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AUGMENTED HORIZONTAL AXIS WIND ENERGY SYSTEMS ASSESSMENT

Executive Summary. Final Report

December 1979

Work Performed Under Contract No. EG-77-C-01-4042

Tetra Tech, Inc.
Arlington, Virginia

U.S. Department of Energy

Solar Energy

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EXECUTIVE SUMMARY. FINAL REPORT

December 1979

Prepared for:
Solar Energy Research Institute
Wind Energy Innovative Systems Program
Subcontract AH-9-8003-3

TETRA TECH, INC.
1911 North Fort Myer Drive
Arlington, Virginia 22209

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

EXECUTIVE SUMMARY

INTRODUCTION

The Solar Energy Research Institute (SERI) has been authorized by the U.S. Department of Energy (DOE) to provide technical management for the Wind Energy Innovative Systems (WEIS) program for the Wind Systems Branch (WSB). The WEIS program is aimed at determining technical and economic feasibility of innovative concepts and systems. In this study, three horizontal axis augmented systems are critically examined, and the technical status, performance characteristics, and cost projections of these systems are evaluated. The purpose of the study is to determine whether these systems have the potential to be a cost effective energy resource. This assessment should provide guidance and direction for future programmatic efforts in the WEIS program. Although it is not meant to provide an exhaustive study of all aspects of these systems, the current status of horizontal axis augmented systems has been examined.

In a conventional wind turbine system, a dominant cost item is the rotor. Therefore, in augmentation concepts, the rotor must be kept as small and simple as possible, and a net gain in the power-to-cost ratio must be obtained. The systems discussed in this report, if properly designed, will produce power greater than an unaugmented system of the same rotor diameter. The central question is whether the augmentation mechanism is cheaper than enlarging the blades and tower of the conventional machine to achieve the same energy output per year. In this report, augmented and conventional systems are compared based on the cost of electricity for each system operating in the same wind environment.

SYSTEM DESCRIPTIONS

Three concepts are assessed in this report. The first concept is the dynamic inducer, in which tip vanes on a conventional turbine induce increased flow through the rotor. The second is the diffuser augmented wind turbine, in which a diffuser produces a pressure considerably below atmospheric behind the rotor to induce increased flow through the rotor. The third concept is the vortex augmentor, in which the augmentor surface is a highly swept delta wing, creating vortices that concentrate kinetic energy; two turbines then are placed in the vortices to extract this energy.

Dynamic Inducer

The dynamic inducer concept can be considered a horizontal axis augmented system since tip vanes are used to obtain some of the same benefits provided by a diffuser, without the drawbacks of a large duct. The concept was originated by Van Holten at the Delft Institute of Technology in Holland in 1974. AeroVironment, Inc., tested the concept last year. The AeroVironment project included theoretical work, preliminary engineering estimates of cost/benefits, and field testing of a small system. Augmentation was not achieved during the test program, but Lissaman, the principal investigator, believes that it can be achieved with proper design. The dynamic inducer concept is shown in Figure 1 (the figure depicts a test of the tip vane concept on a small three-bladed conventional wind turbine; larger systems would utilize the tip vanes on conventional two-bladed systems; this study analyzed larger, two-bladed versions of the system).

