis, the centrifugal governing characteristic becomes more abrupt, and the natural frequency of the counterweights drops excessively close to the blade torsional frequency, causing potential cross-coupling problems. If the counterweight is angled more steeply than 30 degrees, centrifugal governing is less abrupt, and the frequency margin grows wider. One might say that increasing the "gain" of the inertial speed-governing loop has the effect of reducing the stability of the system – not a surprising result from a general system-dynamic viewpoint.

The pitch governing characteristic itself can take on a strongly-to-slightly regenerative character, as the pitch counterweight is angled progressively away from perpendicular to the inertia plane of the blades in the direction tending to cause blade feathering – recall the discussion of the flat spring angle toward the trailing edge as seen in Fig. 3, view B. This effect is not thoroughly explored, but it is clearly a significant parameter in the design of this system.

Conclusions Regarding Pitch Change Dynamics

There are two natural oscillation periods, or frequencies, of the passive pitch-regulating and speed-governing systems of the illustrated turbine, and variations thereof. For each turbine rotation, the aerodynamic pitch-controlling system undergoes very roughly 1.5 natural oscillations in a strongly damped response. For each of these pitch-change oscillations, the speed-governing counterweight, as drawn, undergoes at least 1.5 natural oscillations on its stalk (or at least 2.25 oscillations per turbine revolution), the ratio being at a minimum when the turbine is in mid-transition between optimum-efficiency operation and constant-power governing operation. If either of these ratios were significantly closer to 1.0, there could be cross-coupling problems leading to instability. These ratios apply for a design tipspeed ratio of 8, the value chosen for the illustrated examples. If the design tipspeed ratio is increased, these frequency ratios become larger in linear proportion to the design tipspeed ratio. Other design adjustments can also increase these ratios, for example, fabricating lighter turbine blades than the solid fiberglass blades considered in these examples. The blades should not be tapered broader toward the root, as that tapering would raise the pitch-change inertia and make the first of these two frequency separations smaller. The blades should not be tapered narrower toward the tip, because that tapering would weaken the aerodynamic pitch stabilization, causing similar problems. Untapered blades appear roughly optimal for the proposed design, with a reversing camber and little net twist going from root to tip. The proportions illustrated here are therefore far from arbitrary – they seem ordained by natural design laws.

The early turbine experiment illustrated in Fig. 1 appears to be governed by similar natural design laws. The design proportions illustrated, with broader blades and lower design tipspeed ratio, were farther from optimum, which was not well understood at the time of design and testing of that turbine. With careful design, that system was made to work and to demonstrate its essential character, though the design was not robust in those proportions. Recognition of that fact was the main disincentive against pursuing further development along those lines. It has taken years of working with dynamic systems, and of understanding some broad overriding design principles, to come back to the old problem, better recognize its nature, and conceive fundamental design improvements. The similarities, and the differences in a positive direction, relating the old experiment to the proposed experiment, lend confidence that the proposed problem will be tractable with good results.

The proposed work includes bringing great computational power to bear on the design problem. It is believed that when detailed numerical calculations are not grounded in good conceptualization of underlying principles and a guiding sense of proportions, the computations are not focused, they converge poorly to good engineering solutions, and they are costly. This proposal moves directly to a “Concept Development” stage because it is believed that the needed numerical computations will go relatively quickly and not hold up the demonstration project. The basic design principles are already understood.

Coning and Self-Orienting Rotor Tendencies

The proposed turbine is expected to self-orient to oppose the movement of the wind. If the turbine is intended for upwind operation and the blades are spinning in the correct direction for that operation, then the blades will naturally orient upwind. If the rotation direction reverses, causing the rotor thrust to reverse and point away from the tower, then the rotor will self-orient downwind. If reversed rotation is prevented, then reversed orientation will also be prevented. The illustrated blades are coned slightly toward the tower – the illustrated 2.9^{o} coning angle balances centrifugal and downwind forces at the design tipspeed ratio, resulting in no blade bending. For strong governing in high winds, however, the blades are bent nearly flat, so that a coning angle that “splits the difference” between the two conditions, about 1.5^{o} coning angle, is probably a better choice for stress minimization. In either case, coning is insignificant for self-orienting tendencies. If a component of wind comes from the side of the turbine, then to the extent that the turbine blades self-adjust pitch to a constant lift angle relative to the wind, blade lift in a downwind direction will vary only as the square of the relative in-plane tangential velocity through the air. Imagine, in Fig. 3, that in the side view on the left, the lower turbine blade is approaching the viewer, out of the page, while the upper blade is moving away from the viewer, into the page. Imagine, further, that wind is coming at the turbine from the side, from the viewer toward the turbine and into the page. The lower, approaching blade therefore has a greater airspeed and greater downwind “lift”, pulling to the left, toward the tower. Similarly, the upper, receding blade develops left lift. As the lower blade comes across the bottom of its sweep, the extra force to the left will impart momentum that displaces the blade to the left when the blade points out of the page, toward the viewer. Thus, the blade will be moved partway across the windmill housing, momentarily obscuring part of the view of the housing from the viewer. The blade moving away from the viewer across the top will see a reduced force to the left, causing it to swing away from the viewer and to the right. The turbine is orienting to face the viewer, and to face upwind. The yaw rotation isn’t quite so well coordinated, because there is a phase lag between blade pitch and the relative wind angle, so that the lift coefficient isn’t really constant as postulated. Nevertheless, the turbine will still self-orient upwind. The high tipspeed ratio implies a relatively low fractional difference in windspeeds for blades moving upwind and downwind, so that the self-orienting tendency will be relatively gentle. This is fortunate, since eddying gusts coming from above or below the horizontal tend to stress the blades where they are constrained against self-orienting for face down or up.

