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Research Results for the Tornado Wind Energy System: Analysis and Conclusions

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NOTICE

RESEARCH RESULTS FOR THE TORNADO WIND ENERGY SYSTEM: ANALYSIS AND CONCLUSIONS

Eric Jacobs*

ABSTRACT

The Tornado Wind Energy System (TWES) concept utilizes a wind driven vortex confined by a hollow tower to create a low pressure core intended to serve as a turbine exhaust reservoir. The turbine inlet flow is provided by a separate ram air supply. Numerous experimental and analytical research efforts have investigated the potential of the TWES as a wind energy conversion system (WECS). The present paper summarizes and analyzes much of the research to date on the TWES. A simplified cost analysis incorporating these research results is also included. Based on these analyses, the TWES does not show significant promise of improving on either the performance or the cost of energy attainable by conventional WECS. The prospects for achieving either a system power coefficient above 0.20 or a cost of energy less than $0.50/kWh (1979 dollars) appear to be poor.

NOMENCLATURE

A	cross-sectional area of TWES tower (=HD)
A_s	surface area of TWES tower (= $2\pi HD$)
A_t	turbine swept area (= $\pi D_t^2/4$)
COE	cost of energy
c_p	power coefficient (= $P/1/2\rho A V_\infty^3$)
$c_{p,max}$	maximum power coefficient
d_c	vortex core diameter
D	TWES tower diameter
D_t	turbine diameter
H	TWES tower height
P_R	rated power output
r	spiral tower radius
r_o	minimum spiral tower radius
S	width of spiral tower inlet
V_r	tangential velocity of vortex at radius r
V_t	air velocity through turbine
V_∞	freestream wind velocity
α	coefficient used in spiral tower equation
ΔP_t	pressure drop across turbine
Γ	vortex circulation (= $2\pi r V_r$)
ρ	air density
θ	angle used in spiral tower equation

INTRODUCTION

The Tornado Wind Energy System (TWES) was proposed by J.T. Yen of the Grumman Aerospace Corp. [1]. The TWES concept entrains ambient winds to generate a vortex within a hollow tower. The vortex core then serves as a low pressure exhaust reservoir for a vertical axis propeller-type turbine located at the bottom of the tower. The turbine inlet air is provided by a separate ram air supply.

A sketch of the originally proposed tower configuration is shown in Figure 1. This spiral shaped tower has been presumed to provide the maximum performance attainable by a TWES. However, the spiral configuration is inherently impractical for large TWES as it would require unidirectional winds. Thus the omni-directional, fixed multi-vane tower configuration, such as shown in Figure 2, has been used for many of the more recent studies. However, the spiral tower configuration remains useful in ascertaining upper limits for potential TWES performance.

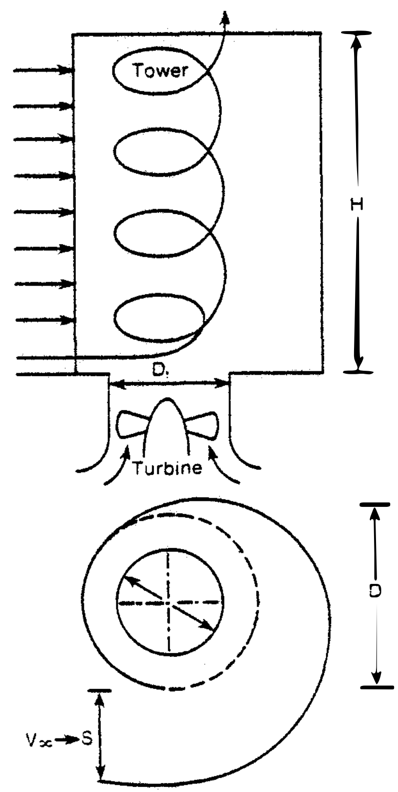

Figure 1. Sketch of a Model for the Tornado-Type Wind Energy System. Spiral Tower Configuration

Several experimental and analytical research efforts have investigated the potential of the TWES as a wind energy conversion system (WECS). The present paper summarizes and analyzes much of the research to date on the TWES. Detailed analysis of these research results provides several broadly supported conclusions regarding prospective TWES performance. As cost of energy is generally the bottom line in evaluating a WECS, a simplified cost analysis of the TWES is also presented to further delineate the potential of the TWES for cost competitive wind energy conversion.

EXPERIMENTAL INVESTIGATION OF THE TWES

Several experimental investigations of the TWES have been performed, including those by Yen [2,3], Müller et al [4],

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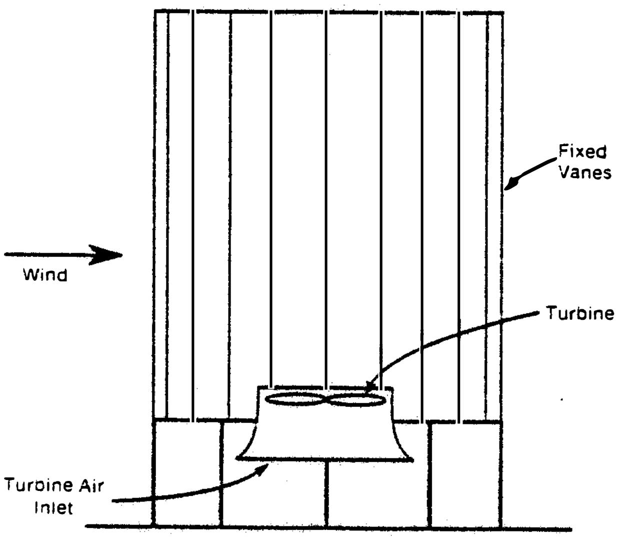

Figure 2. Sketch of the Omnidirectional Multi-Vane TWES

Windrich et al. [5], and Hsu and Ide [6]. These investigations have utilized both the spiral and multi-vane configurations for the TWES, and have studied the effects of several parameters, e.g., tower height-to-diameter ratio (H/D) and turbine-to-tower diameter ratio (D_t/D), on system performance. The results of these research efforts provide substantial indications of the potential of the TWES as a wind energy conversion system (WECS).

All of the power coefficients reported by these studies have been based on the frontal area HD of the TWES tower, i.e.

$$C_p = \frac{\Delta p_t V_t A_t}{1/2 \rho V_\infty^3 HD} \qquad (1)$$

For the spiral tower configuration, D is defined as in Figure 3 and does not include the width of the tower inlet. Use of the total cross-sectional area H(D+S), or

$$C_p = \frac{\Delta p_t V_t A_t}{1/2 \rho V_\infty^3 H(D+S)} \qquad (2)$$

would provide power coefficients better suited for comparisons with conventional horizontal and vertical axis wind turbines as well as with similar TWES configurations. Similarly, use of system power coefficients which include turbine, transmission, and generator losses would also provide more equivalent bases for performance comparisons. Such losses would presumably total at least 20%. However, unless otherwise stated, power coefficients present herein for the spiral tower configuration are based on the original definition of tower frontal area HD and the power available to the turbine as in Equation (1). All power coefficients presented for the multi-vane tower configuration are also based on Equation (1) with D defined as twice the mean radius of the vanes from the tower axis.

The Experimental Setups: Discussion and Comments

Discussions of the TWES experiments performed by Yen [2,3], Miller et al. [4], Windrich et al. [5], and Hsu and Ide [6] are presented below. Of particular importance are any apparent experimental errors and uncertainties which significantly weaken the results and conclusions obtained during these investigations. Any use of the reported results should be tempered by an awareness of these errors and uncertainties.