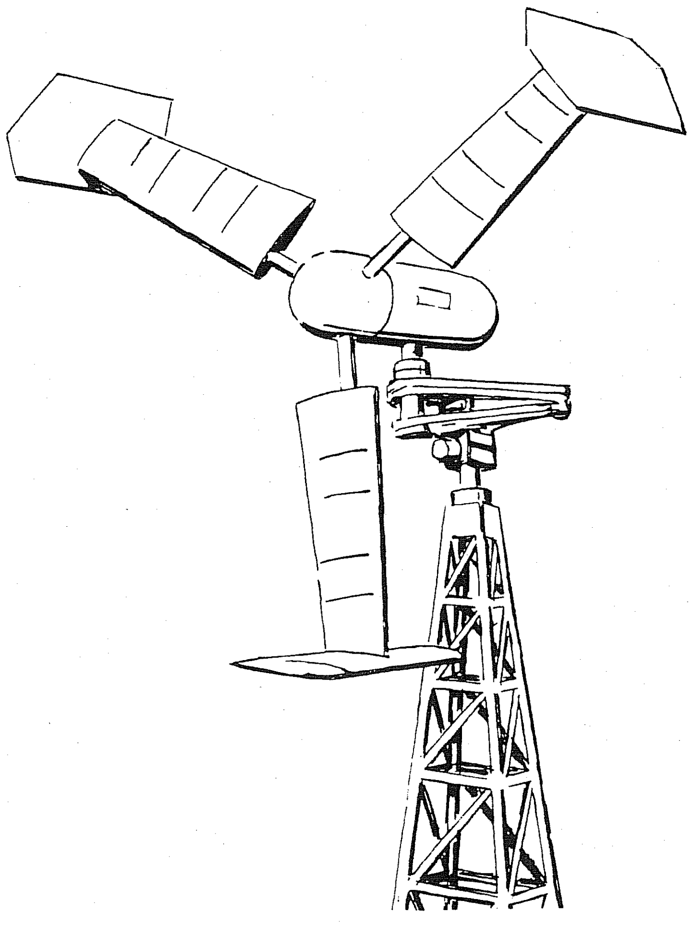


Figure 1. DYNAMIC INDUCER

Source: Victor Chase, "Energy Experts Evaluate 13 Wind Machines," *Popular Science*, September 1978.

The dynamic inducer, like the diffuser augmented system, produces power augmentation by inducing increased mass flow through the rotor. The augmentor surface (the tip vanes) is much smaller than the static duct in the diffuser system, but power is required to drive the tip vanes to overcome their drag.

Diffuser Augmented Wind Turbine

The diffuser augmented concept (shown in Figure 2) consists of a diffuser around a conventional horizontal axis rotor. The Grumman Aerospace Corporation has been developing this system over the past several years. The diffuser increases the mass flow through the turbine by producing a pressure considerably below atmospheric behind the rotor. The major problem has been to produce a diffuser short enough to be cost effective, but one that does not allow flow separation. Slots are used to introduce external air to energize the diffuser boundary layer. An augmentation ratio (power output of the augmented system compared to an unaugmented system) of about six is expected to be achieved with a short diffuser. The diffuser has the effect of quieting flow fluctuations, but whether the short diffuser can avoid flow separation under the influence of fluctuating atmospheric winds remains to be proven.

Vortex Augmentor

Unconfined vortex systems have been examined at both the Polytechnic Institute of New York and West Virginia University. Such systems use wing-like structures to create a vortex. A turbine is then placed in the vortex to extract power. The Polytechnic Institute of New York system is shown in Figure 3. This system employs a horizontal delta wing to create the vortex. Little information on this system has been published to date. Some data on power as a function of speed was published by Sforza for a small wind tunnel model, and a prototype for field testing has been constructed, but data on this prototype has not been presented.[1,2] Cost data on this system also has not been published.

West Virginia University studied a vortex system using a vertical wing to create the vortices. The conclusion of the work was that the high kinetic energy produced by the vortex is not available for energy extraction by a wind turbine. West Virginia University has discontinued work on its vortex concept, and it was therefore not evaluated in this project.

The vortex augmentor concept, if developed, would allow the use of small rotors, and if a flap on the delta surface were used to control flow, pitch change would not be necessary. Passive yaw control utilizing a vertical stabilizer is also a possibility for cutting cost. A potential problem with this concept is vortex breakdown; if the vortices break down before they reach the turbines, augmentation cannot be achieved.

