COMPUTATIONAL FLUID DYNAMIC (CFD) ASSESSMENT OF A WARP™ WIND POWER SYSTEM

WIND POWER 1996, June 26, 1996, Denver, CO, USA

Mr. Alfred L. Weisbrich
Principal
ENECO
West Simsbury, CT, USA

Prof. Dr. Karl Pucher
Technical University Graz
Graz, Austria

INTRODUCTION

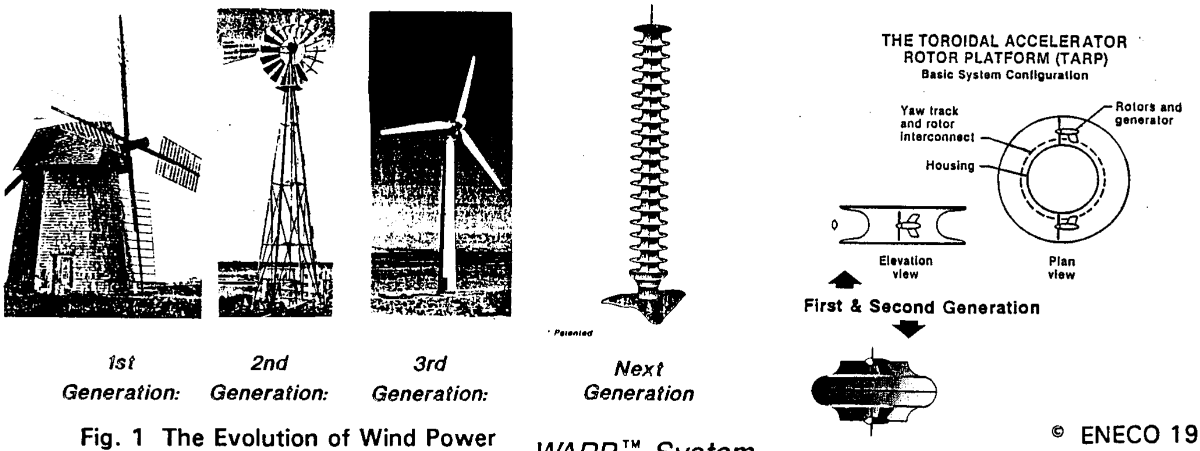
The **Wind Amplified Rotor Platform (WARP™)** system configuration, consisting of stacked patented Toroidal Accelerator Rotor Platform (TARP™) modules [Ref. 1-6], differs dramatically from the traditional single, large-diameter horizontal-axis windmill rotor mounted on a tower. Yet this "smart tower" wind power design draws heavily on the latest technology developments of today's high-efficiency horizontal-axis wind turbines (HAWT). This system is conceptually illustrated in Fig. 1 in relation to traditional windmills. However, unlike conventional wind turbines, which stress ever larger diameter rotors for increased energy capture, the proposed system, using TARP™ Windframe™ building-block technology, focuses on wind speed amplification from the multi-purpose toroidal structure.

Each TARP Windframe provides highly amplified wind flow fields at each rotor level to tailored conventional, low risk, small diameter wind turbines. It also serves as a support for the wind turbines, yaw assembly and protective housing for a core tower and other internal sub-systems.

WARP Systems are tall TARP module arrays about a simple core tower. These "smart", yet simple aerodynamically-faired, towers can be flexibly and incrementally deployed into multi-megawatt size wind power plants. While heavily building on proven windmill technology, WARP Systems may be shown to surpass current technology windmills in all aspects of system characteristics. WARPs have improved performance as a result of amplified gearless and shrouded turbine operation. Other benefits include user-friendly operation and maintenance, and high reliability and low risk due to small, simple and robust dynamic components. Environmental benefits include an order of magnitude less land requirement for equal conventional windmill wind farm installation power capacity, absence of bird kill potential, attractive appearance, lower far field noise and EMI/TV interference, and improved rotor safety through containment means (Ref. 7). Operation under extreme icing is also afforded due to both rotor shielding and inherent self-sustaining tower anti-icing capability. This avoids the destructive rotor imbalance and ice shedding predicaments possible with conventional windmills. System components are suited for low cost mass production, ease of transportation, erection and servicing.

