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PRELIMINARY TECHNICAL AND ECONOMIC EVALUATION OF VORTEX
EXTRACTION DEVICES

Summary Report

By
T. R. Kornreich
R. J. Kottler, Jr.
D. M. Jennings

April 1980

Work Performed Under Contract No. AC02-77CH00178

JBF Scientific Corporation
Arlington, Virginia

U.S. Department of Energy

Solar Energy

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A Division of Midwest Research Institute
1536 Cole Boulevard
Golden, Colorado 80401

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FOREWORD

The Solar Energy Research Institute (SERI) has been authorized by the U.S. Department of Energy to provide technical management services for the Wind Energy Innovative Systems (WEIS) program. The major focus of the WEIS program is to assess the technical and economic feasibility of innovative concepts and systems. Since a large number of these concepts may have potential merit, a critical examination of their technical and economic attributes will provide guidance and direction for future WEIS programmatic efforts.

This report summarizes a critical evaluation of two vortex extraction devices (the Tornado Wind Energy System and the Vortex Augmentor Concept) which are currently being funded by DOE.

A companion report, SERI/TR-8003-1, contains the full and detailed results of the evaluation.

COMMENT

During FY79, studies were performed by subcontractors to assess the performance and cost potential of ongoing R&D efforts in the Wind Energy Innovative Systems program. To provide a baseline for the comparison of the different studies, specifications were provided for the calculation of the cost of energy, useful service life, wind environment and maximum design wind speed.

Innovative wind systems may have operating characteristics which are different from conventional wind systems. Optimum performance and minimum cost of energy may be sensitive to wind environment and wind loads. Future assessment studies will consider the effects of these conditions on the potential of the innovative system.

Irwin E. Vas
Manager
Wind Energy Innovative
Systems Projects

PREFACE

The technical staff personnel of the JBF Scientific Corporation who participated in this study were Dr. Theodore R. Kornreich (Principal Investigator), Richard J. Kottler, Jr., and Diana M. Jennings.

Dr. T.G. Toridis and Dr. K. Khozeimeh, Professors of Civil Engineering at the George Washington University, supported by Mr. S. Mehrkar, performed structural analyses of the Tornado Wind Energy System configurations. Dr. Daniel Schiff also served as a consultant on this project.

James T. Yen of the Grumman Aerospace Corporation and P.M. Sforza of the Polytechnic Institute of New York were very gracious in supplying information required for analyzing the Tornado Wind Energy System and the Vortex Augmentor Concept.

Dr. Irwin Vas and the Wind Energy Innovative Systems program staff have been both helpful and supportive of our efforts to complete this study.

In addition, many vendors and material suppliers (cited throughout the report) willingly supplied current price quotations so that the most up-to-date economic analysis could be carried out.

The JBF staff would like to express their sincere appreciation to all of these people whose outstanding cooperation enabled this study to be performed within the specified time period.

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SECTION 1.0

INTRODUCTION AND ANALYSIS APPROACH

1.1 INTRODUCTION

Two innovative vortex extraction devices--The Tornado Wind Energy System (TWES) and the Vortex Augmentor Concept (VAC)--were evaluated to determine their technical and economic viability as compared to conventional horizontal axis wind energy systems. A principle advantage of these concepts is their ability to produce more power than a conventional wind turbine with the same rotor diameter, referred to as augmentation. Since the rotor subsystem is one of the major cost drivers in a conventional horizontal axis wind system, the TWES and VAC offer potential for successfully competing on a cost basis with comparable conventional wind systems. However, the unconventional designs of the TWES and VAC bring with them technical and economic uncertainties which must also be carefully evaluated in order to gauge system potential.

The basis for economic comparison used in this study is the energy cost that could be achieved by "mature product" versions of the TWES, and comparable conventional wind systems. This comparison is carried out over a range of power output and augmentation levels in order to facilitate understanding of the viability of the TWES and VAC. However, conclusions contained here must be tempered by the fact that firm designs have not yet been developed and experimental data are available only from small-scale model testing of the TWES and VAC.