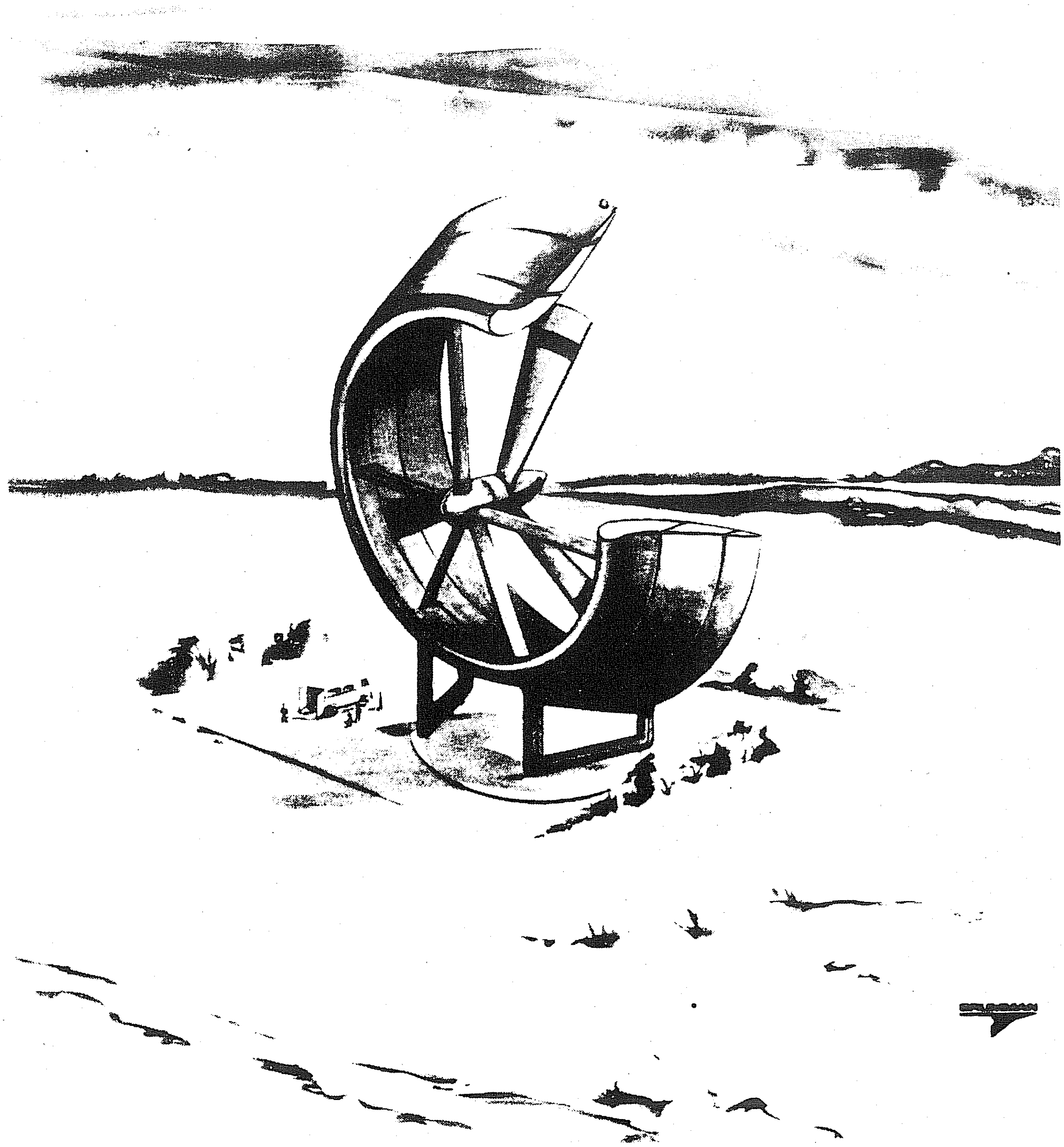
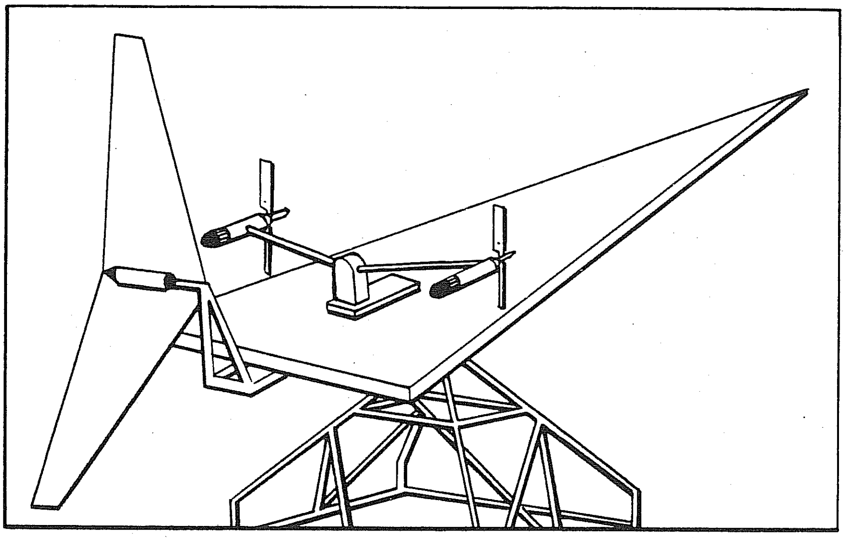


Figure 2. CONCEPTUAL INSTALLATION OF A DIFFUSER AUGMENTED WIND TURBINE

Source: R.A. Oman, K.M. Foreman, and B.L. Gilbert, "A Progress Report on the Diffuser Augmented Wind Turbine," *Third U.S. Wind Energy Workshop*, CONF 77-0921, September 1977.



