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A PUBLICATION OF THE IEEE INDUSTRY APPLICATIONS SOCIETY

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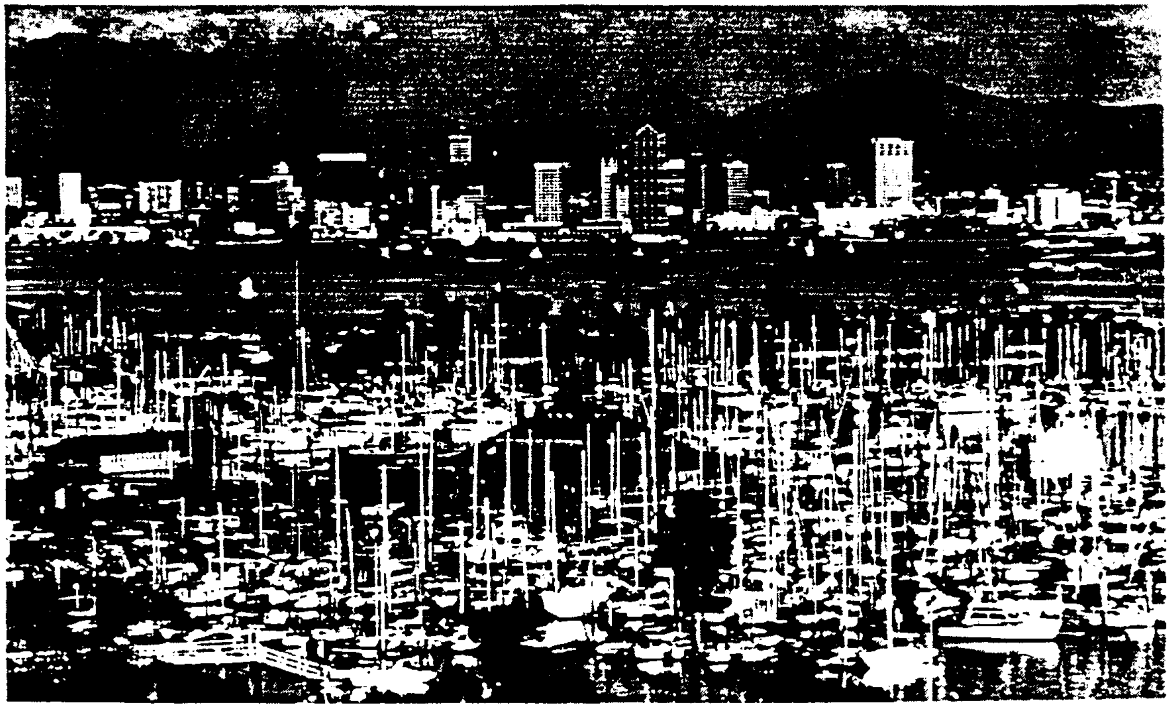
JULY/AUGUST 1996 VOLUME 32 NUMBER 4 ITIACR (ISSN 0093–9994)

Note:
This paper does not reflect higher WARP flow amplification findings of Tech. Univ. Graz, Austria; see WIND POWER '96 paper; Also, missing are cost benefits of latest patent configuration.

INDUSTRIAL AND COMMERCIAL POWER SYSTEMS DEPARTMENT

Power Systems Protection Committee

Rural Electric Power Committee



SAN DIEGO: SITE OF THE 1996 IAS ANNUAL MEETING

UPDATE NOTICE:

Basis for Improvements to Pre-1997 Reported WARP^{TM} System Cost & COE

WARP flow velocity amplification was estimated at about 50% on average over free stream velocity for cost estimates published in 1996 and earlier. The 50% amplification value was based on Rensselaer Polytechnic Institute wind tunnel velocity survey data from a ***single isolated*** WARP module with limited cylindrical extensions which attempted to simulate the presence effect of numerous adjacent modules. When using CFD generated results for WARP^{TM} analyzed by the Technical University of Graz, Austria, which simulated actual stacks of WARP^{TM} modules, together with recently patented WARP configuration enhancements, performance and cost-of-energy (COE) may be considerably improved over that reported in 1994,1995 & 1996 American Power Conference papers, and the 1996 IEEE Conference and IEEE TRANSACTION papers (Ref. 1-3).

As noted above, a comprehensive WARP^{TM} System computational fluid dynamic (CFD) velocity amplification analyses was conducted by the Technical University, Graz Austria on identical configuration modules but to actual anticipated system scale. Using an industry recognized CFD computer program, FIRE, developed at the Imperial College of England, wind speeds at WARP^{TM} wind turbine rotor locations were found to be on average, when integrated over the rotor disc, substantially higher than 1.5 times free stream (i.e.; up to about 70% to 80% higher than free stream). The impact on cost of energy may be determined as follows:

Since COE ~ System Annual Cost/Annual Energy Generated

&

Annual Energy Generated ~ Wind Speed Cubed = $[V]^3$

The impact of using a conservative 65% higher wind velocity than free stream [i.e.; 1.65 over ambient free stream wind] versus 50% as reported in earlier reports implies:

$$[1.65/1.5]^3 = 1.33$$ or a 33% increase in power and energy.

The energy increase impact on COE is thus about [1/1.33] or 75% of prior values; (lower yet when using potential 70% to 80% amplification levels possible).

Combined with the lower projected capital and O&M cost of the newly patented WARP^{TM} configuration, a significant cost reduction may be realized that can lower energy cost from that reported in the reference IEEE TRANSACTION report and others noted below to well under \$0.03/kWh in moderate wind sites and even under \$0.01/kWh in excellent wind sites.

REFERENCES:

1. Dr. Ostrow, S. L. (Raytheon), Padalino, J. (Raytheon), Weisbrich, A. L. (ENECO), **WARP^{TM}: A Modular Wind Power System For Distributed Electric Utility Application**; IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, Vol. 32, No. 4, July/Aug. 1996 & the IEEE Rural Electrification Power Conference, Nashville, TN, May 1, 1995.

2. Dr. Ostrow, S. L. (Raytheon), Padalino, J. (Raytheon), Weisbrich, A. L. (ENECO), **COE Projections For The Modular WARP^{TM} Wind Power System For Wind Farms & Electric Utility Power Transmission**; American Power Conference, Chicago, IL, April 18, 1995.

3. Dr. Duffy, R.E.(RED Assoc.), Rigamonti, G. (Raytheon), Weisbrich, A. L. (ENECO), **WARP^{TM}-X: A Wind Power System For The 21st Century**; American Power Conference, Chicago, IL, April 26, 1994.

IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 32, NO. 4, JULY/AUGUST 1996

WARP^{TM}: A Modular Wind Power System for Distributed Electric Utility Application

Alfred L. Weisbrich, Stephen L. Ostrow, and Joseph P. Padalino

***Abstract*— Steady development of wind turbine technology, and the accumulation of wind farm operating experience, have resulted in the emergence of wind power as a potentially attractive source of electricity for utilities. Since wind turbines are inherently modular, with medium-sized units typically in the range of a few hundred kilowatts each, they lend themselves well to distributed generation service. A patented wind power technology, the Toroidal Accelerator Rotor Platform (TARP^{TM}) Windframe^{TM}, forms the basis for a proposed network-distributed, wind power plant combining electric generation and transmission. While heavily building on proven wind turbine technology, this system is projected to surpass traditional configuration windmills through a unique distribution/transmission combination, superior performance, user-friendly operation and maintenance, and high availability and reliability. Furthermore, its environmental benefits include little new land requirements, relatively attractive appearance, lower noise and EMI/TV interference, and reduced avian (bird) mortality potential. Its cost of energy is projected to be very competitive, in the range of from approximately 2¢/kWh to 5¢/kWh, depending on the wind resource.**

I. OVERVIEW

The Wind Amplified Rotor Platform (WARP^{TM}) system configuration, consisting of a number of stacked Toroidal Accelerator Rotor Platforms (TARP^{TM}) [1]–[4], differs dramatically from the traditional single, large-diameter horizontal-axis windmill rotor mounted on a tower. Yet this "intelligent tower" wind power design draws heavily on the latest technology developments of today's high-efficiency horizontal-axis wind turbines. This concept, shown in relation to traditional windmills, is illustrated in Fig. 1. However, unlike these conventional wind turbines, which stress ever larger diameter rotors for increased energy capture, the proposed basic system TARP^{TM} Windframe^{TM} building-block technology focuses on wind speed amplification using a patented multipurpose toroidal structure.

Although a variety of other wind power augmenters have been considered [5], these have generally failed to realize commercial success because of technical constraints, and/or marginal cost trades between dynamic and static components. However, a TARP^{TM} multipurpose configuration differentiates it technically, economically, and in terms of appealing features. All of these noteworthy features, innovations, and improvements in wind power technology, will produce a highly attractive utility-grade wind power system. Its potential includes: 1) a very competitive cost of energy compared with traditional power systems; 2) reduced environmental impact; and 3) much greater and more diverse market applicability of wind power. A major application of this system technology is to distributed, combined electric generation/transmission systems (i.e., WARP^{TM}-GT systems). A sketch of such a possible configuration is given in Fig. 2.

Traditional Department of Energy (DOE) and Electrical Power Research Institute (EPRI) wind power plant estimates, combined with the potential application for distributed power, project to a market opportunity potential of over 25 000 MW by the year 2000. Projected new electric transmission requirements (up to 15 000 circuit miles by the year 2000, as shown in Fig. 2), use of existing electric utility rights-of-way, and multipurpose structural use, provide an opportunity for a wind industry market expansion over the next ten years of 300% over the current DOE and EPRI projections of 7000 MW from now to the year 2000 using current technology windmills. Corresponding environmental and economic benefits would also result.

II. TARP^{TM} WINDFRAME^{TM} MODULE

A. Major Components and Subsystems

The fundamental TARP^{TM} building-block configuration (shown in Figs. 1 and 3) is characterized by its aerodynamic toroidal housing or windframe. The wind accelerates around the housing amplifying the available resource energy density. Each TARP^{TM} Windframe^{TM} thus provides a highly augmented, omnidirectional, peripheral flow field to two small diameter wind turbine rotors located about 180° from each other around the toroidal flow channel. These rotors are typically 10 ft or less in diameter and directly coupled to a generator with brake, but *without step-up gearbox*. The windframe also serves as the turbine support structure, a yaw assembly, and a protective housing for the tower support structure, electrical and control equipment, and other internal subsystems. The configuration includes a module yaw rail about the core tower with modular yaw electric transfer umbilical and tray. A monitoring and control system, which may be integral with electronic power-conditioning equipment for turbine variable-speed operation, provides the needed logic and control of turbines under start-up, shutdown, umbilical

Paper ICPSD 95-45, approved by the Rural Electric Power Committee of the IEEE Industry Applications Society for presentation at the 1995 IEEE Rural Electric Power Conference, Nashville, TN, April 30–May 2. Manuscript released for publication November 22, 1995.

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Publisher Item Identifier S 0093-9994(96)04156-4.

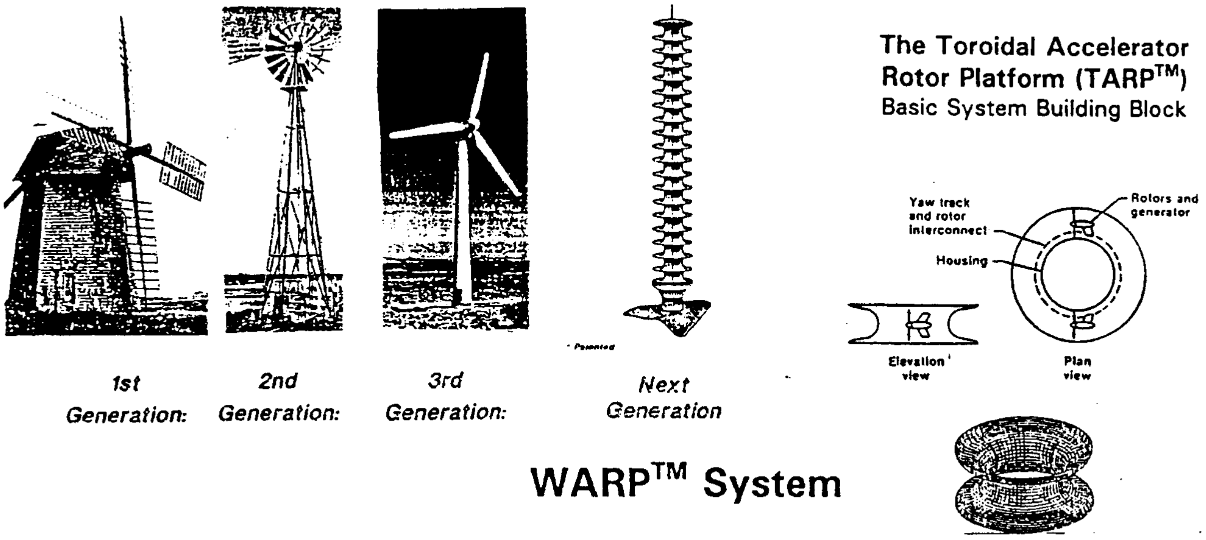


Fig. 1. The evolution of wind power technology.