1.2 ANALYSIS APPROACH

The approach used in the economic analysis is shown in Figure 1. A baseline case was established as the point of reference for each device. These two baseline cases included selection of both a nominal rated power level and an augmentation ratio which was representative of experimental data and other supporting evidence. In addition, a spectrum of cases involving smaller and larger power ratings and larger augmentation ratios were also evaluated. Table 1 defines the baseline case conditions for the TWES and the VAC as well as the conventional wind systems with which they were compared.

Required TWES and VAC subsystems were identified and sized for these baseline cases. Since each of these innovative concepts is a very early stage in its design phase, firm design data were not readily available. Therefore, on the basis of information supplied by the TWES and VAC principal investigators, a number of design assumptions were made in order to conduct the analysis.

Figure 1. Economic Analysis Approach

Table 1

TWES AND VAC BASELINE CASES

	<u>TWES</u>	<u>VAC</u>
<u>Baseline</u>		
Rated Power (kW)	1000	200
Augmentation Ratio ^a	4.5	6
Conventional Wind System Counterpart	MOD-2	MOD-OA

^aAugmentation ratio is defined as the ratio of the power extracted by an augmented rotor and the power extracted by an unaugmented rotor of the same diameter.

Table 2 displays the additional cases considered in the analysis. Higher augmentation ratios were selected based on optimistic performance claims of the TWES and VAC principal investigators, and have been normalized to the same conventional system power coefficient.

For each case, the mature product hardware cost for TWES and VAC subsystems was obtained by direct price quotations from vendors or by computing materials cost and scaling to a total fabricated subsystem cost. The total hardware cost was obtained by summing all of the fabricated subsystem costs.

Product non-hardware costs (associated with site preparation, system assembly, installation and checkout, transportation, general and administrative expenses, contractors' fees, etc.) were estimated to be a fixed percentage of the hardware costs. The sum of hardware and non-hardware costs provided the total installed cost of the TWES and VAC.

A power output vs. wind speed curve was developed for each case evaluated. The combination of this power output profile and the wind duration profile, specified by SERI for use in this study, enabled the total annual energy output to be calculated. A 90% availability factor was used for all systems to allow for planned and forced outages. The energy cost for each TWES and VAC case was determined using the standard equation for computing the levelized busbar cost of electricity generation.

The energy costs for the TWES and VAC were then compared to the costs for comparably-sized, "mature product" horizontal-axis systems in the same wind regime. This comparison enabled conclusions to be drawn concerning the potential economic viability of the TWES and the VAC across a spectrum of size and performance levels.

Table 2

SPECTRUM OF CASES CONSIDERED

Augmen- tation Ratio	Rated Power	<u>TWES</u>						<u>VAC</u>		
		0.2MW	0.6MW	1MW	3MW	4MW	12MW	40kW	200kW	1MW
4.5		X		X		X				
6								X	X	X
13.5			X		X		X			
16								X	X	X

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SECTION 2.0

THE TORNADO WIND ENERGY SYSTEM (TWES)

The TWES concept involves the creation of a confined, tornado-like vortex within a stationary tower through injection of ambient wind flow. The proposed tower design has fixed vanes, no moving parts and will admit a wind flow from any direction. The tower is expected to be placed on a base structure which diverges downward from the rotor to the ground plane. This structure houses several of the major TWES subsystems including rotor, transmission and generator. A detailed drawing of a baseline TWES configuration is shown in Figure 2.

Since the tower vane design has not yet been finalized, two alternative design concepts were considered. The first has circular inner and outer tower walls with vane ends assumed to have both inward and outward parabolic curvature. The second design uses "wing-like" vanes in an effort to improve aerodynamic efficiency.