Source: U.S. Energy Research and Development Administration, "Vortex Augmentors for Wind Energy Conversion," E(49-18)-2358, December 1976.

Figure 3. VORTEX AUGMENTOR

SYSTEMS PERFORMANCE

Performance of augmented systems is usually defined in terms of an augmentation ratio, the ratio of power output of an augmented system to the power output of a conventional wind turbine of the same diameter. Expected values of augmentation ratio range from about 1.6 for the dynamic inducer, to about 4 for the vortex augmentor concept, to a range of 4 to 8 for the diffuser augmented system. To calculate the energy output of augmented systems, the mean wind speed, wind speed distribution, and extrapolation of wind speed with height must be utilized. As with conventional systems, wind speed characteristics at the hub height must be used.

For each of the augmented systems, rated power was calculated for a range of augmentation ratios, using assumed rotor characteristics and the wind characteristics specified in the subcontract. Annual energy output was then calculated for the same parameters using rotor characteristics and the augmentation ratio to determine power as a function of wind speed. This information was combined with a velocity frequency curve at the appropriate height (hours per year that each velocity increment is expected) to derive energy output for each velocity increment. These increments were then summed, resulting in annual energy output in kilowatt-hours.

Dynamic Inducer

Annual energy output for the dynamic inducer was calculated for a range of sizes, using the wind characteristics specified in the subcontract, an augmentation ratio of 1.6, and conventional wind turbine rotor characteristics. Energy output for the augmented system is about 67 percent higher than for the conventional system for the same rotor diameter because of the augmentation ratio of 1.6, plus approximately 5 percent because the system can begin operating at a lower wind speed than a conventional wind energy system.

Diffuser Augmented Wind Turbine

Rated power and annual energy output for the diffuser augmented wind turbine were calculated for a range of sizes, using wind characteristics specified by SERI, conventional rotor characteristics, and a range of augmentation ratios. The range of output power considered for this system was from about 20 kW to 200 kW. Hub height was chosen by using a Grumman design for an 18-foot rotor diameter system, and scaling linearly with rotor diameter. The Grumman Windstream 25, a typical small conventional wind turbine, appropriately scaled up or down, was used to provide rotor characteristics.

Annual energy output was calculated using the turbine characteristics, an augmentation ratio, and an appropriate velocity frequency curve. Annual energy output increased with augmentation ratio, with increasing hub height, and on the order of 10 percent because of the augmented system's ability to begin operating at a lower wind speed.

Vortex Augmentor

Rated power of the vortex augmentor concept depends on the diameter of the two rotors, rotor characteristics, hub height, augmentation ratio, and the free stream velocity. Characteristics of the rotors were taken from the Grumman Windstream 25, a representative small wind turbine rotor.

Annual energy output was calculated using rotor characteristics, the augmentation ratio, and the velocity frequency curve at the appropriate height. Annual energy output of the vortex augmentor concept was estimated for augmentation ratios of two, three, and four as a function of rotor diameter. Annual energy output increased with augmentation ratio and with an additional increase in performance because augmented systems can begin operating at lower wind speeds than conventional wind energy systems. Energy output also increased faster than the square of the diameter because of the increase in hub height as the system is enlarged.

COST ANALYSIS

Analyses were conducted to estimate the comparative capital investment and annual operations and maintenance costs of both conventional and augmented wind energy conversion systems. The costs of producing and acquiring the augmented systems at power ratings comparable to those of conventional systems were estimated. The sizes of the augmented systems were scaled to produce the same power ratings as the conventional systems. Costs were estimated as a function of size—primarily weight and physical dimensions. Each wind energy conversion system was divided into three subsystems—turbine, turbine support structure, and augmentor—to estimate capital investment costs. Annual maintenance costs were estimated as percentages of capital costs. The costs of the 100th unit were estimated using a 90 percent cost improvement curve unless more specific information was available for variation of cost with quantity for a particular system.