What has just been described as differential forces that are coordinated with gyroscopic phase lag to create stress-free yaw, but with stress-producing pitch-up or pitch-down tendencies of the rotor to track vertical wind components. A turbine on a hillside will experience constant, though relatively weak, cyclic bending stresses. A turbine cocked up from the horizontal for greater blade clearance will experience similar ongoing bending stresses. These stresses will be similar for three-bladed (versus two-bladed) turbines – different scaling factors work in partially-offsetting directions.

A large tail is to be avoided in the proposed design. Some tail is needed to get a stopped turbine oriented upwind for starting in the intended direction. A more complicated inverter circuit could boost the turbine into rotation, causing it to self-orient and start delivering power if a sufficient wind is present. In high winds, a large tail tends to yaw the turbine without gyroscopic "coordination," causing cyclic stresses, particularly in a two-bladed turbine. If the tail furls when hit by strong side winds, its effect will be rendered harmless. If the tail does not force the turbine, then the severe vibration problems associated with yaw orienting of a two-bladed turbine – the inertia asymmetry that affects upwind two-bladers should not be a problem.

Electronic Load Torque Control

The self-regulating turbine design just described is intended for use with an economical variable-RPM generator or alternator, whose design is to be determined during the project. Variable speed, high frequency alternators are preferred for light weight, low cost, and ease of control. (They are what is used in every car.) Electronic control of power transfer to the load, e.g. using controlled inversion or field current regulation of an alternator, optimizes the match between the proposed turbine and its generator load.

Technical explanation of regulation

For a reasonably efficient generation, system, turbine shaft power is a large and relatively constant fraction of delivered electrical power. If an inverter system, or a field regulation system, or a combination of the two, causes electrical power to vary as the cube of turbine rotation speed, then the turbine will turn at a constant tipspeed ratio, torque will vary as the square of rotation speed, and shaft power will vary as the cube of both rotation speed and windspeed. If the generation system regulates for constant power output, independent of the speed-indicating frequency coming from the generator or alternator, then torque will vary as the reciprocal of rotation speed, instead of as the square of rotation speed. Thus, as power governing kicks in, the turbine is allowed to speed up. Increasing turbine speed can do two things: increase the downwind resistance of the turbine due to greater blade tangential speed; and decrease the downwind resistance due to progressive centrifugal feathering of the blades. If the blades have begun to self-govern and feather significantly when the generation systems switches to constant governing power, and if that feathering tendency is already causing the turbine to err from optimum aerodynamic resistance on the low side, then the turbine will "relax" smoothly into governing, speeding up slightly, becoming less efficient, continuing to gather equal power from the increasing wind, and exerting progressively less downwind force on the tower. Since the efficiency peak of a wind turbine around optimum downwind rotor thrust is fairly broad, it makes sense to err on the low side of optimum rotor thrust as the system approaches the point of power governing – the loss of efficiency is minimal, yet the wind forces and stresses are reduced, and a smooth path into constant-power governing is provided. The optimally designed generation system "relaxes" into governing with lowered torque, lowered forces, and a slight increase in rotation speed.

Comparison with STALL type governing turbines

Systems that govern by blade stall follow a more mechanically stressful path into governing, depending on the details. The constant-RPM, fixed-pitch systems resist increasing winds with increasing rotor thrust, but that thrust may not climb as steeply as the optimum square-law relation – it depends on tipspeed ratio and blade pitch. At fairly high tipspeed ratios, and approaching stall, the tendency is for the turbine to let the wind through with too little resisting thrust as the wind increases. Stall accelerates this tendency. The variable-RPM systems that flatten pitch as they speed up may tend to approach governing on the high-force side. The comparisons being touched upon here will be subject to study during the proposed turbine development, to provide a baseline for comparison of the new design. At present, there is insufficient data to make a reliable comparison. An efficiency chart shown below uses estimates based on past experience and the most reasonable possible estimates of performance of the new system. The comparisons will be uncertain. This is a research project, intended to answer exactly these questions.

E. PLAN FOR TECHNOLOGY DEVELOPMENT

The extensive discussion above covers both the existing design concept and important aspects of how the concept will be developed. Scheduling information is provided below. Here are the major technology development work items.

- Simulation Study: The largely completed formulas and analyses described above will be followed by dynamic simulation studies to refine the design.
- 3-foot Model: A small model will answer basic performance questions.
- Design of 8-foot model: The understandings of simulation studies and small model results will inform this design. A more practical aspect will be composite fabrication techniques and mechanical engineering of the hub and pitch change mechanisms.
- Design instrumentation for the 8-foot model: This will consist of anemometers, strain gauges, power measurements, and data acquisition equipment run by a portable computer.
- Set up the truck test: Operate the system on a flat bed truck, inducing turbulence and gusts, gathering instrumentation data.
- Evaluate test data, comparing with model data.
- Ongoing development of industry partnership.
- Design and build 20 foot turbine: This is after a design review and go-ahead, with a commercial partner to be determined.