A structural analysis of the TWES tower using both vane design concepts was performed to establish the tower dimensions necessary to withstand maximum winds of 53.6 m/s (120 mph) and provide necessary 1 MW of rated power. The results are shown in Table 3. To assure structural integrity, reinforced concrete construction is required. From the data in Table 3, it is evident that a massive tower weighing approximately 70 to 100 million kg (151 to 219 million lbs) would be required in the 1 MW baseline case.

Applying current reinforced concrete office building construction costs (1) of \$69/m³ - \$76/m³ (\$1.95/ft³ - \$2.15/ft³*), TWES tower costs for the 1 MW baseline case were estimated to be about \$2.1 - \$3.1 million. Table 4 shows that the 1 MW baseline TWES cost ranges from about \$3.2 - \$4.5 million. A comparable conventional wind system similar to the MOD-2 is estimated to have a mature product cost of \$0.8 - \$1.0 million (1).

A similar analysis was performed for all the TWES cases specified in Table 2. The estimated installed mature product TWES costs as a function of system size and augmentation ratio are shown in Figure 3. Under baseline augmentation assumptions (see Table 1), the TWES has installed capital costs that range from 4 - 5.5 times higher than conventional systems at the 200 kW size to 2.5 - 4.5 times higher than conventional systems at the 4 MW size. Under optimistic augmentation assumptions (see Table 2), the TWES has installed capital costs that range from 1.5 - 2 times higher than conventional systems at the 600 kW size to roughly equal to conventional systems at the 12 MW size.

*Which likely understates the TWES tower cost because of its unique construction requirements compared to office buildings.

Figure 2.
TORNADO WIND ENERGY SYSTEM
Base Line Design - First Concept ^a

^aDimensions in ft

Table 3

STRUCTURAL CHARACTERISTICS OF TWO TWES
TOWER DESIGN CONCEPTS: 1 MW BASELINE CASE

	<u>First Concept</u> <u>(Parabolic Vanes)</u>	<u>Second Concept^a</u> <u>(Wing-Like Vanes)</u>
<u>VANES</u>		
Number	12	12
Length - m (ft)	103.4 (340)	103.4 (340)
Thickness - m (ft)	3 (10)	1.2 - 1.8 (4 - 6)
Cross-Section Area - m ² (ft ²)	3 (10)	19.3 - 28.8 (208 - 310)
Total Weight - 10 ⁶ kg (10 ⁶ lb)	81.8 (180)	57.7 - 86.3 (127 - 190)
<u>SUPPORT COLUMNS</u>		
Number	12	12
Dimensions - m (ft)	4.6 x 3.0 (15 x 10)	9.2 x 3.0 (30 x 30)
Total Weight - 10 ⁶ kg (10 ⁶ lb)	3.6 (8)	7.7 (17)
<u>SUPPORT RINGS</u>		
Number	2	2
Total Weight - 10 ⁶ kg (10 ⁶ lb)	6.8 (15)	3.3 - 5.5 (7.2 - 12)
<hr/>		
TOTAL TOWER		
WEIGHT - 10 ⁶ kg (10 ⁶ lb)	92.2 (203)	68.6 - 99.5 (151 - 219)
<hr/>		

^aWhere ranges are given the minimum value refers to the minimum usage of steel reinforcing rods allowed by the American Concrete Institute (ACI) specifications. The maximum value is associated with "good design practice," allowing for reasonable safety factors, and use of ACI specifications.

Table 4

MATURE PRODUCT TWES COST ESTIMATE:
1 MW BASELINE CASE

	<u>Cost (1979 \$x10⁶)</u>
Tower ^a	2.14 - 3.10
Generator, Rotor, Duct, Transmission	0.13
Total Hardware Costs	2.27 - 3.23
Non-Hardware Costs ^b	0.91 - 1.29
TOTAL INSTALLED COST	3.18 - 4.52

^aFoundation and site acquisition costs not included.