The costs that Tetra Tech estimated for the augmented systems are parametric estimates and not the result of detailed engineering analysis. With few exceptions, the augmented systems are concepts or preliminary designs and have not been built or even designed to the level of detail required for estimating production and fabrication costs.

The costs of the diffuser and delta wing augmenting surfaces were estimated from their overall dimensions and factors for cost-per-unit areas of their various materials; that is, aluminum, steel, and ferrocement for the diffuser and fiberglass-encased trussing for the vortex. On the other hand, sufficient data on the dynamic inducer permitted a more detailed analysis and more reliable cost estimates of its major components, particularly the rotor tip vanes and supporting tower.

Tetra Tech's analyses show that rotor and tower capital costs are the major components of the total costs of the conventional systems and the dynamic inducer. The dominant cost items for the diffuser augmented wind turbine depend on the size (or rated power) of the machine and the diffuser material. For the smaller sizes, the diffuser is the dominant cost item, while for the larger sizes, the turbine becomes a dominant cost item, especially if the diffuser is made of an inexpensive material such as ferrocement. The dominant cost items in the vortex augmentor system are the augmenting surface (delta wing) and its supporting tower.

COST OF ELECTRICITY AND SYSTEM COMPARISON

Once the performance (in terms of annual kilowatt-hours), total initial capital cost, and operations and maintenance cost of each system are known, the cost of electricity can be calculated.

Dynamic Inducer

Cost of electricity was calculated for the dynamic inducer for medium (200 kW) and large (2,000 kW) sizes, and this cost was compared to that of conventional wind energy systems of the same output power.

For the 200 kW system with aluminum, steel, fiberglass, or wood blades, the cost of electricity for the dynamic inducer was found to be virtually the same as for the conventional system. The prime reason for the similar cost of electricity is that the 1 to 5 percent lower cost of the dynamic inducer is offset by the approximately 4 percent lower energy output. For the 2,000 kW system, the dynamic inducer cost of electricity is about 1.2 to 4.3 percent less than for the conventional system. The 4.3 percent value is for aluminum blades and 1.2 percent is for steel, fiberglass, or wood blades; future blades are expected to be made of steel, fiberglass, or wood.

The dynamic inducer appears to offer about a 1 percent cost-effectiveness advantage. However, this value is insignificant because of the uncertainties in the cost estimates. In addition, the weight (and therefore the cost) of the tip vanes assumed by AeroVironment seems very low. Using the values assumed by AeroVironment for blade length and chord, and tip vane span and chord, the area of the tip vane is about 1.75 times that of the blade, yet its weight was assumed to be less than one-third of blade weight. While centrifugal and lift forces may tend to cancel on the tip vane, it still seems hard to believe that the weight per area of the tip vane would be less than one-fifth that of the blade.

Diffuser Augmented Wind Turbine

To determine the cost of electricity of the diffuser augmented wind turbine, the performance was calculated using an augmentation ratio of six. This value may be optimistic, but Grumman believes it can be even higher. Also, a shroud (diffuser) length of one-half the rotor diameter was used; Grumman believes the shroud can be even shorter, and therefore less expensive.

The cost of electricity for steel, aluminum, and ferrocement diffuser systems is shown as a function of rated power in Figure 4. Uncertainty of the cost estimate