Section II: Benefits and Barriers

A. POTENTIAL BARRIERS

A challenge to this project is unfamiliarity with a control system whose behavior is quite different from existing wind turbine and blade designs. The most significant area of unfamiliarity is stability, while a related area is unlikely wind events – for example, where a whirlwind catches a blade and spins it about its feathering axis, damaging the tension cable. The hazard is in what is not named here, because it was not expected. The hazard is in events or modes of operation that might fail to be elicited, despite testing and simulation efforts, things that might arise in the field, over the years, affecting product lifetime. These uncertainties of an unfamiliar technology impact negatively on investor confidence.

A related unknown is wear and fatigue of a dynamic system after in years of service – the same unknowns that arise with aging aircraft and space shuttles, which are difficult to predict.

Noise is another unknown. It is believed, and stated within this proposal, that stalled turbine blades make significantly more noise than unstalled, feathered blades. There is undoubtedly research available on this issue, but this is information not available here, at the time of this proposal writing. It is reported that upwind turbines are quieter than downwind turbines, because the noise of blades passing through tower wake exceeds the noise of a tower encountering blade wake. Hence, an upwind design is anticipated. It is also reported that three-blade turbines make less noise that two-bladed turbine, but this result can be contingent on design specifics. The projected cost saving of two-bladed turbines may be trumped by a finding of unexpected noise problems.

B. IDENTIFYING AND MITIGATING BARRIERS

The simulation and testing experiments described here represent an effort to elicit, and quantify, all the types of events that might damage a wind turbine system of the new design.

Concerning wear and fatigue, instrumenting structural stress with strain gauges, and operating experimental turbines in turbulent conditions, will help identify certain long-term weakness. Experience of specialists will be sought, for example, from those who know what happens to a composite material after years of solar exposure.

The proposed truck tests will do little for noise evaluation, due to noise of the truck. The turbine will be left outdoors on its truck bed, however, and noise will be observed in natural wind at Altamont.

C. COSTS AND PERFORMANCE ENHANCEMENTS

The mechanical components of the proposed system are familiar: bushings, castings, cables, composite blades. As stated in a cost comparison table below, the increment in blade cost is expected to be on the order of 15% – more per-blade, but it is expected that two blades can be used instead of three, offsetting part (if not all) of the extra cost per blade. Since blades are a small fraction of overall costs, this 15% figure is not a problem

The most important performance enhancement is better power regulation and stress reduction, so that a larger turbine can be fitted to a given generator and tower structure. Beyond the quantitative estimates and the guesses shown in this proposal, many of the tasks described here are directed toward this performance question.

Putting this system in the larger context of the current economy, the economic benefit of this technology is marginal when compared to alternative fossil generation. Simply put, wind is only marginally competitive when compared to fossil generation in 2003. This technology will decrease the cost of wind technology significantly, but no claim is made that it will make it more economical (ignoring social costs) than fossil. In comparison with existing technology, this technology reduces initial capital cost and ongoing O&M and FO costs by about 15 %, the result derived in the next section.

ENERGY SAVINGS

The costs and energy savings of the proposed design are not known – the design is too new and too different from familiar designs for confident projections of either costs or energy savings. A primary objective of the proposed project is to quantify both, and show whether or not this is a "worthwhile" design for further development. The figures that follow are therefore considered a goal, a possible and desirable project outcome that goes along with a risk. The comparison chart developed below is in relative, not absolute units: when an SWT system in a particular size range is modified to operate with a larger turbine, the cost of the system will change by a projected fractional amount, the average annual energy recovery will change by a second projected fractional amount, and the benefit/cost ratio will then be computed, based on an initial baseline of 1.0 for the unmodified system.

This calculation reflects the was that the proposed system will actually be promoted to potential industry partners: as a blade turbine modification to a developed system design, involving costs and producing product improvements and energy benefits.

The turbine's energy savings is derived from allowing larger windmills for any size tower support or power train. The unit of savings is measured:

$$"Units" = \frac{kWh/Year}{Capacity\ Costs/Year} \quad = kWh/Annual\ Capacity\ Costs$$

The following table is based on a site average windspeed of 9 mph and a full-power rated windspeed of 12 mph, but these figures are arbitrary. The ratio results apply to any system where average windspeed is 75% of rated windspeed: this is a good ratio for overall system economy. It is assumed that an existing design is used for tower, bearings, and generator, but rotors of the new design are used in place of rotors of older design for new manufactured units.