WARP PERFORMANCE CHARACTERISTICS

A WARP power plant's ability to amplify the wind and also access the higher energy winds aloft on tall towers significantly improves pollution-free energy generation capability. The synergism of cited system features results in a very attractive projected cost of energy in below $.02 to $.03 per kilowatt-hour range. This is based on both engineering and cost studies conducted with Raytheon Engineers and



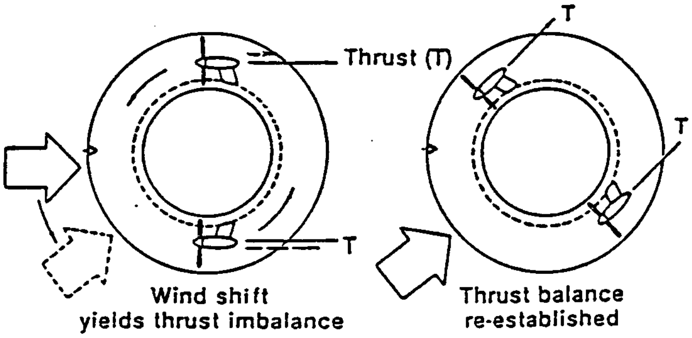
1st Generation: *2nd Generation:* *3rd Generation:* *Next Generation*

Fig. 1 The Evolution of Wind Power *WARP™ System*

Constructors (RE&C), in response to a U.S. Department of Energy advanced wind turbine program using exclusively U.S. labor rates and material cost (Ref. 4-5) for 50 MW size electric utility systems, and on the computational fluid dynamic (CFD) study conducted by the Technical University of Graz. Furthermore, WARPs are calculated to provide excellent user return on investment for other applications such for such remote dual-use power systems in conjunction with wireless telecommunications, off-shore oil platforms or buildings, among others.

The fundamental WARP building block, the TARP, is characterized by a toroidal housing. This is an elegantly simple, strong, aerodynamically versatile and multi-functional structure. Fig. 1 illustrates both first and second generation configurations. The toroid housing amplifies and concentrates the energy density of the wind as it accelerates around it. This provides highly augmented omnidirectional peripheral flow fields to small diameter wind turbine rotors located about 180 degrees from each other at the same level about the toroid flow channel. The flow fields are similar to those of coveted saddle ridge sites found in nature. WARP rotors are typically 1 to 3 meters (3ft. to 10ft.) in diameter and are directly coupled (*i.e.; without step-up gearbox requirement*) to a generator due to their high RPM.

Operationally, each module wind turbine assembly about each TARP can passively align to the wind. Turbine load control is achieved simply by either relatively small braking action or tilt of one of the module wind turbine rotors. This action initiates module yaw and positions the turbines in the low or zero flow velocity stagnation or wake regions of the module.



TARP™ Modules on WARP™ Systems:

- Amplify wind about 80%
- Provide fail-safe control
- Passively align with wind
- Shield rotors, core tower & equip

Fig. 2 Passive WARP Rotor Wind Alignment

Most significant, however, is wind turbine rotor power output enhancement with WARPs due to wind amplification. The reason for this is that wind power output and energy capture are proportional to the cube of wind velocity at the rotor. Ambient wind amplification, even with isolated basic TARP configurations, can give rise to significant multiples of power output by a turbine.

MODEL TESTS & CFD ANALYSES

Scaled TARP model wind tunnel testing at Rensselaer Polytechnic Institute (RPI), as shown in Fig. 3, under New York State Energy Research & Development Authority (NYSERDA) sponsorship allowed establishment of the flow fields of various TARP configurations. (Ref. 2)

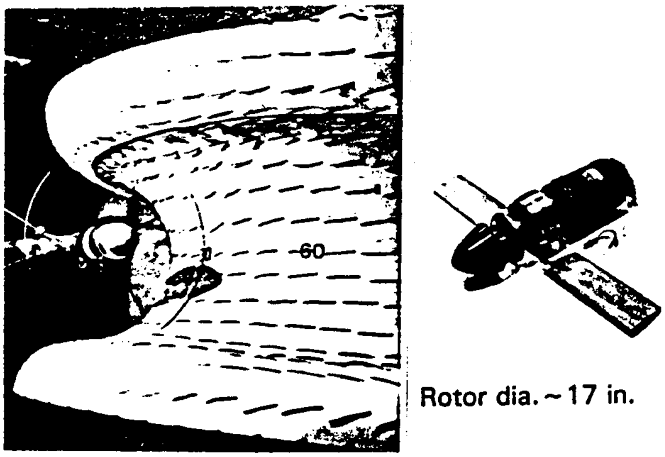


Fig. 3 TARP Wind Tunnel Test at RPI

Fig. 4 shows the measured flow field relative to free stream velocity at the rotor for a select isolated baseline TARP module. Note that the approximate average amplified flow is about 1.2 times free stream. A wind turbine was then tested in this basic TARP flow field. As Fig. 5 shows, it yielded a maximum power coefficient, as expected, of about 1.7 times that of the best free air performance of this turbine ($1.2^3 \sim 1.7$). Note the low absolute