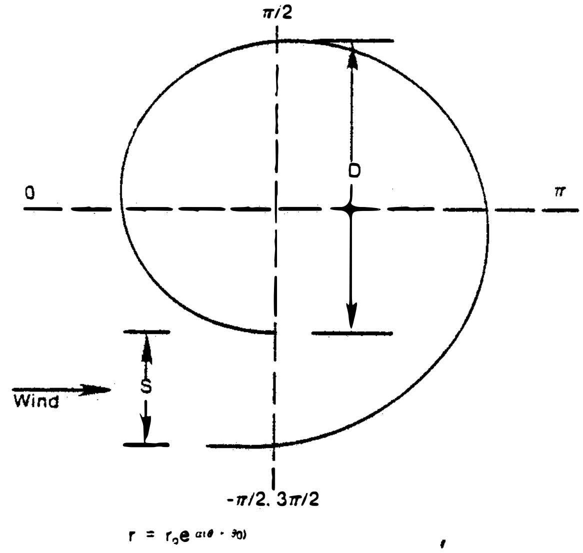

Figure 3. Top View of TWES Spiral Tower Configuration

The Yen Experiments

Extensive research of the TWES has been performed by J.T. Yen of the Grumman Aerospace Corporation [2,3]. The U.S. Federal Wind Energy Program supported two phases of the research during the periods of September 1976 through February 1978 and September 1978 through April 1980. Support has also been provided by the New York State Energy Research and Development Authority (NYS-ERDA). The initial research phase included an experimental study of two small models based upon the unidirectional spiral tower configuration [2]. The spiral shape is given by

$$r = r_o e^{\alpha(\theta + \theta_o)} \qquad (3)$$

where θ is defined as in Figure 3 with $\theta_o = \pi/2$ and, for the Yen spiral tower models, $\alpha = 0.129$. The chosen tower diameters (D) were 12.7 cm (5 in) and 25.4 cm (10 in), corresponding to r_o = 5 cm (2 in) and r_o = 10 cm (4 in), respectively. The total spiral tower cross-sectional area H(D+S) is 1.5HD for the Yen models. A schematic of the experimental setup used by Yen for the spiral tower models is shown in Figure 4. The tests were conducted in the 2.1 m x 3.0 m (7 ft x 10 ft) Grumman Low Speed Wind Tunnel with this setup for both screen-simulated and bladed turbines. Several parameter affecting TWES performance were studied, including tower height-to-diameter ratio (H/D), turbine-to-tower diameter ratio (D_t/D), and system size.

During the second phase of Federally funded research on the TWES by Grumman Aerospace Corp., an omnidirectional fixed multi-vane tower was tested [3]. As with the spiral tower, two small models of the multi-vane configuration, having diameters D = 25.4 cm (10 in) and D = 50.8 cm (20 in), respectively, were wind tunnel tested to ascertain potential TWES performance. Top and side views of the omni-

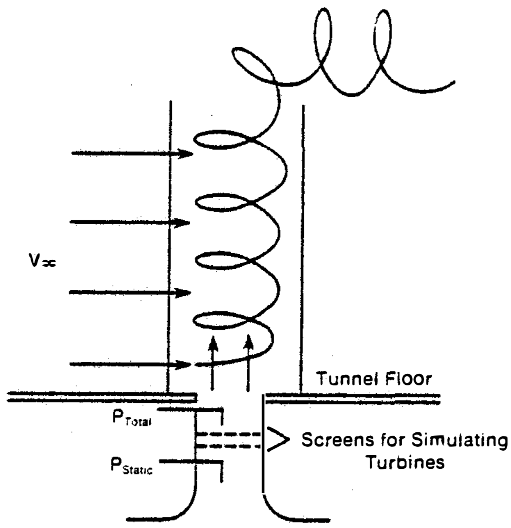

Figure 4. Experimental Setup with Screen-Simulated Turbine, Yen Spiral Tower TWES Model [from Ref. 2]

directional multi-vane tower models are shown in Figures 5 and 6 respectively. The tests were conducted in both the 1.2m x 1.8m (4 ft x 6 ft) Grumman Research and the 4.25m x 7m (14 ft x 23 ft) NASA Langley V/STOL wind tunnel. The parameters investigated during these tests included tower height-to-diameter ratio (H/D), vane angle, and turbine wake-vortex interaction.

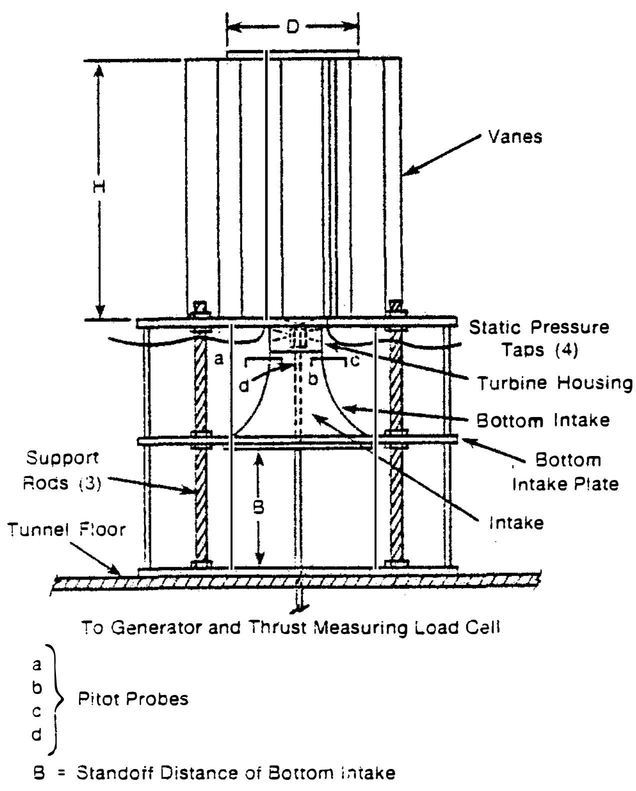

Figure 5. Experimental Setup, Side-View of Yen Multi-Vane TWES Model [from Ref. 3]

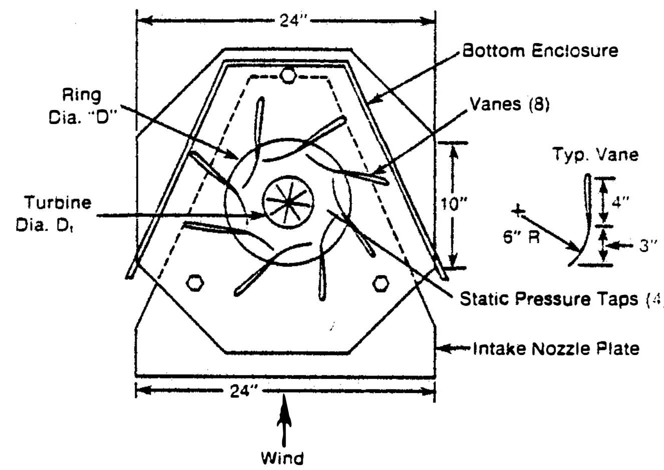

Figure 6. Experimental Setup, Top-View of Yen Multi-vane TWES Model [from Ref. 3]

Note that the turbine intake for both sets of multi-vane tower tests consisted of a ram air inlet, referred to as the bottom enclosure in Figure 6, with a cross-sectional area at least as large as the tower cross-sectional area. In many cases the ram air intake was significantly larger than the TWES model tower, being at least 0.155m^2 (1.67 ft^2) for the Grumman wind tunnel tests and 0.34m^2 (3.6 ft^2) for the Langley V/STOL wind tunnel tests. The models ranged in cross-sectional area from 0.13 to 0.77m^2 (1.4 to 8.3 ft^2) with the peak power coefficients being found with a tower cross-sectional of 0.13m^2 (1.4 ft^2). Thus a reduction by at least 50% of the peak power coefficients reported by Yen for the multi-vane tower configuration appears to be warranted. Although this reduction has not been incorporated in the results reported by the present paper, it should be considered when gauging the potential of the TWES as a WECS. Also, note that the size of the ram air intake significantly impacted wind tunnel blockage effects for the Grumman wind tunnel tests. This is apparent in the marked reduction in peak c_p measured at the Langley V/STOL tunnel relative to that at the Grumman wind tunnel, despite the increased size of the ram air intake.