The calculation is based on graphical methods developed by a proposal investigator[7] under DOE contract for projecting performance of complete wind energy conversion systems of varying configurations, based on Rayleigh wind statistics and on non-dimensional performance curves. The actual families of curves used here are reproduced in Fig. 6 at the end of the PDF file. The turbine performance curve, called "Turbine 6"[8] here, is actually the curve of coefficient-of-performance versus tipspeed ratio for a turbine similar in performance to that of the Enertech 44-40, a fixed-pitch 40KW turbine that is used with an induction generator to govern by blade stall in high winds. The tower drag performance for the Enertech is estimated, based on its published power curve[9] and a familiarity with its aerodynamics. The curve of power versus windspeed for this Enertech system is similar to that computed for "Turbine 6" at constant RPM. The Enertech governing is not sharp, with efficiency falling significantly for output above 35 KW at windspeeds above 26 mph, with power continuing to rise to 45 KW. This curve is similar to the non-dimensional power curve of P* as a function of V* reproduced in Fig. 6 for Turbine 6, Load 7. Here, "Load 7", a straight vertical line indicated on the inset in the P* versus V* graph, indicates operation at constant angular velocity (labeled "OMEGA," in figure 6) which is approximately consistent with an induction generator load. The power curve for Turbine 6, Load 7 differs from the Enertech curve for high winds, where stall causes power to peak and fall to zero, whereas power in the Enertech system continues to climb more gradually, instead of

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[7] Seale, 1983, "Matching Wind Turbine Rotors And Loads", DOE/Rockwell report under contract No. DE-AC04-76DP03533

[8] Generic turbine type 6 from original report.

[9] Thie URL http://www.nooutage.com/enertec44-40.htm contains the power curve.

bending over into a decline. A graph of "efficiency," the coefficient-of-performance Cp, plotted against tipspeed ratio λ for Turbine 6, is set into the upper left corner of the average performance family of curves in the lower part of the Turbine 6 and Load 6 graphs.

The comparison case for the proposed turbine is represented by the combination of the same Turbine 6 characteristic with "Load 6," a straight-line graph of torque versus rotation speed that is tangent to the ideal square-law curve, at a windspeed controlled by the choice of a normalized gear ratio, "G*" chosen for one of the curves of average normalized power in the lower graphs. It is seen that the non-dimensional power curve, P* versus V*, with Load 6 is very close to the ideal cube-law dashed curve, in contrast to the peaking and falling curve with Load 7. The Load 7 curve is self-governing, whereas the Load 6 curve requires that an upper governing limit be imposed. The lower, normalized average power output graphs are based on a normalized governing windspeed, Ug, at which the rising power output is limited to a constant output for non-self-governing turbines. In the baseline Load 7 case where the average windspeed is taken to be 75% of the governing windspeed, or the fraction ¾, the value Ug = 4/3, that is, the governing windspeed is133.3% of the average windspeed. The families of normalized average power as a function of Ug, and of the cube-law governing power axis Ug^3, show that if Ug is set too high, average output declines. This occurs because the system produces no power below a certain fraction of the governing windspeed, so a high-rated system spends much of its time not operating. The "gear ratio" parameters "G*" scale the load, which for a constant angular velocity load amounts to scaling the fixed rotation speed. A value G* = 1 sets optimum performance to take place at the site average windspeed.

Underlying analysis that follows, the major difference is not found in the P* versus V* performance curves, but in the assumed turbine size. Two considerations enter: 1) does a given system govern sharply, or must the generator be over-sized to handle infrequent high power levels where efficiency is declining; and 2) does a given system develop high peak drag forces, imposing an upper limit on turbine size so that the tower is not over-stressed. For the power-governing consideration, the Enertech sees a ratio of 45KW/35KW, or 128.6%, from an approximate "governing" elbow to a peak power that the generator must handle. A question for which firm data are lacking is the worst-case tower drag. Based on experience with stall-governed wind turbines, an educated guess here is a margin of 150% (a 1.5-to-1 ratio where 100% represents no over-design) for comparative peak tower loading, comparing the stall-governed system to the proposed system, which enters its governing regime on the low-side of the optimum turbine thrust curve.

Deriving a single number from these 128.6% and 150% overhead ratio figures for power and turbine load, it is assumed that the new turbine diameter will be 120% of the old turbine diameter, giving an area ratio of 144%. Some sacrifice in efficiency is factored in for the pitch-stable outer airfoil, dropping the ratio of "effective swept area" just under 3%, from 144% to 140%. Thus, a 40% figure in entered in the table below for fractional increase in effective swept area. For a large turbine comparison, the 40% effective swept area advantage is dropped to 10%, since the existing servo pitch governing is not expected to be quite as good as individual self-feathering control of each blade in the new design. In the small mill, the 20% larger diameter rotor is estimated to cost 15% more – pitch-change bushings or roller-bearings add cost, as does the separate blade clamp assembly, while some cost savings is expected in going from three blades to just two. The slightly larger rotor for a large mill is expected to cost no more at all, due to simplified construction with no servo control, so a 0% figure is entered in the table. In each case, the rotor is estimated to amount to 20% of the entire system cost. That total cost fraction lowers the cost increase as a fraction of total system cost, as opposed to just the fractional increase in rotor cost. A small mill increase of 40% in effective swept area yields 40% more power below governing windspeed, but at no increase in full-rated power, this fractional increase is effective only up to a lowered full-power rated windspeed. The increase in average power was computed using the normalized graphs of Fig. 6, from the DOE report (*op. cit.*) A 40% increase in swept area buys a 40% increase in power below the governing windspeed, but no increase when the system reaches the same 100% capacity level of the generator. Applying the formulas detailed in the DOE report, the 40% effective swept area increase nets an energy recovery increase of 19%, while the 10% effective swept area increase for the large mill nets a 6% figure. Factoring in the increased cost of the small mill, and no cost increase for the large mill, the improvements in Energy/Cost ratio are 15.5% and 6%, in the last row.