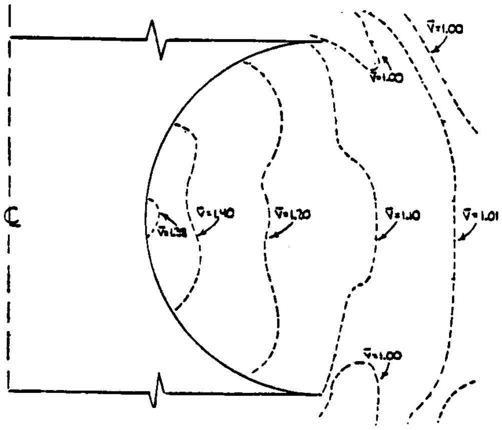


Fig. 4 Basic TARP Flow Field Map (Re# ~ 8×10^5)

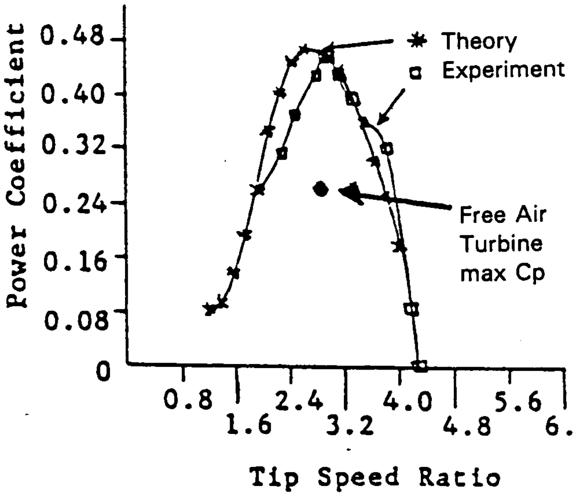
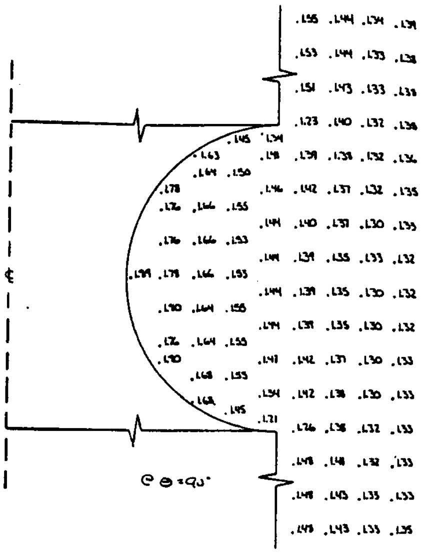


Fig. 5 Turbine Performance in Free Air & Basic TARP

performance values due to the low Reynold's No., thick airfoils (NACA 0018) and low aspect ratio (2.7) blade planform of the rotors used in these tests. However, of primary practical interest are WARP configurations which are stacked, integrated arrays of TARP modules. A stack of the basic TARP module could not be introduced into the RPI wind tunnel without encountering blockage problems. In an attempt to extrapolate to stacked TARP flow fields, the basic module of Fig. 4 was fitted with limited straight cylindrical extensions which gave a configuration still well within the blockage limits of the wind tunnel. Fig. 6 shows that an average amplification level of about 50% over free stream wind speed is achieved [i.e.; velocity amplification factor (VAF) = 1.5]. Subsequent WARP engineering performance analyses, as reported in References 1 through 6, used this flow field in conjunction with a multiple streamtube analysis which accounts for the horizontal shear flow to a rotor. A roughly 3.5 times higher power output is thus achievable by *each* turbine on a TARP module compared to the same diameter turbine in the free stream.



Nondimensional Experimental Velocity Ratio
Supercritical Flow: RN = 8.0×10^5

Fig. 6 Quasi-WARP Flow Field Map With Basic TARP

In order to corroborate the RPI results and determine WARP performance potential more accurately, a computational fluid dynamic (CFD) study was commissioned at the Technical University of Graz (TU Graz), Austria. This established a high end analytical flow field framework for WARP Systems having different scale and configurations. The CFD code employed by the TU Graz for analysis was FIRE. FIRE is a well established and recognized industry code in Europe and was originally developed at the Imperial College of England. Its accuracy is said to be well within 10% of actual measurement (Ref. 8). It can predict and quantify both diverse three dimensional viscous fluid dynamic behavior and complex thermodynamic flow found in combustion chambers.