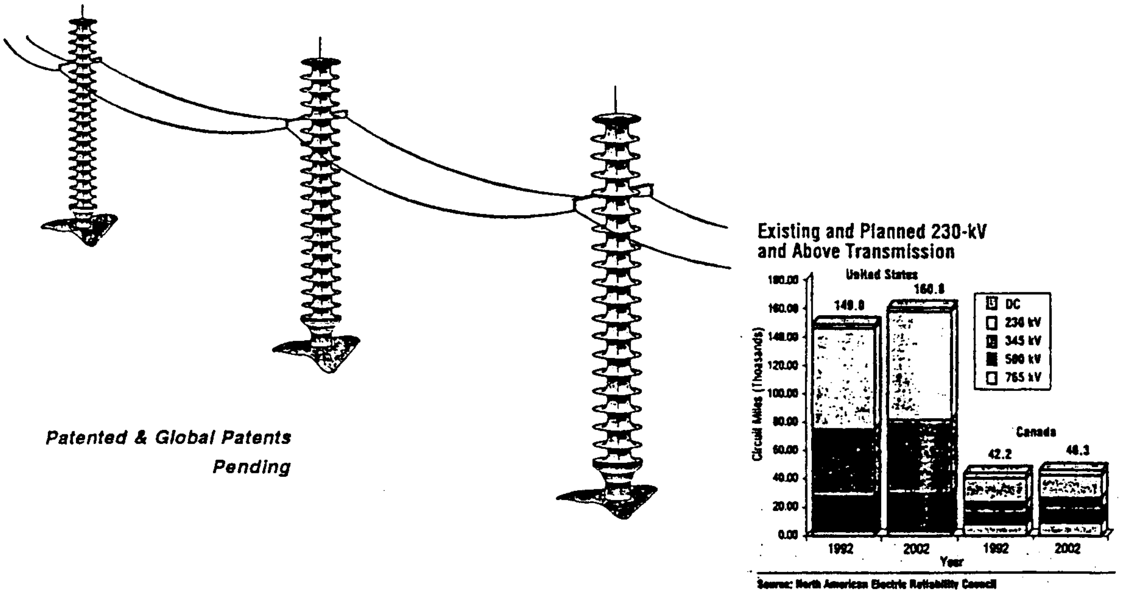


Fig. 2. WARP$^{\mathrm{TM}}$-GT system application for dual-use utility power generation and transmission.

rewind, electrical fault, or extreme environmental conditions. Initiation and control of twin rotor thrust differential is one of the key operational strategies employed for system load control and limiting umbilical travel.

The baseline WARP$^{\mathrm{TM}}$ wind turbine rotors are based on the National Renewable Energy Laboratory (NREL) funded Flexbeam Rotor System developed by PS Enterprises, Inc. (one of the participants developing this concept) under the NREL Innovative Subsystem Program. These rotors use a very economical fiberglass pultrussion process for blade and flexbeam fabrication. This rotor design evolved from the tail rotor design of the Sikorsky Blackhawk helicopter, which operates in an extremely demanding flow field environment to accommodate cyclical loads.

B. Operational Characteristics

Operationally, the presence of twin wind turbines 180° apart on each TARP$^{\mathrm{TM}}$ module provides for passive yaw alignment to changing wind direction, along with flow pregrooming to the rotors. In contrast to conventional windmills, which tend to precess out of the wind, TARP$^{\mathrm{TM}}$ twin turbines passively, and in a stable manner, squarely align themselves to the wind. This is assured by their inherent desire for thrust equalization, as corroborated in model wind tunnel testing (Fig. 3).

TARP$^{\mathrm{TM}}$ turbine load control is achieved using the twin rotor system thrust vectors, by applying relatively small braking actions, either mechanically or electrically, on either one of the rotors. This action initiates module yaw, causing the rotor assemblies to weathervane out of the wind, and continue to weathervane until allowed to resume operation following brake

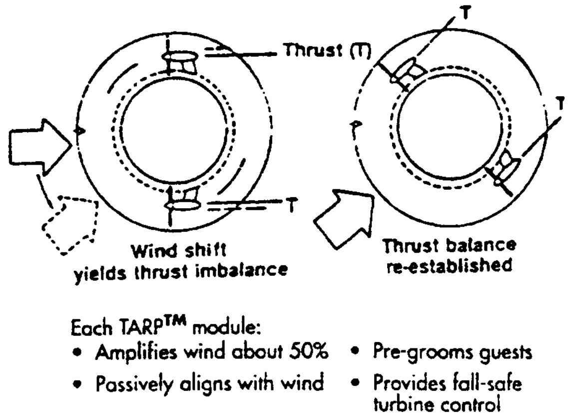


Fig. 3. TARP^{TM} rotors can seek the wind naturally.

release. The turbines are then situated in the relatively benign stagnation flow, or wake flow, region of the TARP^{TM} module structure, which protects the TARP^{TM} rotors from high winds. Large-bladed windmills are not able to "stow" rotors in such a protective manner, nor achieve load control in such a simple, fail-safe fashion.

TARP^{TM} turbines are typically subjected to a steep horizontal wind shear gradient in an operational TARP^{TM} flow channel. NASA wind turbine research has verified that windmills operating in a wind shear will realize higher energy recovery than if the same wind energy is uniformly distributed over the rotor disc area. This results because the rotor hub contributes little in terms of rotor torque, and because the velocity cubed term in the power equation skews the energy output in favor of the high-speed tip region. On a TARP^{TM}, the high working rotor tip region is in the high-energy flow field against the channel wall, and can concurrently benefit from tip loss reduction via tip shrouding where the flow energy density is highest. The latter phenomenon will also help rotor start-up.

A wind shear gradient, however, introduces cyclic stress loading on the rotor blades. Effective solutions are inherent in the teetering rotor approach used for decades within the helicopter industry. As previously mentioned, the TARP^{TM} rotor is a derivative of the Black Hawk helicopter tail rotor and uses an elegantly simple and effective quasi-teetering flexbeam hub [6].

NASA research and operating wind turbine experience have also shown a 10%–20% degradation in energy output performance when blades are exposed to precipitation such as direct rain drop impact. By virtue of TARP^{TM} rotor blade shielding within the TARP^{TM} channel, such degradation is expected to be minimized.

C. Model Tests and Analysis

Scaled TARP^{TM} wind tunnel testing in the mid-1980's at Rensselaer Polytechnic Institute (RPI), under New York State Energy Research & Development Authority (NYSERDA) sponsorship, has helped establish the technical feasibility of the TARP^{TM} concept, through TARP^{TM} configuration flow mapping, TARP^{TM} rotor/turbine testing with flow visualization, and yaw response behavior experiments [1].