The New York University Study (Miller et al.)

Experimental research on the TWES has been performed by Miller et al. [4] at New York University (NYU) under joint support by the New York State Energy Research and Development Authority (NYSERDA) and the Power Authority of the State of New York (PASNY). The study included the testing and optimization of a 0.61m (2 ft) diameter wind tunnel model and atmospheric testing of a 6.1 m (20 ft) diameter prototype.

TWES models 0.61 m (2 ft) in diameter and 1.22 m (4 ft) in height were tested in the NYU 1.83 m x 2.44 m (6 ft x 8 ft) wind tunnel. Both the spiral and fixed multi-vane configurations shown in Figures 7 and 8, respectively, were employed. However, as can be seen in Figure 7, the turbine was significantly misaligned with the vortex core and most likely was effectively destroying any vortex generated within the tower. Thus, although NYU found the spiral tower performance to be only 18-24% of the multi-vane tower performance, this result is suspect due to injudicious placement of the bellmouth inlet in the spiral tower bottom. This problem did not occur in the testing of the multi-vane configuration.

The atmospheric testing of the 6.1 m (20 ft) diameter multi-

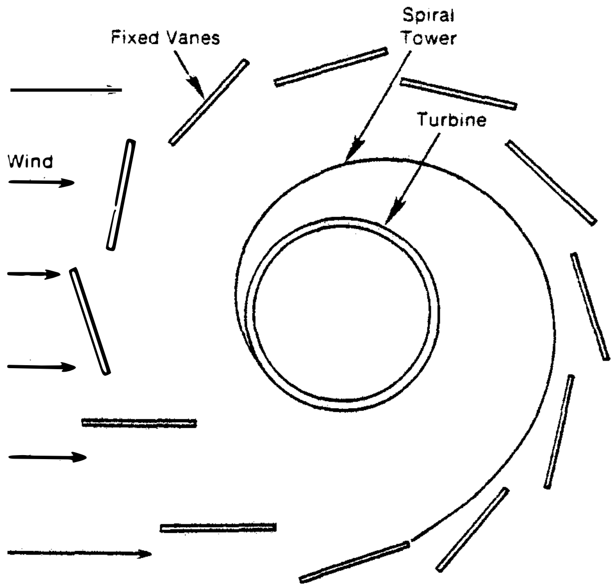

Figure 7. Top View of Spiral Tower Model Tested by NYU [from Ref. 4]

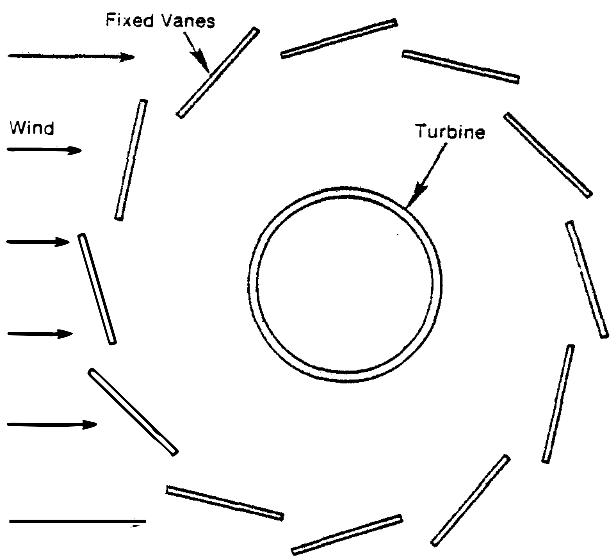

Figure 8. Top View of Fixed Multi-Vane Tower Model Tested by NYU [from Ref. 4]

vane TWES by NYU was intended to confirm the wind tunnel test results. In addition, the effect of increasing system size, i.e., increasing tower diameter at constant height to diameter ratio and turbine to tower diameter ratio, on TWES performance was also investigated. The tests were limited in scope and therefore inconclusive although the results tended to qualitatively support the wind tunnel test results.

The Experiments of Windrich, Henze, and Fricke

An experimental investigation of the TWES has also been undertaken by Windrich, Henze, and Fricke [5]. The TWES model tested utilized a spiral configuration based upon Equation (3) with $\alpha = 0.1$ and $r_0 = 0.1$m (3.94 in), thus providing a tighter spiral than used by Yen. Measurements were made of the tangential velocity distribution, V_θ, the vortex circulation, Γ, and the vortex core diameter, d_c. Available power was deduced from the measurements by

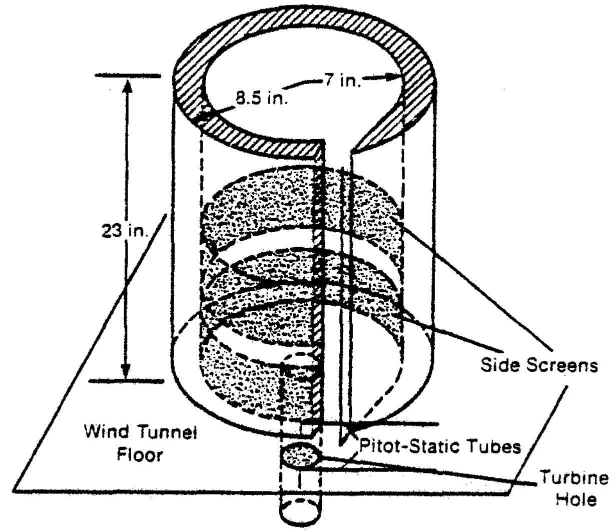

Figure 9. Sketch of a Circular Model [from Ref. 6]

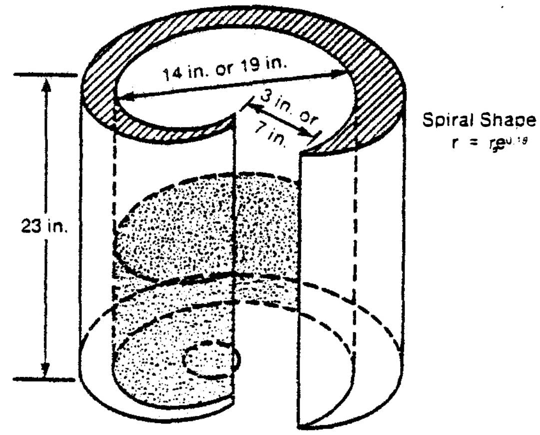

Figure 10. Sketch of a Spiral Model [from Ref. 6]

assuming a rectangular pressure distribution based on the maximum pressure deficit found at the vortex core and a diameter determined from the experiments. Thus, these experiments do not provide a quantitative assessment of TWES potential. However, several tower height to diameter ratios (H/D) between 1.5 and 4.5 were used during the tests, and the relative effects of this parameter on TWES performance are readily ascertained.