Increased Energy Calculation		Small Mill stall governed	Large Mill pitch governed
Increase, Swept Area		40%	10%
Increase, Rotor Cost		15%	0%
Rotor Cost / Total Cost		20%	20%
Increase, Total Cost		3%	0%
Net Energy Increase		19%	6%
Change (Energy/Cost)		15.5%	6%

D. OTHER BENEFITS: ENVIRONMENTAL BENEFITS

Where the marginal fuel is fossil sources, there will be a direct reduction in all emissions through increased penetration of windmills due to economic effects. This environmental savings will be diminished by possible differential increase in pollution from the production and operation of these mills. In comparison with existing technologies the environmental advantages are derived from a lighter mill, tower, and power train for any level of power.

The potential for noise reduction is mentioned throughout this proposal. Uncertainties remain, as stated just above, but there is every expectation that noise will be low in a feathering blade design that reaches its top rotation speed in relation to a moderately low windspeed and subsequently streamlines its aerodynamic components to the wind.

Section III: Market Assessment and Business Planning

The potential market for the proposed concept, from the business standpoint of the developers, is any small wind energy system company that would be motivated to use this technology to enhance the performance of their system. Future events may bring an entrepreneur interested in developing an entirely new product around the new blade and rotor technology, but that is for the future to decide.

The performance data gathered in the proposed work, and the fabrication techniques and their costs, will all impact the market value of the new turbine. Early fabrication of a 3-foot rotor is intended partly as a communications and public relations tool – people, including wind energy professionals, need to see a new system working to get excited about it, which is at the foundations of business advancement. Meeting with industry partners and involving a partner in fabrication and testing of the 20-foot turbine are central components of the business plan.

Section IV Roles, Responsibilities, and Capabilities

1. PROJECT MANAGEMENT CONCEPT

Overall project management will be directed by Dr. Ely. It will be his responsibility to get the project completed successfully and out on time. Much of the preliminary work has been competed by the individuals who are highly self motivated in this subject area, as evidenced by the density and breadth of the proposal's technical sections. The project concept is "containment and direction". Motivation is not needed, restraint and focus on the objective is. Individual responsibilities are very clear. The team has worked on projects of different types.

Individual Responsibilities

The areas of responsibility are shown in the following table.

Personnel	Area	Tasks
Ely	Overall Management, finance, reporting, physical construction and testing. Statistical analysis and power summaries	Key Tasks 1,5,7,8,9,10 Secondary Tasks 2,3,4,6
Seale	Theory, modeling design, construction plans, and mechanical response analysis of telemetry data	Key Tasks 3,4,6,7 Secondary 8,9
Bergstrom	Electrical loads, controls, and telemetry, all data gathering and electrical controlling	Key Task 2 Secondary Tasks 4,5,6,7,8,9
Sloan	Details of bushings, bearing, fastenings, input on materials, process, and assembly - manufacturability	Secondary Tasks 4,7
Burkhart	Written Report Production, web sites, promotional material, and field hand	Secondary Tasks 9,10

Reporting to Dr. Ely as consultants are 4 of his long time friends, employees, and coworkers of many years. Dr. Ely will control all money and all scheduling as well be the hands-on constructor of the test rotors and test mills.

2. & 3. CAPABILITIES ROLES AND RESPONSIBILITIES

Mr. Joseph Seale - Principal Scientist & Mechanical Engineer.
Mr. Seale is the designer of the windmill blade, his role is the chief mechanical engineer and he will be responsible for all data analysis and modeling. This project will start with Mr. Seale's self feathering design and adapt it to modern blade manufacturing techniques. Mr. Seale is capable of handling all design elements of airfoil and mill design, as well as modeling and analyzing all stable and unstable responses observed in the field. Mr. Seale has designed and tested a prototype a self-feathering windmill blade demonstrating the underlying principle used in this research.

Dr. Richard Ely - Project Manager, Project Engineer, Marketing
Dr. Ely role is the administration of this project and will also head the test facility construction and operation. He has extensive composite fabrication experience in hand building 4 wooden/glass sail boats and years of field instrumentation experience as a high resolution seismic equipment builder and surveyor. He will build the test mill and provide all logistics needed for the tests.

Mr. Gary Bergstrom - Electrical Engineer – Instrumentation, Wind Market Analysis
Mr. Bergstrom's role is that of electrical engineer and will be responsible for all instrumentation and data recovery. His work will address instrumenting the attitude, transient response, power, stability of a rotating windmill blade on a moving truck bed.

Mr. Walter M. Sloan – Mechanical Engineer –Hardware Detail Engineering (Limited Role)
Mr. Sloan has worked with Dr. Ely and Mr. Seale on wind projects in the past and will provide a consulting review role on this project. One of the key areas under study is the design and strength of the feathering weight and its support. Mr. Sloan will focus his review in this area and assist Mr. Seale in bearing, bushing, attachment, and fastening designs under high vibration and fatigue producing loading.