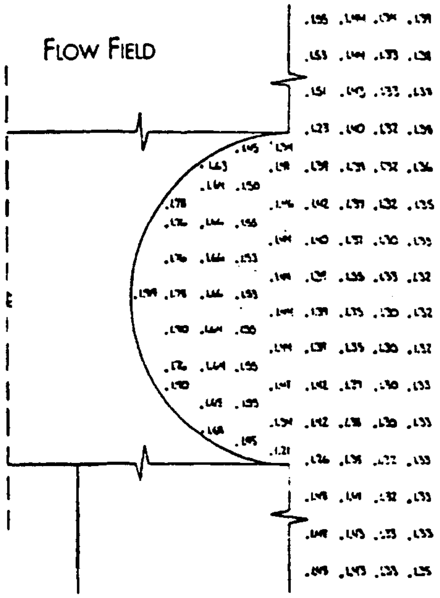


Fig. 4. Flow field mapping.

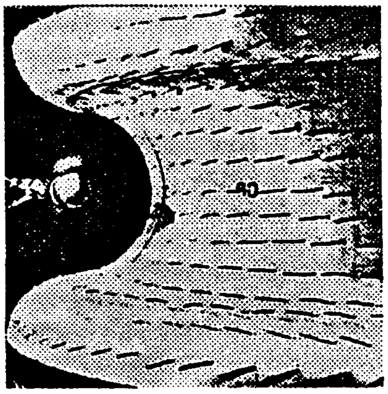
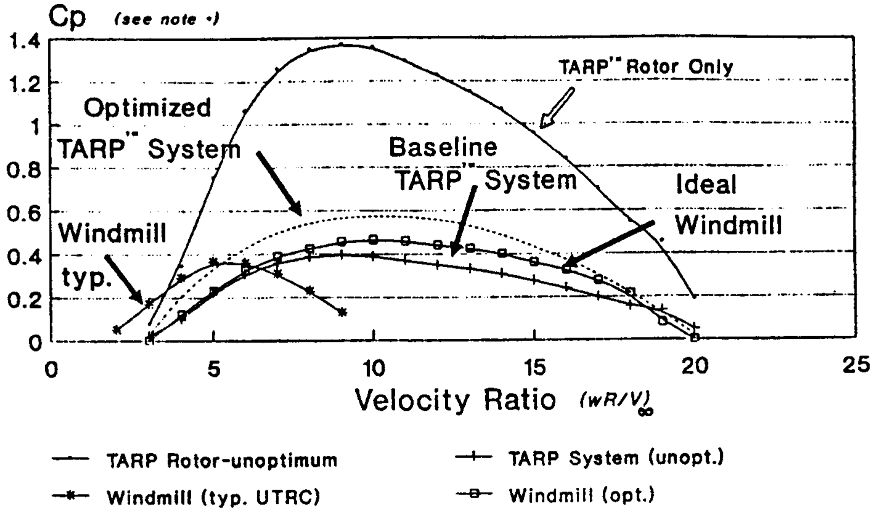


Fig. 5. TARP^{TM} scale model wind tunnel test.

Flow field mapping has determined a wind flow amplification of over 50% at the location of each rotor disc plane relative to free stream for practical configurations (see Fig. 4). This augmented flow velocity to a rotor translates to an over 3.5-fold increase in power compared with an identical diameter wind turbine in the free stream.

With the presence of loaded wind turbine rotors operating in the TARP^{TM} module channel, flow remained fully attached through the rotor disc, and well behaved far downstream of the rotor disc plane. This provides for excellent energy recovery potential and reduced TARP^{TM} center body wake. TARP^{TM} flow pregrooming to the small rotors largely eliminates the troublesome turbulent inflow environment experienced by large bladed conventional windmills, and the concomitant large errors in load prediction [7].

Using the wind tunnel test flow field illustrated in Fig. 4 for analysis, a full-scale TARP^{TM} rotor maximum power coefficient (C_p), based on free stream velocity and an unoptimized baseline untwisted and untapered 10-ft diameter wind turbine rotor within the TARP^{TM}, is calculated at close to 1.4. This



• Augmentors can exceed Betz limit
ref. DOE/SERI DAWT report TP-211-1984

Fig. 6. Performance chart test.

does not take into account the flow-influencing projected area of the associated TARP™ module structure having a major to minor toroidal diameter ratio of 0.42. From a systems point of view, inclusive of the latter system projected area, a maximum C_p of about 0.4 is realized.

A conventional windmill, with identical untwisted, untapered rotor platform, achieves a C_p of about 0.35 in the free stream. The high wind shear and partial tip shrouding of a TARP™ module largely account for this improvement. The system C_p curve closely approaches that of an optimized conventional windmill (see Fig. 6). An *optimized* TARP™ rotor is anticipated to add a minimum of 5%–10% in efficiency. As tested and documented by Grumman Aerospace, augmentor windpower systems have also been shown to be able to exceed the Betz limit with C_ps over 0.6 [8].

Wind tunnel yaw response has been demonstrated to be effective and stable for the system under virtually any test situation. This held true even when the wind turbine rotors were subjected to unrealistically demanding yaw release scenarios in high-velocity conditions, while initially positioned in maximum off-wind facing orientations.

III. WARP™-GT SYSTEM RATIONALE AND CHARACTERISTICS

Description of a baseline WARP™ configuration is presented below for networked distributed electric utility grid service. As a combined generation and transmission system, WARP™-GT represents a highly distributed network system which builds on existing utility infrastructure resources and needs. Conventional wind turbines are unsuitable for such combined applications.

A. Improved Resource Utilization

A WARP™-GT system encompasses and improves on the traditional benefits of both small- and large-diameter conventional wind turbines without the inherent drawbacks of either [9]. It has the manageability and mass producibility of small-scale turbines without the massive land sprawl, and encompasses the high-energy access, output, and capacity per unit of very large-diameter turbines without their problematic structural and O&M characteristics. Maximization of the energy output per installation is made possible via access to the high-energy wind resource at high elevations through vertical integration (see Fig. 7). Furthermore, shifts in wind direction over significant height differences (referred to as the "Ekman spiral") are readily accommodated by the WARP™-GT system modules and rotors at each local level over the anticipated short, 10-ft or less, diameter rotor spans.

The usual engineering and economic structural limits on height imposed on conventional windmill designs (e.g., rigging height/lift limits) do not apply to the WARP™-GT design with its TARP™ modules on a uniform core support structure. Heights may range from under 200-ft tall towers to over 750 ft, depending on wind resources and utility considerations. The ability to guy the system anywhere between apex and ground provides additional design flexibility. Elimination of separate land requirements along utility transmission rights-of-way is also a resulting benefit (see Fig. 8).