The Hsu and Ide Experiments

The experimental study by Hsu and Ide [6], also supported by the U.S. Federal Wind Energy Program, was focused on developing methods for intensifying the vortex generated within the TWES tower. The intensification methods tested included generating a radial inflow through the inner tower wall, partial closing of the tower exist, and increasing the number of turns used for the spiral tower configuration. The spiral tower models were based on the configuration given by Equation (3) with $\alpha = 0.10$ with tower diameters (D) of 0.36m (14 in) and 0.48m (19 in), corresponding to $r_0 = 0.15$m (5.9 in) and $r_0 = 0.2$m (8 in), respectively. Total tower cross-sectional area H(D+S) was 1.33 HD. A circular tower model ($\alpha = 0$) .36m (14 in) in diameter was also tested to more closely simulate the multi-vane tower configuration. Sketches of the models are shown in Figures 9 and 10. The radial inflow was added to the vortex flow through side screens on the inner tower walls as shown in both figures. The inflow was generated by utilizing the dynamic pressure differential between the freestream and the vortex at the inner tower wall.

The models were tested in a 1.22m x 1.22m (4 ft x 4 ft) open cycle low speed wind tunnel at Iowa State University with a maximum attainable wind speed of 7 m/s (15.7 mph). No blockage corrections are included in the reported results. However, blockage effects may have been significant, especially for the interaction between the tunnel flow and the tower exit wake. All of the measurements were made with screen-simulated turbines either 10cm (4 in) or 5cm (2 in) in diameter.

Results of the Experimental Studies

Of primary importance in gauging the potential of the TWES as a wind energy conversion system is determining both the maximum attainable performance and which geometric, operational, and environmental parameters significantly affect the performance of the TWES. The following sections summarize the effects of these parameters and the maximum power coefficients found in the experimental studies of Yen [2,3], Miller et al. [4], Windrich, Henze, and Fricke [5], and Hsu and Ide [6]. Results are presented, and correlated when appropriate, for all three TWES tower configurations tested, i.e., spiral, circular, and multi-vane.

Tower Height-to-Diameter Ratio (H/D)

The experiments by Yen showed that for constant turbine-to-tower diameter ratio (D_t/D), the TWES power coefficient decreases with increasing tower height-to-diameter ratio (H/D) for both the spiral and the multi-vane tower configurations. This relationship was confirmed by Windrich et al. with the spiral tower model, and a similar result was obtained by Miller et al. for the multi-vane tower model. A plot of maximum or peak power coefficient ($c_{p,max}$) versus H/D for $D_t/D = 0.3$ based on the Yen results obtained for the spiral tower model with screen-simulated turbines is shown in Figure 11. These results indicate that c_p is inversely proportional to H/D within the tested range of H/D = 2.1 to H/D = 4.2. The ranges of H/D tested by Yen with the multi-vane tower and by Windrich et al. with the spiral tower were 1 to 6 and 1.5 to 4.5, respectively.

Turbine-to-Tower Diameter Ratio (D_t/D)

The power coefficient (c_p) was found by Yen to increase with increasing turbine-to-tower diameter ratio (D_t/D) for the spiral tower model. A plot of the Yen results for $c_{p,max}$ as a function of D_t/D with H/D = 2.1 and screen-simulated turbines is shown in Figure 12. Based on these results, $c_{p,max}$ is proportional to D_t/D within the tested range of $D_t/D = 0.1$ to $D_t/D = 0.3$. Measurements made by Yen with a bladed turbine showed a similar effect with D_t/D varied from 0.2 to 0.4. Tests of the circular tower model by Hsu and Ide corroborated this result as c_p was found to be higher for $D_t/D = 0.21$ than for $D_t/D = 0.105$. The increase in c_p with increasing D_t/D indicates that the vortex core diameters exceeded the turbine diameters for both sets of experiments.

System Size

Both Yen and Hsu and Ide achieved an improvement in spiral tower performance by increasing the model size while keeping H/D and D_t/D constant. For $D_t/D = 0.3$ and H/D = 2.1, Yen obtained an increase in $c_{p,max}$ of 82% from 0.033 to 0.06 using the spiral tower model with screen-simulated turbines. However, both the Yen and the Hsu and Ide tests were limited to only two different tower sizes and therefore cannot be extrapolated to the tower sizes necessary for full scale TWES. Furthermore, the small sizes of the models

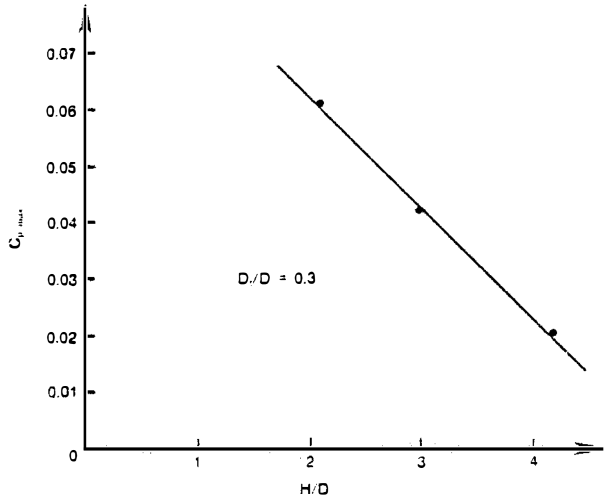

Figure 11. Variation of $C_{p,max}$ with Tower Height to Diameter Ratio (H/D) Based on Yen Experiments [2]

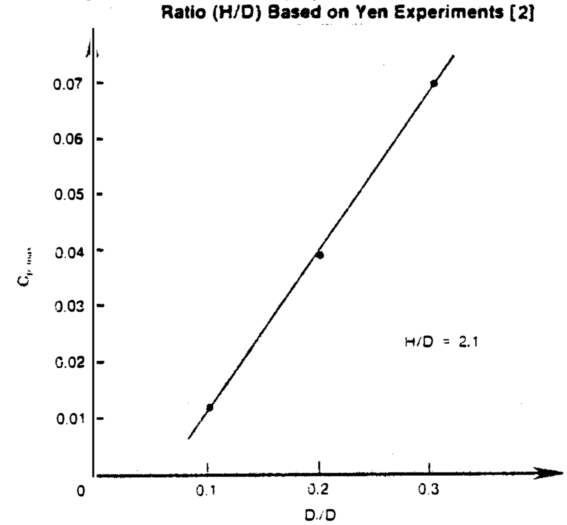

Figure 12. Variation of $C_{p,max}$ with Turbine to Tower Diameter Ratio (D_t/D) Based on Yen Experiments [2]

tested provided Reynolds numbers limited to the laminar and transition ranges which also precludes extrapolation to full scale TWES in the turbulent range. For the multi-vane tower configuration, Miller et al. found no significant performance improvement between the 0.61 m (2 ft) diameter wind tunnel model and the 6.1 m (20 ft) prototype, although wind shear effects on the prototype due to the atmospheric boundary layer may have mitigated any size effects between the two measurements. Thus these results do not provide conclusive proof regarding any beneficial size effects on TWES performance.

Turbine Wake-Vortex Interaction

For both the spiral and multi-vane tower configurations, the Yen results indicate that the turbine wake can adversely affect vortex strength and available vortex power. For the spiral tower model with the bladed turbine, the maximum power coefficient found by Yen was 0.18 for $D_t/D = 0.4$ and H/D = 2.1. However, the c_p values were based upon approximate measurements of apparent available vortex power and the maximum c_p based upon turbine shaft power output was 0.045 or 4.5%. Because the turbine was extremely crude and inefficient, operating at a deduced efficiency of 25% for peak c_p conditions, the turbine wake contained significant angular momentum coincident with the circulation of the vortex. Thus the potentially adverse effects of axial turbine wake flow may have been mitigated by a rotational component in the wake. In comparison, the maximum power coefficient, based on available vortex power, measured by Yen for the spiral tower model with screen simulated turbines providing axial wake flow, was 0.06 for $D_t/D = 0.3$ and $H/D = 2.1$.