Mr. Richard Burkhart - (Minor Role) Documentation production, reporting, WEB support
Mr. Burkhart is responsible for production of all paper products and reports. He will also create the web pages and keep them up to date with contract progress. He will also provide field assistance as needed.

All Project Team members are acting as independent contractors. TDC is set up under the Direction of Dr. Ely with no full time employees as a series of different collaborative teams to address different research questions.

Capabilities

TDC was set up to develop and promote TDC team members' technology. Each team member on this project has appropriate commercialization experience. Mr. Seale – our lead scientist has an extensive suite of products that have led to commercialization both as an independent scientist. He has also had experience in developing aerodynamic blades for Bell helicopter, has designed new small mills for New Alchemy back in the 1970's.

Mr. Bergstrom has years of experience in electronic instrumentation experience in metrology and this application is within his experience and abilities. Mr. Bergstrom has developed instrumentation for a range of products from solar cell load banks for NASA to eye measurements as well as numerous products for Keithley Instruments. Independently he designed, marketed, and sold a digital decibel meter. For this project, he is bringing his experience in telemetry and power supply design.

Dr. Ely was co founder of New Found Power company which built hydropower turbines of his design for many years in Rhode Island. HE was the hands-on chief engineer and has built turbines for 20 hydropower sites, - all known are currently operating Dr. Ely has spent the last few years as marketing Director of ADM Associates in Sacramento ($4m/year), promoting energy efficiency technologies and projects occasionally of his design. This experience will extensive will assure responsible project completion. To support the blade building tasks, he has extensive fiberglass construction experienced such as recently rebuilding a 45' wood and epoxy fiberglass catamaran. With Mr. Seale, he and has built and tested a 16' diameter vertical axis wind mill. Dr. Ely is a proficient analyst, and may assist Mr. Seale in analyses.

Mr. Sloan and Mr. Burkhart will have consulting roles. Mr. Sloan is a practicing mechanical engineer designing mechanical medical equipment. He brings a detailed understanding of fatigue, wear, bearings, fastenings in a high vibration environment. He has also built windmills with Mr. Seale and Mr. Ely in the 1970's. Mr. Burkhart has been producing reports, graphics and websites for Dr. Ely at ADM for years. Some of his work can be seen at www.adm-energy.com.

Facilities Made Available for Project:

TDC has thee offices: Davis, California (D), Chagrin Falls (C), Ohio, and Gorham, Maine (G). Each has overlapping capabilities:

D	Office with 4 work stations networked to lab. 7 printers and plotters from HP LJ 4 printer to a Xerox E size plotter, Data analysis, and statistical software such as SPSS.
C,D	Both with extensive electronics shops, with scopes, counters, power supplies, etc.
G,D	Two CAD design centers with AutoCad Mechanical, Inventor, & Solidworks.
G,C	System simulation, DAC, circuit simulation, and dynamic modeling capability
D	1,600 square foot lab. With loads, dynamometers, Prony brakes, etc. Access to UCD hydraulics lab for instrumentation calibration. As-needed TDC will lease separate space for blade fabrication in the Davis Area – this is included in the budget.

TDC facilities are currently in-use designing and building hydro plants, electromagnetic valves, and improved fish passage structures as well as fish herding research projects with near-by UCDAVIS. TDC focuses on energy efficiency and renewable energy products as they interact with our environment.

4. SUMMARY OF RESOURCE COMMITMENTS S:

a. Hours and responsibility of project personnel. The following table is a summary for all tasks. For a complete breakdown by task see budget table,

Ely	1,800	Responsible for management, physical models & reporting
Seale	1,000…	Modeling, design, report preparation, and analysis
Bergstrom	400	Electronics, and data gathering
Others	50	Report production and engineering support

b. Destination of all Travel: All travel will be to two places
   Golden for three meetings (two people for two meetings, and one for one)
   5 trips to California test site, to assist in tests, and work on design improvements

c. Proposed Equipment over $ 5,000: none

d. Proposed Materials over $ 5,000: Materials to build windmills out of. Several extra blades and hubs will be built at the 8 and 20 foot rotor scale. Because this design is very loosely constrained, and will be exhaustive – if not destructively - tested in wind gusts and wind shear, extras of all parts will be used.

5. EXPERIENCE AND QUALIFICATIONS

{Very Abbreviated Tailored Resumes to Conform to Page Restrictions}

Richard Ely:
Education: Ph.D. 1992 Resource Economics, UCONN, MS Economics, UCONN, MS Civil Engineering, Berkeley, 1967 BS, Geophysics/EE MIT 1966. Other course work in programming, neural network modeling, electronics & CAD

Employment: 2002 Director TDC, LLC; 1994-2002 Engineer to Dir. Mkt for ADM Associates Sacramento; 1982 – 2003 Davis Hydro – Independent hydro developer; 1972 – 1982 Survey manger/geophysicist for Ocean Systems. Geophysicist; 1983-1990 principal & CH. Engineer in New Found Power, a hydro turbine manufacturer.