B. Reduced Rotor and Drive-Train Risks and Losses

Robust, small-diameter rotors largely avoid the aeroelastic risks and liabilities of large bladed wind turbines which, by propeller or helicopter size rotor standards, have a fairly limited knowledge-base and history. WARP™-GT wind turbines are quite similar in size and design to airplane and helicopter rotors which typically are subjected to up to 100 times the horsepower loading anticipated for the WARP™-GT turbines and have been safely used for hundreds of millions of passenger miles over many decades [10]. Furthermore, the rotor diameter is such that the operational r/min coincides with off-the-shelf 900–1200 r/min generators. This eliminates costly

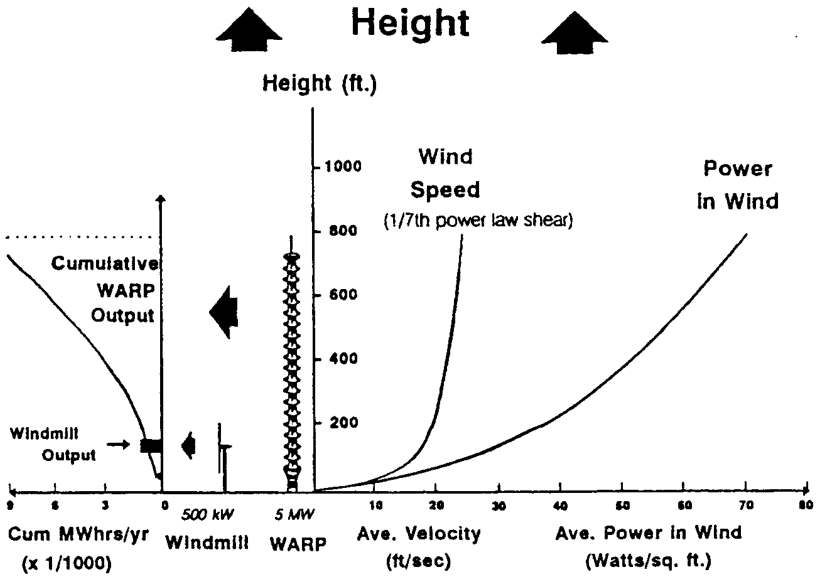
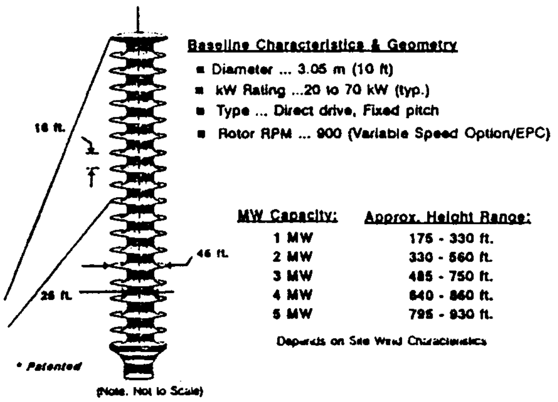


Fig. 7. The power of the 3rd dimension for WARP^{TM} height.



Baseline Characteristics & Geometry

- Diameter ... 3.05 m (10 ft)
- kW Rating ...20 to 70 kW (typ.)
- Type ... Direct drive, Fixed pitch
- Rotor RPM ... 900 (Variable Speed Option/EPC)

MW Capacity:	Approx. Height Range:
1 MW	175 - 330 ft.
2 MW	330 - 560 ft.
3 MW	485 - 750 ft.
4 MW	640 - 860 ft.
5 MW	795 - 930 ft.

Depends on Site Wind Characteristics

Fig. 8. WARP^{TM} wind power system for utility application analysis.

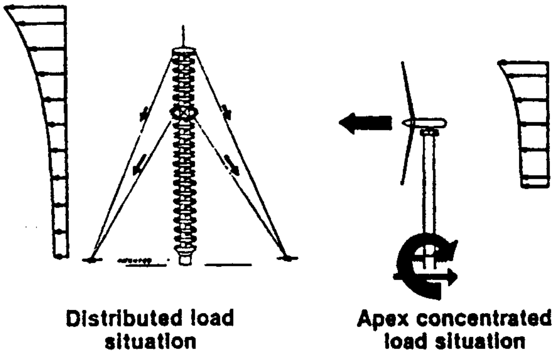


Fig. 9. WARP^{TM} system leading and load reaction are more cost-effective.

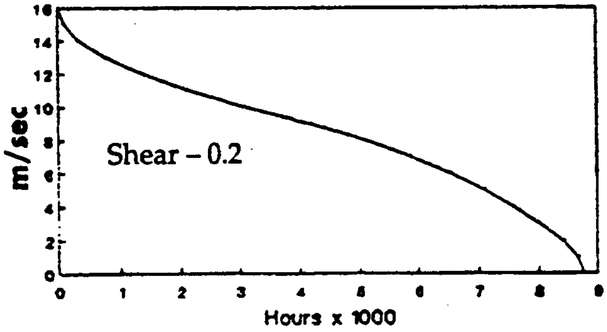


Fig. 10. Wind speed distribution.

gearboxes from the system, and the attendant efficiency losses and potential for malfunctions.

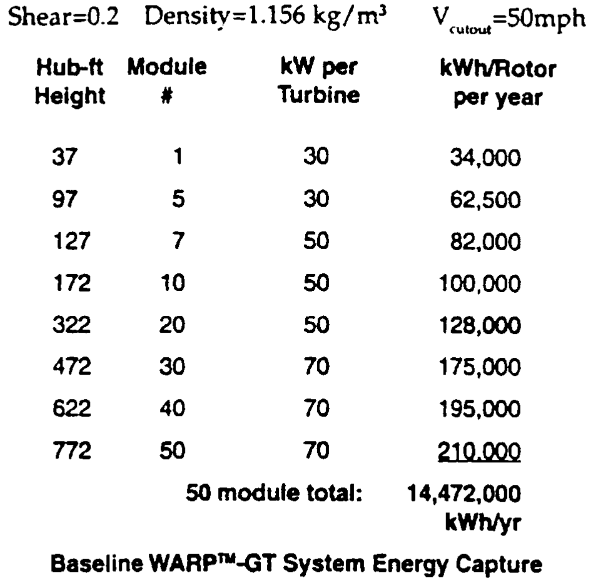
C. Improved Tower Load Reaction and Dynamics

The system has a structural advantage in having distributed loading along its tower structure, in contrast to the concentrated apex loads experienced by conventional windmills (see Fig. 9). Taller WARP^{TM}-GT system loads may be reacted in an efficient and economic manner by guying and using smaller foundations. Vibration is not expected to be a problem due to the dynamic mode decoupling between the low modal frequency of the core tower structure and the high modal frequency of the rotors.

D. Performance

Energy capture performance of different height WARP^{TM}-GT systems has been investigated. For illustration purposes, a 50-TARP^{TM} module, electric utility scale WARP^{TM}-GT system is discussed here. It is assumed to be sited at an excellent wind site, and is analyzed as in [4]. Available measured wind speed and shear (0.2) data were extrapolated to full system height (see Figs. 10 and 11). This is a prudent approach based on available Battelle wind shear and wind power information [11]–[15]. The TARP^{TM} flow field and associated power coefficient (C_p) performance curve for this rotor were discussed previously.