For the multi-vane tower model with a bladed turbine, Yen found that power coefficients obtained with coincident wake and vortex rotation exceeded by more than 25% those obtained with opposite wake and vortex rotation. Also note that both the Yen multi-vane tower tests and the Hsu and Ide tests obtained generally decreasing power coefficients with increasing freestream wind velocity (V_∞). An explanation for this result could be increasingly destructive effects of a fixed diameter turbine wake on increasingly smaller diameter vortex cores produced by the higher freestream wind velocities.

Thus any turbine wake component other than rotation coincident with the vortex circulation apparently has an adverse effect on power available to the turbine. This result is important as high efficiency turbines characteristically have axial wake flows and thus high efficiency and low efficiency turbines may provide essentially equivalent power coefficients based on turbine shaft power output.

Partial Closure of the Tower Exit

Hsu and Ide obtained a significant increase in c_p by partially closing the exit of the spiral TWES tower. This presumably further confined and stabilized the vortex. As shown in Figure 13, for the 0.36 m (14 in) diameter spiral tower model, c_p was maximized by limiting the exit opening to 0.6D.

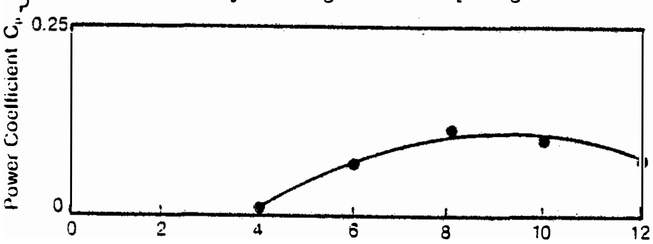

Figure 13. Power Efficiency vs. Top Hole Opening Size for the 0.36 m (14 in) in Diameter Spiral Model with No Radial Inflow Supply [from Ref. 6]

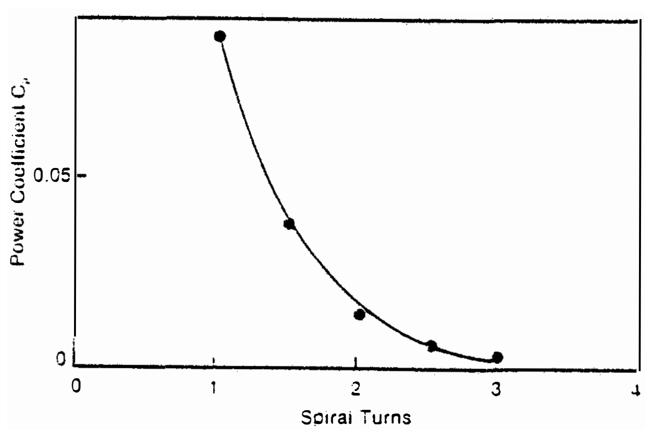

Figure 14. Power Efficiency vs. Spiral Turns for the 0.36 m (14 in) in Inner Diameter Spiral Model with No Radial Inflow Supply [from Ref. 6]

The corresponding increase in c_p exceeded 50%. All subsequent tests of the spiral tower model by Hsu and Ide incorporated this finding. For the 0.48 m (19 in) spiral tower model, Hsu and Ide chose to close off exit flow from the inlet region of the tower.

Number of Spiral Tower Turns

Hsu and Ide also attempted to increase c_p by increasing the number of turns for the spiral tower model. However, as can be seen in Figure 14, adding turns to the model adversely affected c_p, with the maximum c_p found with two turns being only ~15% of that found with one turn. These low c_p were apparently due to increased friction losses and flow separation. Based on this finding, the optimum number of turns for the spiral tower configuration is approximately one.

Radial Inflow/Vortex Intensification

Hsu and Ide found that performance can be enhanced by a radial inflow through screens on the inner wall of the TWES as shown in Figures 9 and 10. The vortex intensifying inflow was generated by the dynamic pressure head between the freestream and the vortex at the inner tower wall. For the circular tower model maximum c_p was increased approximately 80% by adding the radial inflow to the bottom third of the tower. For the spiral tower models, the increase was only 15 to 30% with an optimum side screen height of 0.1H. The lower increase found with the spiral configuration would be expected as the spiral shape naturally induces radial inflow due to decreasing radius of curvature and thus addition of artificially induced radial inflow is less effective.

Vane Angle

The Yen multi-vane tower models utilized 0.1m (4 in) inflexible, uncambered, symmetrical vanes with 0.08m (3 in) flexible extension flaps for a total vane width of 0.18m (7 in). Similarly, the vanes employed by Miller et al. in the NYU study were inflexible. uncambered louvers up to 0.18m (7 in) in width. Vane angle for both studies was defined as the angle be the straight section and the tangent of the tower circumference. Best performance results were obtained by Yen for small vane angles (~30°) with concave inward flaps and for large vane angles (~65°) with concave outward flaps, with the large vane angle performance being slightly greater. Miller et al. found optimum performance at the small vane angle of approximately 20° and no optimum for the large vane angles. The differences between the Yen and Miller et al. results are most probably due to the flexible extension flaps added to the Yen models.

The Chimney Effect

During testing of the multi-vane tower by Miller et al., the tower was wrapped to measure the contribution of the chimney effect on TWES performance. The chimney effect is an upward flow through the tower generated by the viscous airflow across the top of the tower. Miller et al. found that a wrapped multi-vane tower utilizing the chimney effect provided a power output nearly equivalent to that of the multi-vane TWES tower with optimum vane angle. The chimney effect pressure drop, nearly constant across the tower bottom, was approximately equal to the maximum pressure drop found in the vortex core of the unwrapped tower. Thus for the multi-vane tower configuration, the vortex flow may only minimally augment the power provided by the chimney effect.

Maximum Power Coefficients

The maximum or peak power coefficients, determined experimentally by Yen [2,3], Miller et al. [4], and Hsu and Ide [6] for the various tower configurations, are shown in

	tower shape	turbine	radial inflow	D(m)	H/D	D_t/D	$c_{p,max}$[1]	$c_{p,max}$[2]
Yen	spiral	screens	no	0.25	2.1	0.30	0.06	0.04
Yen	spiral	bladed	no	0.25	2.1	0.40	0.18	0.12
Hsu and Ide	circular	screens	no	0.36	1.6	0.29	0.08	—
Hsu and Ide	circular	screens	yes	0.36	1.6	0.29	0.15	—
Hsu and Ide	spiral	screens	no	0.48	1.2	0.21	0.22	0.16
Hsu and Ide	spiral	screens	yes	0.48	1.2	0.21	0.26	0.19
Yen[3]	multi-vane	bladed	no	0.25	2.0	0.40	0.11	—
Yen[4]	multi-vane	bladed	no	0.61	2.0	0.33	0.08	—
Miller et al.	multi-vane	bladed	no	0.25	2.0	0.40	0.027	—

Table 1. Maximum TWES Power Coefficients-Experimental Results of Yen [2,3], Miller et al. [4], and Hsu and Ide [6]

Table 1. The peak values based on both the tower areas HD and H(D+S) are presented for the spiral tower. The Yen results for the multi-vane tower are derived from the maximum average Δp measured across the turbine. The tower and turbine dimensions for which each $c_{p,max}$ was found are also shown in Table 1.

The discrepancies between the respective tests of each tower configuration are largely attributable to differences in model geometries. Specifically the Hsu and Ide spiral tower models incorporated partial exit closure and smaller H/D and D_t/D ratios than those of Yen. Similarly, the Yen multi-vane tower results should be reduced to reflect the use of ram air inlets exceeding the tower cross-sectional areas. These differences, as well as potential size and wind tunnel blockage effects, need to be factored into any comparisons of the results. When done so the maximum power coefficients compare favorably for each of the TWES tower configurations.