^bTaken to be 40 percent of total hardware costs. Includes site preparation, TWES assembly, installation and checkout, general and administrative expenses, transportation to the site, contractors' fees, etc.

Figure 3.

TOTAL INSTALLED MATURE PRODUCT TWES COSTS

It must be noted that the total TWES costs presented are considerably understated. As will be discussed in Section 2, the estimates do not include the cost of the foundation which, for such a massive tower, would add a large cost burden for the TWES.

Figure 4 presents an energy cost comparison of the TWES and competing conventional systems at an annual mean wind speed of 5.4 m/s (12 mph) using the wind duration profile specified by SERI for use in this study.

In only one case, a 12 MW size with optimistic augmentation, is the TWES energy comparable to that of the conventional horizontal axis counterpart. However, this apparently favorable comparison for the TWES is misleading because:

- o Significant additional costs for the foundation were not included in the TWES cost estimate;
- o The energy cost quoted for the conventional wind system at $\bar{V} = 5.4$ m/s (12 mph) was for a system optimally designed for a higher wind speed regime. If a conventional wind system, optimally designed for $\bar{V} = 5.4$ m/s (12 mph) were available, its mature product energy cost would likely be less than 7 cents/kWh;
- o There is no experimental evidence available to support the contention that the optimistic TWES augmentation ratio could be attained.

It appears that even under optimistic projections as to TWES capability and resolution of uncertainties, TWES systems will be at best only marginally competitive with comparably-sized conventional wind energy systems.

Figure 4.

MATURE PRODUCT VAC ENERGY COSTS

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SECTION 3.0

VORTEX AUGMENTOR CONCEPT (VAC)

The VAC uses aerodynamic design techniques, similar to those used in supersonic aircraft design, to concentrate the natural wind density. The "augmentor" of the VAC is a triangular (delta) aerodynamic surface configuration. This surface has a sharp leading edge which, when directed into the wind at an appropriate angle, causes the natural wind flow to separate from the surface. It is this flow separation which leads to the production of vortices. The VAC concept incorporates two rotors because the delta surface produces two identical vortices rotating axially in opposite directions along each edge. A detailed drawing of a VAC system is shown in Figure 5.

The VAC output is defined by the strength and velocity of the vortices. The vortex characteristics and the VAC power output are a function of the angle of attack of the augmentor surface.

There are some technical uncertainties associated with VAC operation relating to vortex breakdown, structural and aero-elastic considerations and potential drag problems. Resolution of these uncertainties awaits the analysis of field test data currently being gathered.

A structural and cost analysis for a baseline mature product VAC (200 kW rated power) was carried out. The weight and cost for the baseline case is given in Table 5. The total weight of all of system components on top of the tower is 239,500 kg (527,000 lb) with an estimated total fabricated cost of about \$345,000. A reinforced concrete tower is used in the baseline case instead of the open truss steel tower proposed by the principal investigator in order to obtain a considerable cost saving.

The total installed cost of the baseline 200 kW VAC is estimated to be \$617,000. This cost estimate includes the use of a concrete foundation assumed to be equal in weight to the weight it supports. Since it is likely that the foundation weight would be several times the weight that it supports in any practical installation, the baseline VAC cost estimate is understated by 15 - 30%.

A similar analysis was undertaken for all of the VAC cases specified in Table 3. The estimated VAC costs as a function of power output and augmentation ratio are shown in Figure 6.

Under baseline augmentation assumptions, the mature product VAC would have installed capital costs that range from 3 times larger than conventional systems at the 40 kW size to 1.5 - 2 times larger than conventional systems at the 1 MW size. Under optimistic augmentation assumptions, the mature product VAC would have installed capital costs about 2.5 times higher than conventional systems at the 40 kW size to roughly the same or slightly higher than conventional systems at the 1 MW size.