Rotational speed and generator rating were determined for most effective energy capture. The best r/min approximately coincides with stock 900 r/min generators, which provides



Shear=0.2 Density=1.156 kg/m^3 V$_{cutout}$=50mph

Hub-ft Height	Module #	kW per Turbine	kWh/Rotor per year
37	1	30	34,000
97	5	30	62,500
127	7	50	82,000
172	10	50	100,000
322	20	50	128,000
472	30	70	175,000
622	40	70	195,000
772	50	70	210,000
	50 module total:		14,472,000 kWh/yr

Baseline WARP™-GT System Energy Capture

Fig. 11. Wind speed distribution, 8 m/s mean.

significant system simplification and cost benefit due to elimination of step-up gearbox hardware and associated efficiency and reliability losses.

Using the site wind distribution and shear data shown, an energy capture analysis was done for the fifty modules of a tower at their respective elevations. A constant r/min induction generator was assumed for the base case analysis. An additional 5%–10% performance gain due to use of optimized planform rotors, and an additional 15%–20% energy capture gain potential with variable-speed generators using electronic power conditioning (EPC) controls are projected. However, such enhancements were not reflected in the above analysis [16].

Results of energy capture and system generator capacity are noted in Fig. 11. Generator capacities are conservatively high, based on rotor stall and cut-out speed. Comparable or greater output may be achieved with lower capacity generators employing service factor margin and/or variable speed control. An integrated system energy capture value is given for all 50 modules.

E. Production, Transportation, Erection, Maintenance, and Availability

1) Production: The relatively small, symmetric, and repetitive modular component nature of a WARP^{TM}-GT system ideally lends itself to volume production economy. A TARP^{TM} module assembly, shown in Fig. 12, where the wind turbine operates in yaw within a stationary TARP^{TM} module structure, represents but one of several operational design arrangements possible. Turbines may alternatively be fastened to the windframe module with the module operating in yaw about the core tower. These small scale subcomponents do not require extraordinary capital equipment expenditures or consequent high initial manufacturing expenditures. Due to the modular nature of the TARP^{TM} assembly, learning factor benefits can enhance assembly speed, efficiency and productivity.

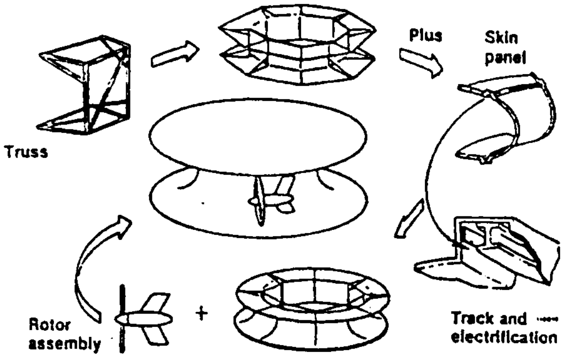


Fig. 12. Small identical TARP^{TM} subcomponents are well suited for mass production.

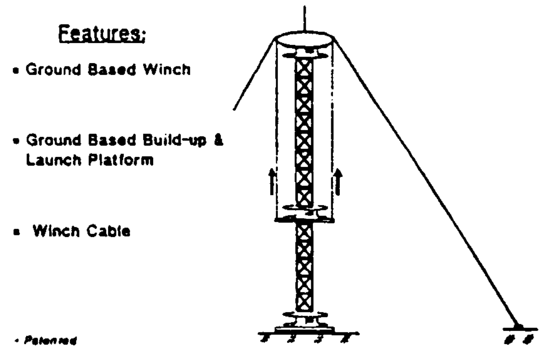


Fig. 13. WARP^{TM} erection can be simple and safe.

2) Transportation: Relatively small subsystem components and assemblies are suited for ease of transportation. No extraordinary cargo, containerization, or transport fixtures are anticipated, nor are special routing or transport permits required due to oversize cargo. Transport is possible by conventional trucking means for component assembly on site. Use of helicopter for transport and erection is also a possibility. This approach permits power plant installation to be made in very windy and difficult-access remote areas as well.

3) Erection: Erection complexity and cost increase with increasing system component size and weight. This favors the WARP^{TM}-GT system which lends itself to the use of small-scale hoists, small self-climbing gantry cranes, and jack-up erection as used in conventional high-rise building and communication tower construction (see Fig. 13). TARP^{TM} module assemblies may even be lifted into place by helicopter as is current practice for electric utility transmission tower installations.

4) Maintenance and Availability: WARP^{TM}-GT systems have several attractive maintenance and availability features (Fig. 14). One of these is internal access to each TARP^{TM} subsystem through either an access hoist or ladder within the WARP^{TM} "intelligent tower," providing both safety and convenience. For the externally mounted wind turbines, access hatchways through each TARP^{TM} aerodynamic skin faring will permit convenient servicing, or retrieval into the tower of the manageable-size components. This may be of particular importance in hostile environmental conditions.

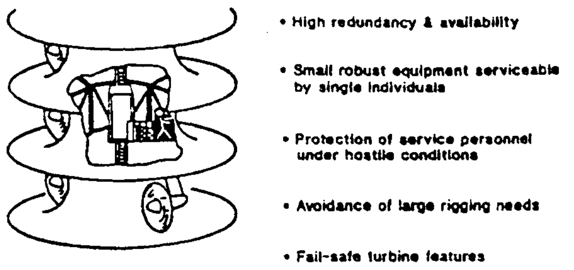


Fig. 14. WARP™ systems are user- and maintenance-friendly.

Critical components, such as less than 5-ft-long rotor blades and typical 20-kW–70-kW (max.) generators, may be handled by only one or two individuals. With a small capacity portable hoist at their disposal, the generators can be retrieved into the WARP™-GT and deposited at the tower base enclosure operations and spares area.

TARP™ wind turbines are anticipated to be highly reliable due to their relative simplicity and robustness with direct drive generators. Each module structure partially shields its critical rotors from adverse environmental conditions such as hail, rain, and, to a limited extent, ultraviolet radiation. Lightning protection can be simply achieved by placing lightning arrestors on the core tower.

Additionally, failure of any one module component will not jeopardize the rest of the system, which will remain operational. Another fail-safe feature is that a failure on any one wind turbine (i.e., bearing failure or generator seizure), will result in a thrust differential with its twin, automatically causing that TARP™ module assembly to yaw out of the wind into a shutdown mode. A networked electronic monitoring and control system can signal such events for appropriate shut-down and service dispatch [15], while the balance of the system remains on line and operational.

F. WARP™-GT Environmental Impact

WARP™-GT systems have several environmental impact advantages when compared to conventional, large-bladed wind turbines.

1) Land Use Reduction: A major benefit of WARP™-GT systems is a dramatic reduction in land use requirements due to dual-use application in existing utility rights-of-way.