Initially, an *isolated* first generation TARP configuration from RPI wind tunnel tests [R_{mill}/R_{TARP} = 0.42], was analyzed with FIRE above super-critical Reynold's No. This module configuration is essentially identical, though larger [R_{mill} = 4.2 m] to those used in the engineering assessments of Ref. 3-

6 [R_{mill}=3.05 m], and is shown in Fig. 7.

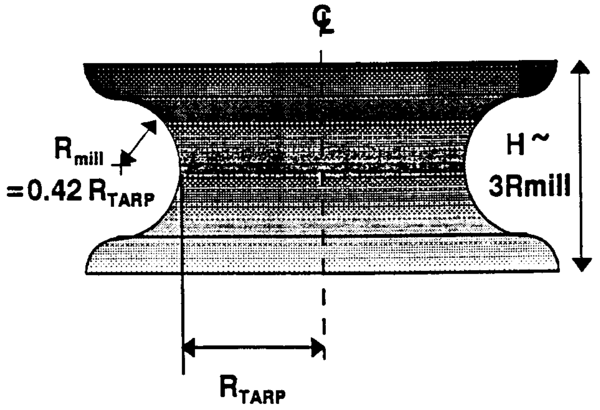


Fig. 7 Fundamental WARP Module Configuration

Subsequently, a WARP, using a stacked array of these modules, was investigated with FIRE. The flow field at the rotor disk location was determined to be about 80% on average to the rotor over the free stream velocity [i.e.; velocity amplification factor (VAF) = 1.8] as shown in Fig. 8.

Note that the local amplification reaches 2.16 times ambient speed at the windframe minimum wall diameter and decreases in a horizontal shear fashion.

Based on the findings of TU Graz, a substantial increase in WARP performance, hence decrease in cost-of-energy (COE), may be expected over that reported in Ref. 4 and Ref. 5 for 50 MW wind farms. The potential COE decrease due to a VAF increase from 1.5 to 1.8 with respect to the Ref. 4 & Ref. 5 reports is well over 50% [i.e.; $(1.8/1.5)^3$ - 100] due to proportionately higher energy capture. In conjunction with the cost reductions of recently patented WARP improvements (Ref. 9), adjusted COE values are well under \$.02/kWhr in excellent wind sites with about 18 mph average such as Kahuku Hills, Hawaii and under \$.03/kWhr for poorer wind sites with about 13 mph average velocity.

SUMMARY

Based on a WARP™ System computational fluid dynamic (CFD) velocity amplification analyses conducted by the Technical University, Graz Austria using the recognized computer program FIRE,