Related Experience & Abilities: Built and tested prototype windmill ~ 1979. Extensive project management experience and marketing at ADM, and Ocean Systems. Proficient in 3D CAD design, dynamic simulation and data analysis tools. Hands on field experience in building field survey equipment for Dr. H. Edgerton, building 4 wood & plastic sail boats with many foreign carpenters, environmental & high resolution seismic surveying all over SE Asia. Hand built hydro turbines/ and provided site engineering for clients across US.

Joseph Seale:
Education: 1968 BS, Harvard, in Physics

Employment: 2002-Present, Project Team Lead TDC, LLC; 2000-Present, co-founder & partner, Magnesense LLC (electric engine valves under dynamic microprocessor control); 1996-2000, FluidSense Corp. (co-founder & inventor of medical infusion pump product); 1990-92, consultant, DEKA R&D (Dean Kamen, infusion technology);1985-90, Critikon Corp., researcher, blood pressure monitoring; 1979-85, Director, Wind Energy Research, New Alchemy Institute; 1966-67, Bell Helicopter Corp., computer simulation of helicopter rotor blades.

Related Experience & Abilities: 1991-2002 developed statistical mechanics model & computer simulation of stress & fatigue in polymers & composites; 1983 author "Matching Wind Turbine Rotors and Loads – Computational Methods for Designers" (DOE/Rockwell International, RFP-3423, UC-60, Contract No. DE-AC04-76DP03533); 1979-80 designed and tested aerodynamically controlled wind turbine (see Fig. 1); 15 U.S. Patents, including "System and method for quantifying material properties" (claims allowed, viewable on internet); "Spring for valve control in engines" (6,341,767); "Fluid energy conversion system" (4,441,872 – variable-displacement heat pump with adaptive load match to wind turbine);

Gary Bergstrom
Education: 1977 MSEE, Electrical Engineering, Ohio State, 1973 BA Physics Wittenberg U.

Employment: 2002-Present, Project Engineer TDC, LLC; 2000-Present, co-founder & partner, Magnesense LLC (electric engine valves under dynamic microprocessor control); 1990-Present Independent Electrical Engineering Consultant; 1985-1990 Consultant and partner in Symtrac Corp: 1980-1985 Keithley Instruments, senior design engineer.

Related Experience & Abilities: Extensive Electronic metrology, embedded controllers, fluid measurement and pump for medical instruments. DAS experience circuit simulation, and related analysis capability. Wrote software to control dynamic load for testing solar cell system on international space station for NASA Lewis Research Center.

Mr. Sloan is a senior mechanical design engineer at http://www.medevelop.com/resume.html . And has also built windmills with two of the principals.

d) Statement of Commitment and Cost Sharing

Cost sharing will be met by contributing primarily labor, office space, and small amounts of equipment usage by all participants. This is to certify that the three principal members of this TDC Collaborative will make accountable contributions greater than 50 % of what is funded by

DOE under this contract. Thus, The Davis Collaborative will contribute in excess of 33 % of the project effort and a cost sharing commitment.

Contribution	Amount	Cash Value
Dr. Ely : Hours	400	$ 30,000
Equipment/Office/Shop/Lodging /	$ 1,200/Month for 25 months	$ 36,000 Plus currently undefined excess IDCs.
Mr. Seale: Hours	320	$ 24,000
Equipment/ Office/Software	600/Month at 50 % for 12 months	$ 9,000
Mr. Bergstrom: Hours	300	$ 22,500
Equipment/Lab/Software	600 per month for 4 months	$ 2,500
Total	(At Least)	$ 124,000

e) Requested Technical Assistance

The final part of our proposal is field testing a 20 foot rotor. Ideally this should be done next to an identical current state-of-the-art rotor on an adjacent tower. We will request, but do not require, USDOE Golden assistance in independent testing of this final rotor. We currently have budgeted sufficiently to test the unit at a windy facility in California, however, independence and side-by-side instrumented tests are invaluable, and would be appreciated in our Task 8.

f.) Statement of Objectives

This project sets out to demonstrate an inexpensive wind turbine accomplishing passive centrifugal and aerodynamic blade pitch control without hub linkage: A first objective is to show that this turbine develops significantly lower maximum tower forces, lower blade stress and fatigue, and better power governing, than competing designs of comparable power-gathering ability. Following from this, a second objective is to demonstrate that an existing design of tower, bearings, generator, and inverter can reliably and safely be mated with a significantly larger turbine of the proposed design, yielding significant increases in average power for little or no increase in cost. While bushings or bearings must be added to permit blade feathering, rigid blade construction will be simpler and less fatigue-prone than many flexing and bend-twist blades. Based on indications that this design will self-orient upwind in a two-blade configuration and not suffer the yaw vibrations of other upwind two-blade turbines, a third objective is to realize the economy of just two rather than three blades.

To maximize the advantages of its passive blade pitch control, the new turbine will be operated with programmed control of electronic inversion, creating an optimum torque load match for efficient low-wind operation and constant-power high-wind operation. The blades, modified from constant cross-section by warping the thin trailing edges, will be compatible with inexpensive composite fabrication, making a system appropriate for domestic manufacture, international sale, distributed generation capacity, and fossil fuel savings.