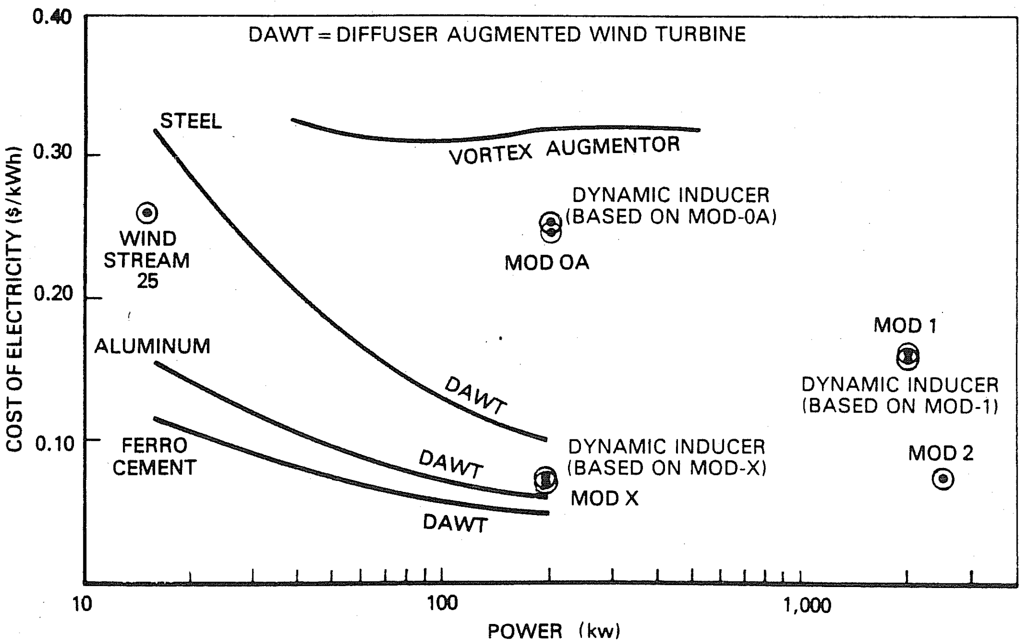


Figure 4. COST OF ELECTRICITY

increases as the rated power increases. The cost of electricity for steel shrouded systems at the lower power ratings is higher than that of the conventional Windstream 25 wind turbine (it is not expected that a steel shroud would be cost effective in this size range). The cost of electricity for this system at 200 kW is less than that of the expensive MOD-0A conventional wind turbine but still is likely to be more than that of an advanced conventional system, such as the MOD-X. It is not expected that steel diffuser systems will be cost effective.

Aluminum diffusers may be cost effective. Using primarily the Grumman data, the cost of electricity appears to be less than for conventional systems. More work is needed to determine if aluminum shrouds could really be this inexpensive.

Cost of electricity values for ferrocement shrouds may be even lower than the estimates for aluminum. Costs were derived from the cost of building boats out of this material. While the estimates are somewhat crude and the scaling laws are not well-known, the results appear promising enough to justify a closer look at the economics of ferrocement shrouds. Although costs for the fiberglass diffuser were not established, it may be cost effective, and further work appears justified.

Vortex Augmentor

To calculate cost of electricity for the vortex augmentor an augmentation ratio of four was assumed. Since performance data is still lacking on this sytem, this is only a rough estimate. The cost of electricity for this concept, shown in Figure 4, appears to be too high to be competitive with the conventional system. In addition, the cost of electricity does not decrease with size because the augmentor surface will be more difficult to build in the large sizes.

CONCLUSIONS

Dynamic Inducer

The cost of electricity of the dynamic inducer may be slightly less than that of a conventional system at the larger (megawatt) sizes, if an augmentation ratio of 1.6 could be achieved. However, augmentation has not yet been achieved, and tip vanes may be heavier and therefore more expensive than has been assumed. The choice of material does not appear to affect this conclusion.

Diffuser Augmented Wind Turbine

Of the augmented systems examined, the diffuser augmented wind turbine with a ferrocement, fiberglass, or aluminum diffuser appears the most promising. Steel shrouds for the diffuser augmented system do not appear to be cost effective in any size range. Ferrocement does appear promising for this application. In addition, fiberglass and aluminum shrouds may be cost effective.

More work is needed to establish the augmentation ratio achievable. Augmentation ratios of about 3.5 have been achieved in wind tunnel tests, but reaching values of 6 or more depends on several trends and assumptions. (As a first order approximation, cost of electricity varies inversely with augmentation ratio.) A test of the best diffuser combined with an appropriately designed turbine, running at the proper tip speed ratio, is desirable. If this test is successful, the next logical step would be to test a system in a real wind environment.

More work on the economics of diffusers built of ferrocement, fiberglass, or aluminum is also recommended. Some of these materials may be effective, but more work must be performed to reach firm conclusions.

Vortex Augmentor

Performance data on the vortex augmentor concept are scarce, so that quantifying cost effectiveness is difficult. It appears, however, that the system requires too large (and therefore too expensive) an augmentation surface, especially at medium to large sizes. Unless future data show very high augmentation ratios, further work on medium or large size systems is not recommended.

REFERENCES

1. Sforza, P.M., "Vortex Augmentor Concepts for Wind Energy Conversion," *Wind Workshop 2*, The Mitre Corporation, NSF-RA-N-75-050, September 1975.