Figure 5.
**CONCEPTUAL VORTEX AUGMENTED
WIND ENERGY SYSTEM**

Base Case Design

top view

^aDimensions in ft

- Key:**
- A: Delta Surface
 - B: Rotor Blade
 - C: Hub
 - D: Rotor Shaft
 - E: Nacelle
 - F: Nacelle Support
 - G: Fairing
 - H: Generator
 - I: Gear Speed Increaser
 - J: Deflecting Flap
 - K: Vertical Tail
 - L: Bedplate
 - M: Spring
 - N: Vertical Right Angle Gearbox
 - O: Hinge
 - P: Tower

side view

Table 5

WEIGHT AND COST ESTIMATE FOR 200 kW
BASELINE VORTEX AUGMENTOR SYSTEM

<u>Major Component</u>	<u>Weight - kg (lb)</u>		<u>Total Fabrication Cost (1979 Dollars)</u>
Rotor (4 blades, 2 hub)	5,453	(12,000)	\$ 22,000
Augmentor Surface (Flat Plates, Flanges)	167,240	(368,000)	130,000
Deflecting Flap (Including Supports)	20,900	(46,000)	14,000
Vertical Tail (Including Support)	17,724	(39,000)	12,000
Fairing	4,544	(10,000)	3,000
Transmission (2 Gear Drives and 4 Shafts)	12,724	(28,000)	143,000
Generators (2 @100 kW)	1,136	(2,500)	9,500
Industrial Springs (9)	3,272	(7,200)	5,100
Bedplate	- 6,817	(15,000)	6,000
TOTAL ON TOP OF TOWER	239,820	(527,700)	\$ 344,600
Tower (Reinforced Concrete)	718,960	(1,582,300)	\$ 21,400
TOTAL HARDWARE	958,900	(2,110,000)	\$ 366,000
Foundation ^a	958,900	(2,110,000)	\$ 105,500
Non-Hardware Costs ^b	N/A	N/A	\$ 145,500
TOTALS	1,917,800	(4,220,000)	\$ 617,000

^aFoundation cost is \$0.05/lb; actual foundation weight would likely be several times the total hardware weight. Estimated weight given is minimum under any circumstance.

^bSite acquisition costs not included.

Figure 6.

TOTAL INSTALLED MATURE PRODUCT VAC COSTS

Major cost drivers for the VAC with baseline augmentation are the transmission subsystem and the augmentor (delta) surface. In the optimistic augmentation cases, a much smaller augmentor surface is needed to produce the same power output, thereby, lessening the augmentor surface cost considerably.

Figure 7 presents energy cost comparisons for the VAC and competing conventional systems for an annual mean wind speed of 5.4 m/s (12 mph). In only the 1 MW case does the VAC energy cost with optimistic augmentation compare favorably with that of the conventional horizontal axis counterpart. These comparisons must be cited with care due to the following caveats:

- o The weight and cost of the VAC foundation is likely to be higher than that assumed
- o The energy cost quoted for the conventional wind systems are not based on wind conditions optimal for conventional wind system operation
- o There is no experimental evidence available to support the contention that the optimistic VAC augmentation ratio could be attained.

Figure 7.

MATURE PRODUCT VAC ENERGY COSTS

SECTION 4.0

CONCLUSIONS

The rotor subsystem represents one of the major cost drivers in conventional wind energy systems. Despite the fact that the two vortex extraction systems evaluated have the potential for substantially reducing rotor costs, these cost savings are more than offset by the additional costs required for the augmentation devices. Based on a preliminary analysis of the presently envisioned conceptual designs of the Tornado Wind Energy System and the Vortex Augmentor System, it does not appear that either system could achieve economic parity with conventional horizontal axis wind systems even if all of the technical uncertainties surrounding these innovative concepts are favorably resolved.

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SECTION 5.0

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1. George Hyman Construction Company, 4930 Del Ray Avenue, Bethesda, Maryland.
2. Boeing Engineering and Construction Company (1979), Energy and Environment Division, P.O. Box 3707, Mail Stop 9A-40, Seattle, Washington 98124.