FIRE CFD Analysis Yields a 1.8 VAF for WARP at the Rotor Location

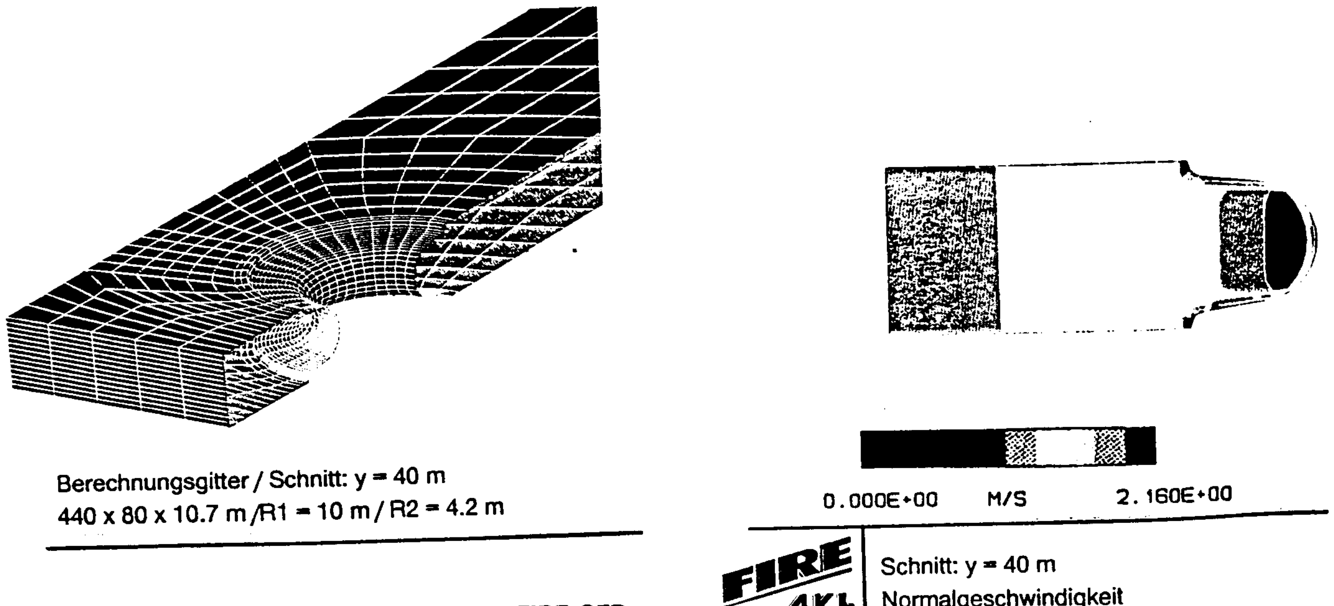


Fig. 8 WARP Flow Field Map Using FIRE CFD

wind speeds at WARP wind turbine rotors are shown to be on average about 80% higher than free stream.

The previously employed WARP flow velocity amplification estimate was about 50% on average over free stream velocity. This value was based on RPI wind tunnel velocity data from a similar single isolated WARP module with limited cylindrical extensions which attempted to simulate the effect of adjacent modules. Hence, together with recent patented WARP enhancements, performance and cost-of-energy (COE) as reported in 1994 and 1995 American Power Conference and IEEE Conference papers (Ref. 4-6) may be considerably improved when using the CFD generated WARP flow field results. Specifically, COE levels reported for the cited 50 MW wind farm installations may be well under $.02/kWhr in excellent wind sites of about 18 mph average and under $.03/kWhr for poorer wind sites with about 13 mph average velocity.

ACKNOWLEDGEMENTS

The authors wish to thank and acknowledge AMST (Austria Metall Systemtechnik, Ranshofen, Austria) for its assistance in helping make the CFD study data available. Grateful acknowledgment is extended to Dr. Robert E. Duffy, former Chairman of Aeronautical Engineering and Dr. Brian Thompson, Aeronautical Engineering Professor, Rensselaer Polytechnic Institute, and New York State ERDA for steadfast encouragement, advice and development support of this technology; special thanks also goes to Dr. Joseph Callerame, Mr. Franco Rigamonti, Dr. Stephen Ostrow and Mr. Joseph Padalino, Raytheon Co. for helping validate the technical and economic veracity of patented WARP™ wind power systems.

REFERENCES

1. Liebowitz, B. Verification Analysis of the Performance of the Toroidal Accelerator Rotor Platform Wind Energy Conversion System, Summary Report; NYSERDA, Project No. 431-ET-RER-82, Sept. 1988.

2. Dr. Duffy, R. E. & Jaran, C.(Rensselaer Polytechnic Institute), Weisbrich, A. L. (ENECO), Summary of Research on the TARP Wind Energy Conversion System, 5rd ASME Wind Energy Symposium, 1986

3. Dr. Duffy, R.E. (Rensselaer Polytechnic Institute), Weisbrich, A. L. (ENECO), Verification Analysis of the Performance of the Toroidal Accelerator Rotor Platform Wind Energy Conversion System, Vol. I (Wind Tunnel Tests), Vol. II (Farm Silo), Vol. III (Wind Power Needle System); NYSERDA, Project No. 431-ET-RER-82, Dec. 1983.

4. Dr. Ostrow, S. L. (Raytheon), Padalino, J. (Raytheon), Weisbrich, A. L. (ENECO), WARP™: 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.

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

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

7. Mr. Burns, R. E., Esq. (National Regulatory Research Institute), Dr. Rainey, D. L. (Hartford Graduate Center), Weisbrich, A. L. (ENECO), Resolution of Critical Environmental Issues With WARP™ Wind Power Systems; Proceedings of the American Power Conference, Vol 58, 1996.

8. Dr. Brian Thompson, Rensselaer Polytechnic Institute, Troy, NY; private communications.

9. U.S. Patent No. 5,520,505 and foreign patents pending for WARP Systems.