2) Lower Noise: System noise is expected to be low due to much higher r/min and ungeared operation of its wind turbines. High-frequency noise dissipates more rapidly with distance compared with the low-frequency noise emitted from large bladed turbines.

3) Reduced EMI/TV Interference: Electro-magnetic TV interference (EMI) is projected to be negligible for WARP™-GT systems because its blades avoid the metal content required by large bladed turbines for lightning protection.

4) Avian Mortality Avoidance: Avian (bird) mortality is minimized with WARP™-GT systems because birds are able to discern building-type structures and high-speed rotors. They are much more easily lulled into entering the large disc area of deceptively slow-moving (low r/min, but high tip speed) large bladed turbines.

5) Height Issues: WARP™-GT height poses a potential issue that is less technical than regulatory. Although the view shed of a tall WARP™-GT can exceed that of a conventional windmill, the impact of nondedicated land usage under distributed wind farm applications is a major off-setting advantage. For systems in excess of 200 ft in height, FAA lighting is easily accommodated on the static tower structure. This contrasts with the complex and costly tip lights required on conventional windmills exceeding this height threshold.

6) Dual-Duty Resource Conservation: WARP™-GT plants provide a unique environmental opportunity to utilities to transmit large amounts of power over large distances in wind-rich regions, such as the central plains states, tundra regions of Alaska, or similar areas. With typically established rights-of-way and land, WARP™-GT systems can serve both as the carrier of conventionally generated power as well as be a highly distributed generation feeder network providing significant capacity potential. Its dual-use capability can benefit both today's trend to decentralized, cleaner energy power plants, suitable for incremental growth and security, and system economics, and better use of structural and land resources. The presence of the aerodynamic skin also affords protection to the core tower for improved tower life.

7) Decommissioning: As with any power plant, life cycle issues that may impact the environment need to be addressed. This includes eventual system decommissioning. WARP™-GT system decommissioning is anticipated to be a simple affair, due to planned incorporation of easily recycled materials, small size components, and absence of harmful chemicals such as hydraulic fluids.

IV. PROJECTED COST OF ENERGY

A. System Cost Development

In order to better understand how the cost of energy (COE) estimate was derived for the proposed WARP™-GT system, it will be instructive to briefly trace the system's evolution through past studies. In 1983, a conservatively engineered WARP™ system design was evaluated for economic merit under a contract with NYSERDA [4]. Costs were independently estimated by an Industrial Risk appraiser for a single-unit installation with no volume production credit. Nonrecurring tooling and other such charges were absorbed in the single unit. Despite this conservatism, a roughly 1000-kW installed cost was determined.

The process used to define current WARP™ and WARP™-GT system costs is shown in Fig. 15. Considerable system design improvements and simplifications have been made since 1983, and estimated on a preliminary basis, as reflected in a technical paper presented at the 1994 American Power Conference [17]. More realistic, multiunit installation scenarios also produce attractive economics. Furthermore, optimization of rotors and variable speed operation is expected to increase energy capture by at least 20%. Improved economics will result from the wind speed amplification by TARP™s which permits high r/min operation of the small turbines. This, in turn, eliminates the need for gearboxes,

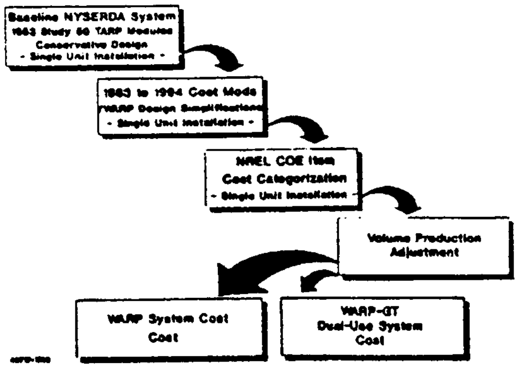


Fig. 15. WARP™ cost definition process.

blade pitch change mechanisms, drive train bed plates, massive hubs and large brakes. Volume production economies of scale are particularly important for reducing system costs. WARP™-GT systems are ideally suited for mass production relative to large bladed conventional windmills even for modest 50-MW capacity deployment.

Estimated O&M comparison of comparable size units and arrays show that WARP™ and WARP™-GT systems have a substantial maintenance cost advantage relative to conventional windmills. An annual O&M factor of 20–25% of traditional windmills is used for COE calculations. Historical and conservative wind industry O&M values are about 2% of capital cost [18], [19]. WARP™ system annual O&M, inclusive of the minor levelized replacement cost, is estimated at about 0.5% of installed capital cost. This may be reduced by about 30%–35% for a WARP™-GT installation because of existing transmission lineman O&M crews, hence, eliminating dedicated wind turbine maintenance personnel.

B. Cost-of-Energy

Cost-of-energy (COE) analyzes were made for a 50-MW WARP™-GT installation using the EPRI TAG methodology of costing [20], also prescribed by NREL. Two different wind resource regimes were considered: a good site with an 8.0 m/s (18 mph) mean wind speed distribution with a vertical shear factor of 0.20; and a fair wind site with a 5.8 m/s (13 mph) mean wind speed distribution with a vertical wind shear factor of 0.14. Two different height units were also examined: a "tall" configuration consisting of 50 stacked TARP™ modules, with a total height of about 800 ft; and a "short" configuration consisting of 11 TARP™ modules, with a height of under 200 ft. For the same total power capacity at a given site, more "short" units than "tall" units are required. Also, for a given height unit, more units are required at the poorer wind site than at the better wind site for the same total energy output.

System performance as a function of height of a unit is illustrated in Fig. 11 for the 8.0 m/s mean wind speed reference site, and in Fig. 16 for the 5.8 m/s site. The analysis for the poorer wind site assumed availability of an improved rotor configuration and variable speed operation with electronic power conditioning to improve performance.

Cost-of-energy analyzes are presented for the 8.0 m/s site and the 5.8 m/s site in Figs. 17 and 18, respectively. 50- and 11-module information is presented in each figure. As expected, the resulting costs-of-energy for the systems situated at the higher wind site, going below 2¢/kWh, are substantially better than that at the lower wind site, just below 5¢/kWh. Furthermore, future system refinements should be able to reduce costs even more.

5.8 M/S MEAN RAYLEIGH WIND

Shear = 1/7 Density = 1.226kg/m^3

Rotor = 10 ft dia. RPM = 900 V_{cutout} = 50 mph_{max}

Hub-ft Height	Module #	kW per Turbine	kWh/Rotor per year
37	1	15	10,000
97	5	15	17,000
127	7	20	20,000
172	10	20	25,000
322	20	20	32,000
472	30	30	41,000
622	40	30	46,000
772	50	30	50,000
		50 module total:	4,999,800 kWh/yr*

*Note: Total energy value reflects + 7.5% points Cp for optimum rotor, and +18% energy for variable speed.