The results presented in Table 1 demonstrate the marked reduction in the power coefficients found with the multi-vane TWES models, indicating that use of an omnidirectional tower design may incur a significant performance penalty relative to unidirectional designs such as the spiral configuration. However, an omnidirectional tower design would be necessary to permit use of winds from all directions.

THEORETICAL ANALYSES OF THE TWES

Several theoretical studies have attempted to analyze the performance attainable by the Tornado Wind Energy System. These include the numerical analysis by Ayad [7,8] and the mathematical solutions derived by Yen [2], Miller et al. [4], Windrich et al. [5], Hsu and Ide [6], Loth [9,10], Hsu et al. [11], So [12] as improved by Johnston and Eaton [13], Chen [14], and Rangwalla and Hsu [15]. Although many lack sufficient experimental verification, some quantitative and many qualitative results can be obtained from these analytical models.

Numerical Analysis of the TWES

The numerical analysis of Ayad [7,8] employed the unidirectional spiral tower configuration on the assumption that it would provide an upper limit to the potential performance of the omnidirectional multi-vane TWES tower. The initial effort by Ayad was to establish the validity of the numerical model relative to experimental data. Comparisons with the data of Yen [2], as shown in Figures 15 and 16, indicated that the model is adequate for predicting mean flow values and performance for TWES. The ensuing study by Ayad analyzed the effects of several geometric and environmental parameters on TWES performance. A uniform axial turbine flow was assumed to enable calculation of power coefficients (c_p). The results of the Ayad study of the TWES are summarized below.

Tower Height-to-Diameter Ratio (H/D)

In agreement with the experimental results of Yen [2,3], Miller et al. [4], and Windrich et al. [5], Ayad determined that increasing H/D adversely affects TWES performance. As

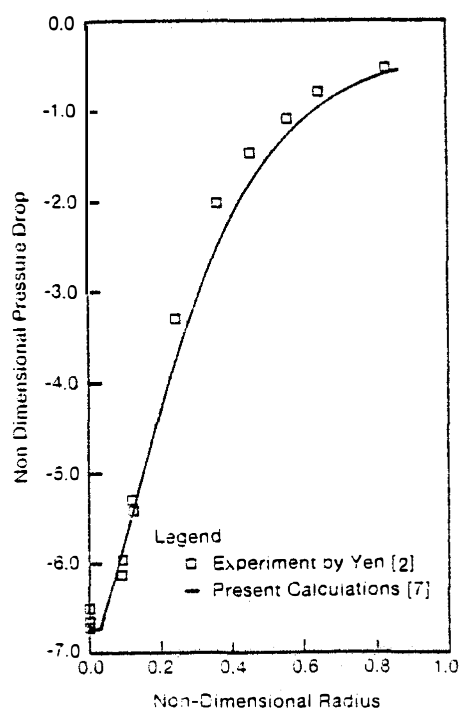

Figure 15. Radial Distributions of Pressure Drop at the Bottom of the Closed Bottom Tower, Values Normalized by 1/2 (ρV_∞^2) [from Ref. 7]

[1] based on tower frontal area HD

[2] based on total spiral tower frontal area H(D+S)

[3] Grumman wind tunnel results

[4] Langley V/STOL wind tunnel results

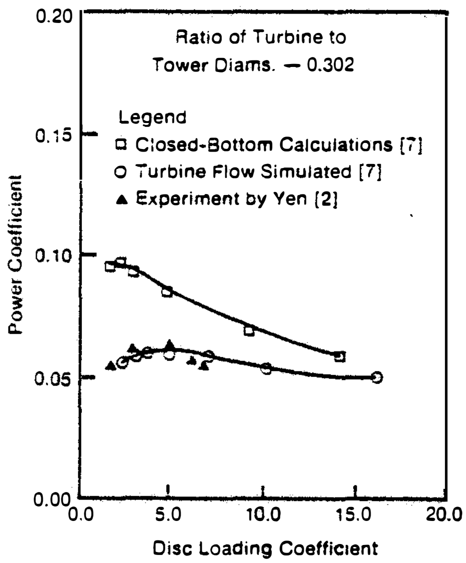

Figure 16. Comparison Between Power Coefficient Obtained for Closed Bottom Tower, Tower with Simulated Turbine Flow and Experiment by Yen [from Ref. 7]

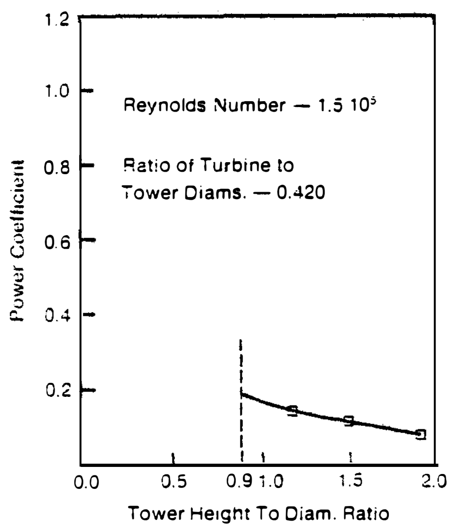

Figure 17. Variation of Power Coefficient with Tower Height-to-Diameter Ratio [from Ref. 8]

shown in Figure 17. c_p was found to be inversely proportional to H/D for the H/D range of 1 to 1.9. Yen [2] obtained the same result with the spiral tower for H/D > 2.1. Because TWES vortex decay would be assymetric, an H/D of 0.9 was estimated by Ayad to be the lower limit of validity for the symmetric model and a minimum H/D of 1.0 was recommended for the TWES.

<u>Turbine-to-Tower Diameter Ratio (D_t/D) and Turbine Wake-Vortex Interaction</u>

Ayad found that the variation of TWES performance as a function of D_t/D was closely related to the effects of turbine wake-vortex interaction. As can be seen in Figure 18, c_p based on the closed bottom vortex pressure distribution was found to continuously increase for $D_t/D < 0.3$. However, the

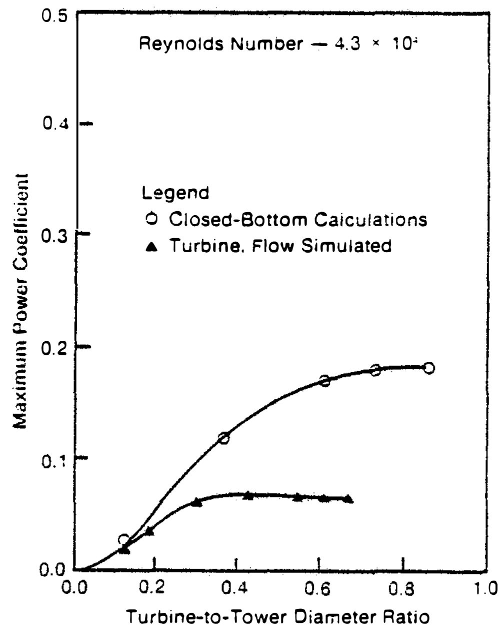

Figure 18. Comparison of Maximum Power Coefficients for a Simulated Turbine Flow and a Closed-Bottom Tower [from Ref. 7]