2. APPROACH TO IMPLEMENTING THE PROJECT

This is a model it/cut it/ and try it proposal leading to a full scale turbine system. We will be focusing almost entirely on blade/hub design. The proposal is in four stages focusing on different aspects of the project.

Stage	Associated Tasks	Focus
1 Model	2,3,4	Modeling a rotating auto-feathering system has not been approached before in the literature. We will build a series of analytical and CFD models of this to look for all modes of instability.
2Analyse	4,5,6	The models will be updated with data from the field tests of the rotors and refined as real data become available.
3Field test	6,7,8	Finally the objective of more power from a rotor at low wind speeds will be tested in the field. Further since life and catastrophic failures are common in these small units failure modes will be carefully documented from the field.
4, Market	1,8,9	As soon as the 4' blades prove their worth we will start marketing the design to other manufacturers. This will be expanded to manufacturing if warranted during life testing at full scale.

3. DESCRIPTION OF ACTIVITIES AND TASKS

The Table of Tasks, Milestones, and Deliverables on the next page shows the program in an outline format. In this project, TDC will build under this project three sizes of turbines after completing additional analytical design work(tasks 2,3). The first, will be a 1.5' bladed model (tasks 3,4) suitable for closely examining the feathering action when driven by a barn fan or mounted on a pick-up. It is intended and a talking model, just large enough to explore simple 1st and second order instabilities, and to examine resonances with triggered GR Strobo-tacs in the shop. Based on that model, and considerable CFD modeling (task 4), we will design a mill with 4' foot (tip-to-tip) blades with ancillary guillotine blinds, to produce sudden and steady shear across the rotor face. This will be tested in task 5 on a modified truck body with radio telemetering instrumentation from the rotating blade hub. Task 6 addresses improvements and retesting of the rotor. We fully intend to test this rotor and blades with every conceivable wind shear and sudden wind shear simulated in winds up to the road speed limits. We will be testing for fatigue, stability, vibration, as well as torsion and planar forces on the rotor and tower during transient and off-design conditions.

Tasks 7 & 8 address a full size unit with 10' (tip to tip) blades designed to be compared to comparison production unit at DOE Golden, or at facilities at Altamont Pass. The intent of these tasks is to show that this design is simpler, cheaper, and safer than other construction methods for any "generator/balance of system" scale. Task 9 is marketing the design, this we intend to do in three different ways, first we have already taken out a provisional patent on the design, and will expand that into a patent to protect the IP. This will lease, second we will pursue supplying replacement blades/rotor to existing mill manufacturers, and finally TDC is strongly considering a path to marketing our own designs in two ways, first as replacement parts for existing designs, and second as complete windmill kits.

4. SCHEDULE & TIMELINE OF ACTIVITIES WITH MILESTONES

Table of Tasks, Milestones, and Deliverables

#	Task & •Subtask	Duration	End Month	Milestone / Deliverables	Lead
1	Admin & Reporting • Start-up & Planning o Kick-off meeting o Workplan • Annual Program Reviews • Progress Reports	Whole Project 2 weeks As Needed As Requested	1& as needed	Workplan	Ely
2	Background • Literature Review • Modeling review • Mechanical 3' build design	2.5 months	3	Design Review I	Seale
3	Modeling • Improve current analytical model • Build new CFD ADAM /WT • Build 3" rotor o Accurate scale model / o Static tests / fan bench tests	4 months (Over lapping)	6	3' Rotor Documentation Strobe pictures of feathering	Seale
4	Expand Core Analysis • Test 3' rotor on small truck • Materials / process review • Design 8' rotor o Complete exhaustive 8' analysis • Test bed design • Initial Marketing Review • Comprehensive Design Review	3 Months (some overlap)	8	Proposed Design & Test Plan	Seale
5	Build 8' Rotor & Test Facility • Build load HF generator. • Build guillotine wind gust/shear gen. • Build controlled load	5 Months Overlapping	11	Project Web site Functioning Test facility Ready	Ely
6	evaluate & retest / APR • Test physically • Start design for 20' rotor	4 Months	15	Test Results	Ely

	• Analyze Telemetry • Refine analytical models • Refine Physical Model • Rebuild / Retest • Evaluate to destruction as necessary • Annual Program Review			Annual Program Review (Go ahead on 20’ foot Rotor) – market connection required	
7	20’ prototype Rotors • Finish 20’ rotor design • Static and dynamic materials testing • Install rotating telemetry for dynamic tests • Static tests • Off-tower tests at speed	3 Months	18	Rotors (two will be built along with surplus blades to compensate for probable intermediate failures)	Ely
8	Field Test of 20’ rotors Test at Altamont / DOE with telemetry with full power into controlled load. • Rebuild / Modify (interim failures) • Test at DOE or Altamont with telemetry • Rebuild/Retest/ Rebuild & retest • Measure via Telemetry Power Parameters, gust responses by blades • Vibration & oscillations • Tower forces & torques	6 Months	24	Document comparison tests	Ely
9	Business connection • Market directly to manufacturers • Results on WEB Site • Develop kits for sale	1 Man Month (During whole Project)	24	Business Plan (Marketing developed throughout whole project)	Ely
10	Close-Out • Final Project Review Meeting Final Report	1 Month	Project Complete at end of month 25.	Final Report	D