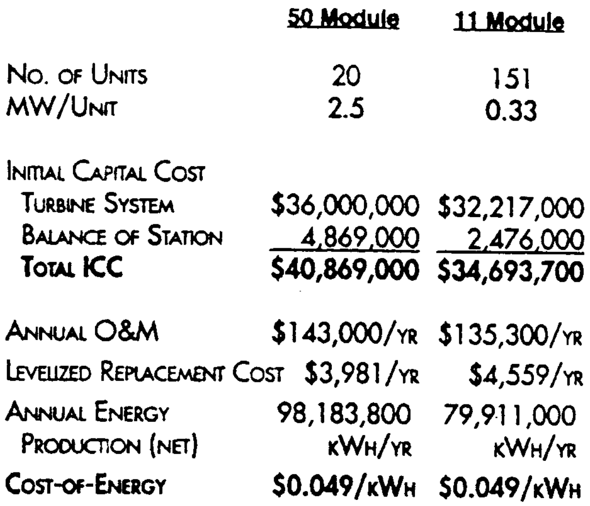
Fig. 16. Wind site performance/COE data.

	50 Module	11 Module
NO. OF UNITS	8	56
MW/UNIT	6.2	0.9
INITIAL CAPITAL COST		
TURBINE SYSTEM	$17,404,000	$19,521,600
BALANCE OF STATION	2,152,000	935,600
TOTAL ICC	$19,556,800	$20,457,000
ANNUAL O&M	$111,280/YR	$135,300/YR
LEVELIZED REPLACEMENT COST	$3,456/YR	$3,645/YR
ANNUAL ENERGY PRODUCTION (NET)	136,850,140 KWH/YR	113,927,520 KWH/YR
COST-OF-ENERGY	$0.016/KWH	$0.021/KWH

Fig. 17. WARP™-GT cost-of-energy, 50-MW wind power production, 8.0 m/s mean wind site.

V. CONCLUSION

The WARP™-GT system of stacked TARP™ modules represents a potentially attractive distributed electrical operating capability for utilities to use along transmission rights-of-way. The concept combines wind turbine energy produc-



	50 Module	11 Module
No. of Units	20	151
MW/Unit	2.5	0.33
Initial Capital Cost		
Turbine System	$36,000,000	$32,217,000
Balance of Station	4,869,000	2,476,000
Total ICC	**$40,869,000**	**$34,693,700**
Annual O&M	$143,000/yr	$135,300/yr
Levelized Replacement Cost	$3,981/yr	$4,559/yr
Annual Energy Production (net)	98,183,800 kWh/yr	79,911,000 kWh/yr
Cost-of-Energy	**$0.049/kWh**	**$0.049/kWh**

Fig. 18. WARP^{TM}-GT cost-of-energy, 50-MW wind power production, 5.8 m/s mean wind site.

tion with transmission towers. Analyzes for different height systems at two different reference wind sites show that cost-of-energy can be below 2.0¢/kWh in excellent wind locations, to about 5.0¢/kWh in poor wind locations.

REFERENCES

[1] B. Liebowitz, "Verification analysis of the performance of the toroidal accelerator rotor platform wind energy conversion system," NYSERDA, Proj. 431-ET-RER-82, Sept. 1988.

[2] R. E. Duffy, "Verification analysis of the performance of the toroidal accelerator rotor platform wind energy conversion system," *Wind Tunnel Tests*, vol. I, NYSERDA, Proj. 431-ET-RER-82, Dec. 1983.

[3] A. L. Weisbrich, *Wind Tunnel Tests*, vol. II, *Farm Silo System*, RPI subcontract for NYSERDA, Dec. 1983.

[4] ——, *Wind Tunnel Tests*, vol. III, *Wind Power Needle System*, RPI/NYSE subcont., Dec. 1983.

[5] ——, "Feature review of advanced & innovative design concepts in WECS," presented at Sec. Annu. Conf. & Exhibition, New England Solar Energy Association, Hartford, CT, Sept. 1977.

[6] P. Spierings and M. C. Cheney, "Design of a self-regulating composite bearing less wind turbine," Final Rep., ERDA COO-2614-76/1 UC-60, Jan. 1978.

[7] R. Thresher and S. Hock, "An overview: Challenges in wind technology development," in *Windpower 1991 AWEA Proc.*, Palm Springs, CA, Sept. 1991.

[8] E. Dick, "Power limits for wind energy concentrator systems," *Wind Engineering*, vol. 2, 1986.

[9] R. E. Duffy and A. L. Weisbrich, "Wind power needle application of the TARP^{TM} wind energy conversion system," presented at 3rd ASME Wind Energy Symp., New Orleans, LA, Feb. 12, 1984.

[10] W. C. Strack, G. Knip, A. L. Weisbrich, J. Godston, and E. Bradley, "Technology and benefits of aircraft counter rotation propellers," in *1982 Aerospace Congress/SAE*, Anaheim, CA, NASATM-82983, Oct. 1982.

[11] R. J. O'Doherty and B. W. Roberts, "The application of U.S. upper wind data in one design of tethered wind energy systems," prepared for the U.S. Dept. Energy, EG-77-C-0104042, Feb. 1982.

[12] G. Riegler, W. Riedler, and E. Horvath, "The transformation of wind energy by a high altitude power plant," in *AIAA Conf.*, Colorado Springs, CO, Research Center Graz Austria, AIAA-81-2568, Dec. 1981.

[13] C. S. Ramage, N. E. Oshiro, and S. T. Yokogawa, "Hawaii Wind Power Survey: Fixed Station Data," UHMET 79-15, Dept. of Meteorology, U. of Hawaii.

[14] H. Riel, *Tropical Meteorology*. NY: McGraw-Hill, 1954.

[15] M. N. Schwartz, private communications & correspondence; T. A. Schroeder, D. Elliot, A. M. Hori, *et al.*, *Wind Energy Resource Atlas*, PNL-3195WERA, UC 60, Pacific Northwest Lab/Battelle Memorial Institute.

[16] D. A. Marckx, J. Lehman, and K. Cohen, (SecondWind), private communications.

[17] A. L. Weisbrich, R. E. Duffy, and G. F. Rigamonti, "WARP^{TM}-X: A wind power system for the 21st century," presented at Amer. Power Conf., Chicago, IL, Apr. 1994.

[18] M. J. Grubb, "The economic value of wind energy at high power system penetrations: An analysis of models, sensitivities & assumptions," *Wind Engineering*, vol. 12, no. 1, 1988.

[19] M. Lotker, "Making the most of federal tax laws for WECS development," *Trans. ASME*, May 1982.

[20] TAG^{TM} *technical assessment guide, vol. 1: Electricity supply-1986*, Electric Power Research Institute, EPRI P4463, Dec. 1986.

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