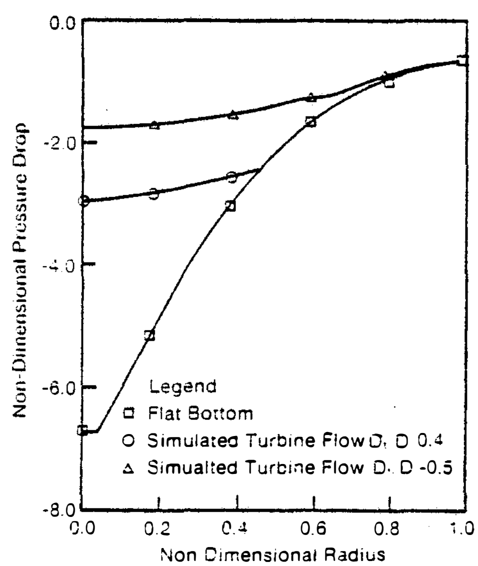

Figure 19. Comparison of the Radial Distribution of Pressure Drop in the Tower for the Case of a Closed Bottom Tower and Those with a Simulated Turbine Flow (values normalized by $1/2\ V_\infty^2$) [from Ref. 7]

results indicate that with simulated turbine flow, a maximum c_p occurs at a D_t/D of ~0.4 for the assumed tower inlet and turbine flow condition. The losses in c_p relative to the closed bottom calculations are an effect of the turbine wake-vortex interaction. The turbine wake flow adversely affects vortex strength causing a severely diminished pressure drop in the vortex core as shown in Figure 19. Note that the increase in c_p with increasing D_t/D for $D_t/D < 0.4$ and the adverse

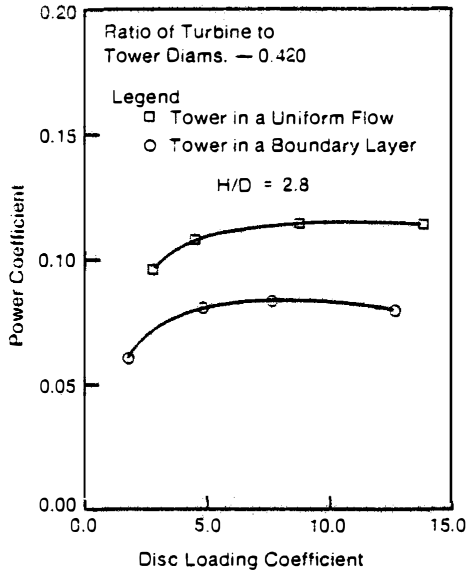

Figure 20. Effect of Atmospheric Boundary Layer on the Power Coefficient [from Ref. 8]

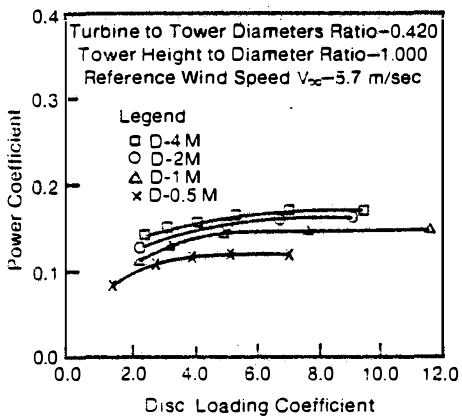

Figure 21. Effect of Systems Size on the Performance of Tornado-Type Wind Energy Systems [from Ref. 8]

effects of turbine wake-vortex interaction were demonstrated experimentally by Yen [2,3]. Hsu and Ide [6] also experimentally verified increasing c_p with increasing D_t/D, albeit for $D_t/D < 0.21$.

Atmospheric Boundary Layer Effects

The experimental results obtained to date for the TWES have been generated in wind tunnels with uniform flow. Ayad analyzed the potential effects of wind shear, such as found in the atmospheric boundary layer, on TWES performance. Assuming a one-seventh power law boundary layer with the freestream wind velocity at the tower top equivalent to the uniform freestream wind velocity, Ayad calculated reductions in power of up to 28% in comparing the boundary layer results to those with uniform flow. These results are shown in Figure 20 and indicate that the strength of the vortex within the bottom region of the tower significantly affects TWES performance. This finding is corroborated by the experiments of Hsu and Ide [6] in which the radial inflow added near the tower bottom was found to be most effective. Yen [2] also discovered considerable boundary layer effects during testing of the spiral tower model.

Size Effects

Results obtained by Ayad indicate that with H/D and D_t/D held constant, the performance of small spiral TWES improves with increasing system size for D< 8m (26.2 ft). However, as shown in Figure 21 the rate of increase diminishes as D approaches the 8m limit. While increasing tower diameter from 0.5m (1.64 ft) to 1.0m (3.28 ft) improves performance by ~23%, increases from 2m (6.6 ft) to 4m (13.1 ft) and from 4m (13.1 ft) to 8m (26.2 ft) only increase performance by 5% and 1%, respectively. Thus, for the spiral tower configuration, power coefficients would apparently be independent of system size for tower diameters in excess of 8m (26.2 ft).

Maximum Power Coefficient

Based on a synthesis of the Ayad results, the predicted maximum power coefficient, $c_{p,max}$, for the TWES would be approximately 0.20 for H/D = 1 and D_t/D = 0.4. Note that the Ayad analysis did not include either partial closing of the tower exit or addition of radial inflow through an inner tower wall, both of which might increase this prediction.

Mathematical Derivations of TWES Performance

The mathematical solutions for TWES performance derived by Yen [2], Miller et al. [4], Windrich et al. [5], Hsu and Ide [6], Loth [9,10], Hsu et al. [11], So [12], Johnston and Eaton [13], Chen [14], and Rangwalla and Hsu [15] are all dependent on several underlying assumptions, idealizations, and/or approximations. These include assumed tower inlet velocity profiles, laminar and/or radially unbounded vortex flow, and assumed vortex velocity profiles. Also the turbine wake-vortex interaction is generally neglected as insignificant or insolvable. Many of these idealizations and assumptions, as well as insufficient experimental verification, severely limit the validity of TWES performance predictions obtained from these analytical models. However, several conclusions regarding TWES performance can be correlated between model results.

Tower Height-to-Diameter Ratio (H/D)

As with the previously discussed experimental and numerical studies of the TWES, the inverse relationship between c_p and H/D, i.e., decreasing c_p with increasing H/D, was again demonstrated by the models which incorporated analysis of this parameter.

Turbine-to-Tower Diameter Ratio (D_t/D)

The analysis of Miller et al. for the multi-vane tower obtained an optimum D_t/D of 0.336. This is close to the results obtained for the spiral configuration. The Miller et al. experiments employed a D_t/D of 0.33 [4].

Vane Angle

The theoretical model developed by Miller et al. also analyzed the effects of varying vane angle for the multi-vane tower. The derivation included the assumption of simultaneous creation, confinement, and concentration of the vortex within the tower. The maximum power coefficient was found to be ~0.20 for a vane or louver angle of 45.5°. However, the experimental work by Miller et al. found simultaneous confinement and concentration infeasible with insufficient confinement at 45.5°. For the experimentally determined optimum of 20°, the Miller et al. model predicted a peak power coefficient of ~0.045 which compares favorably with the experimental result of 0.027.

Vortex Intensification

Several of the analytical models predict increased performance by intensification or strengthening of the vortex, thereby reducing the vortex core diameter. These predictions range up to a cubic increase in power coefficient with decreasing vortex core diameter. Vortex intensification was achieved experimentally by Hsu and Ide [6] with both the circular and the spiral tower configurations by adding radial inflow through an inner tower wall. However, an increase in the number of turns employed by the spiral tower had the opposite effect of weakening the vortex.

COST ANALYSIS OF THE TWES

An approximate but very simple cost analysis of the TWES can be based upon the research results detailed in the previous sections. Here the analysis will employ the multi-vane tower configuration and use the performance and cost characteristics of the MOD-2 2.5 MW horizontal axis wind turbine as a baseline for comparison [16]. Use of the MOD-2 characteristics graphically contrasts the potential of the TWES for cost effective wind energy conversion.

From a synthesis of the research performed on the TWES, a peak system power coefficient of 0.10 appears to be a reasonable expectation of potential TWES performance suitable for estimating a cost of energy. Optimistically a peak system c_p of 0.20 might be attainable. In comparison the MOD-2 has a peak system c_p of 0.375 [16]. The MOD-2 and approximate TWES dimensions are shown in Table 2 with the TWES geometry based on H/D=1 and D_t/D=0.35. The effects of wind shear, due to differing mean tower heights, are incorporated in the TWES dimensions shown. Also included in the table are estimates of the total surface area of the vanes comprising the tower. As the vanes would presumably be hollow (or double-walled) and overlapping, the total surface area is assumed to be approximately twice that of a cylinder of equivalent height and diameter, i.e., $2 \times \pi HD$. This surface area is used to estimate the construction cost of the tower. Note that due to the required vane overlap the actual surface area of a multi-vane TWES tower may be significantly higher.

Construction of a TWES tower would be similar to that of a large natural draft cooling tower. The least expensive construction technique would likely be slip-formed concrete fabrication. However, due to the large size of a 2.5 MW TWES, a uniform cross-section, necessary for slip-forming, may not be feasible, and the slower more expensive technique of jump-forming, such as used for the cooling towers, may be required. All cost estimates presented below are based on slip-forming a concrete tower for the TWES. The original cost estimate by Yen [2] for a concrete tower was $0.91/m² ($3/ft²) of tower surface area. Two sources who have been involved in the design and construction of large natural draft cooling towers were contacted to corroborate this estimate [17,18]. Written communication from these sources provided the following:

> "I consider slip-formed concrete as a most appropriate construction technique for your application. It lends itself in particular to tall structures with a uniform cross section such as the fixed vertical airfoil towers. Full circle structural elements can be accommodated easily by proper design of the moving forms and a start/stop placing technique to provide a monolithic and high strength structure. The airfoil sections might even be slipped as hollow members. An 8" wall is probably near the lower limit of acceptable thickness, but it would probably depend on the redundancy of the structural system. Sections as thin as 6" have been slipped. $3/ft² seems low by a factor of perhaps 10 for 1979 costs of construction. Again, this depends on the final structural design and the height. Slip forming, being an extrusion process, becomes cheaper with height and consequent amortization of form fabrication costs over volume extruded. Permanent (metal) forms may also be reusable and thus further decrease costs." [17]

> "It would seem, by preliminary inspection of the sketches and model photos, that the airfoil sections could be slipped as hollow members. This technique could provide a basis for determining a very preliminary budget estimate opinion, and would require structural engineering verification as to vane wall thickness and reinforcing steel requirements. Twenty to thirty dollars per square foot for the sum of the vane surface area would provide an approximate budget estimate of the structure cost." [18]

Thus a conservative estimate of TWES tower construction costs would appear to be $9.15/m² ($30/ft²) in 1979 dollars. Cost estimates for the TWES tower are shown in Table 2 for peak system power coefficients of 0.05, 0.10, and 0.20. The estimated mature product (100th unit) turnkey cost of the MOD-2 updated to 1979 dollars, is shown for comparison [16]. Cost of energy (COE) for each system can be estimated by using the equation:

$$\text{COE} = \frac{(\text{Capital Cost})(\text{Fixed Charge Rate})}{\text{Annual Energy Output}} \quad (4)$$

	TWES			MOD-2
$c_{p,max}$	0.05	0.10	0.20	0.375
P_R	2.5 MW	2.5 MW	2.5 MW	2.5 MW
H/D	1	1	1	-
D_t/D	0.35	0.35	0.35	-
A	43,000 m^2 (467,000 ft^2)	24,500 m^2 (264,000 ft^2)	12,800 m^2 (138,000 ft^2)	6,570 m^2 (70,700 ft^2)
H	208.2m (683 ft)	156.5m (513 ft)	113.3m (372 ft)	-
D	208.2m (683 ft)	156.5m (513 ft)	113.3m (372 ft)	-
D_t	72.9m (239 ft)	54.3m (180 ft)	39.6m (130 ft)	91.5m (300 ft)
mean (hub) height	104.1m (342 ft)	78.3m (257 ft)	56.6m (186 ft)	61m (200 ft)
A_s	272,000 m^2 (2,930,000 ft^2)	154,000 m^2 (1,360,000 ft^2)	80,600 m^2 867,000 ft^2)	-

Table 2. TWES Dimensions (for $c_{p,max}$ = 0.05, 0.10, and 0.20) Compared to MOD-2 Dimensions

	TWES			MOD-2
$c_{p,max}$	0.05	0.10	0.20	0.375
P_R	2.5 MW	2.5 MW	2.5 MW	2.5 MW
annual energy output (kWh)	9,750,000	9,750,000	9,750,000	9,750,000
capital cost	$87,900,000	$49,700,000	$26,000,000	$2,000,000
cost of energy (COE)	$1.62/kWh	$0.91/kWh	$0.48/kWh	$0.04/kWh

Table 3. Comparison Between TWES Tower and MOD-2 Cost Estimates (1979 Dollars)

Assuming a fixed charge rate of 18% and an annual energy output for both systems of 0.445 x 2500 kW x 8760 hours = 9,750,000 kWh. The 0.445 or 44.5% apacity factor is predicted for the MOD-2 in a 6.3 m/s (14 mph) site [16] and shown in Table 3, the estimated COE in 1979 dollars for the TWES, based upon the tower cost only, would be $1.62 per kWh for $c_{p,max} = 0.05$, $0.91 per kWh for $c_{p,max} = 0.10$, and 0.48/kWh for $c_{p,max} = 0.20$. Note that these COE reflect tower costs only. These estimates compare very unfavorably with the estimated COE for the MOD-2 in 1979 dollars of $0.04 [14]. The COE of a TWES would apparently exceed that of a MOD-2 by more than one order of magnitude. This result is corroborated by Kornreich, Kottler, and Jennings [19] when compared under equivalent performance assumptions.

The tower cost would be the cost driver in a TWES installation. The balance of system costs would approximate those of the MOD-2 without the tower support. Although the smaller rotor would reduce the required gearing ratio and, to a lesser extent, the gearing costs, the rotor would presumably be a cross between a many bladed gas turbine and a wind turbine and therefore would be more expensive on a $/unit swept area basis. Yen [2] estimates the per unit swept area cost of the TWES rotor to be an order of magnitude greater than that of a 1 MW wind turbine. The generator should cost approximately the same as an equivalently sized generator for a conventional wind turbine. Thus, the balance of system costs could apparently be limited to 5 to 10% of the tower cost and would therefore have a much lesser impact on COE. Again this result is corroborated by Kornreich, Kottler, and Jennings [19].

SUMMARY AND CONCLUSIONS

Over the past few years an extensive body of knowledge has been developed on the potential of the Tornado Wind Energy System for cost effective wind energy conversion. Research and development has progressed to the point where several conclusions can be formulated including:

- o The TWES apparently suffers severe physical limitations precluding performance at cost competitive power coefficients. Prospects for attaining power coefficients significantly above 0.20 with practical tower designs are not promising. A power coefficient approaching 2.0 would be needed to be cost competitive.
- o Given the performance levels demonstrated to date the cost of energy (COE) for a TWES would exceed that estimated for the MOD-2 by more than one order of magnitude. Prospects for achieving a TWES COE significantly less than $0.50/kWh (1979 dollars) also are not promising.
- o The Tornado Wind Energy System does not show any substantial promise of improving on either the performance or cost of energy attainable by a conventional horizontal or vertical axis wind turbine.

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