2. Sforza, P.M., "Vortex Augmentors," Polytechnic Institute of New York, *Third Wind Energy Workshop*, JBF Scientific Corporation, CONF 77-0921, September 1977.

ACKNOWLEDGEMENTS

This work was performed under Solar Energy Research Institute (SERI) Subcontract No. AH-9-8003-3. The SERI technical monitor was Dr. Irwin E. Vas.

The following provided information utilized in the report: Peter Lissaman of AeroVironment, Inc.; P. M. Sforza of the Polytechnic Institute of New York; John Loth of West Virginia University; C. G. Justus of the Georgia Institute of Technology; Jack Stotz of Grumman Energy Systems, Inc.; and K. M. Foreman and R. A. Oman of the Grumman Aerospace Corporation. The help of the above individuals is gratefully acknowledged.

CONTENTS

ABSTRACT

Aerodynamic devices that can concentrate and augment natural winds of low kinetic energy density have the potential to provide a cost-effective energy resource system. Research and development (R&D) on several concepts of horizontal axis augmented wind energy systems have been under way for several years, funded primarily by the Department of Energy and its predecessors. Technical management of these R&D projects is the responsibility of the Solar Energy Research Institute (SERI). The purpose of this project was to critically assess these concepts for SERI.

Three such concepts, in which an augmentor surface is used to increase the mass flow through a turbine and thereby increase the turbine's power output per unit of rotor disc area, are analyzed in this report. The three concepts compared are:

- *the dynamic inducer,* in which tip vanes on a conventional turbine induce increased flow through the rotor;
- *the diffuser augmented wind turbine (DAWT),* in which a diffuser produces a pressure considerably below atmospheric behind the rotor to induce increased flow through the rotor; and
- *the vortex augmentor concept (VAC),* in which the augmentor surface is a highly swept delta wing, and creates vortices that concentrate kinetic energy; two turbines are then placed in the vortices to extract this energy.

Performance (annual energy output) and costs (both investment and operations and maintenance costs) were calculated for the augmented systems and compared to those of conventional systems. All systems were compared on the basis of cost of electricity generated. The DAWT with a ferrocement, fiberglass, or aluminum diffuser appears the most promising. The vortex augmentor probably is not competitive with conventional systems at present, but performance data are incomplete. Additional research is needed on augmentation ratios and on the economics of diffusers built of ferrocement, fiberglass, and aluminum.

INTRODUCTION

Because wind is a relatively diffuse energy source, several attempts have been made recently to concentrate this energy. For a conventional wind turbine system, a dominant cost item is the rotor. In concentration (augmentation) concepts, the rotor is kept as small as possible to attempt to gain an increase in the power-to-cost ratio. Various types of horizontal axis augmented systems have been investigated, including dynamic inducer, shrouded, and vortex concepts.

All of these systems will produce power if properly designed, and should produce augmentation; that is, they will produce power greater than an unaugmented system of the same rotor diameter. The central question is whether the augmentation mechanism (e.g., the diffuser, "wing" for the vortex machine) is cheaper than enlarging the blades and tower of the conventional machine to achieve the same energy output per year.

In this report, technical status, performance characteristics, and economic aspects of each system are assessed. A critical technical review of the systems is followed by a system comparison with a conventional, unaugmented wind system. The comparison is based primarily on the cost of electricity for each system operating in the same wind environment. In making these comparisons, data available at the time of writing was utilized. If sufficient data was not available, Tetra Tech conducted its own independent analysis. Data from outside sources is referenced. All other data is from Tetra Tech's own analysis.

BACKGROUND AND SYSTEM DESCRIPTIONS

Conventional wind energy conversion systems are under development by the Department of Energy (DOE). Large systems are being developed by the National Aeronautics and Space Administration (NASA)/Lewis Research Center, while small systems are being developed by DOE's Rocky Flats plant. Augmented systems research and development (R&D) is being managed by the Solar Energy Research Institute (SERI). None of the systems in this program are beyond the wind tunnel or outdoor test model stage. Table 1 lists several large systems (100 kilowatt (kW) or greater) under development by NASA, a small system developed privately (Grumman's Windstream 25), and the horizontal axis augmented wind energy systems studied in this project. The conventional systems presented were used throughout the project for performance and cost analysis. The MOD-X and MOD-2 systems are considered second generation conventional systems; the other conventional systems listed are considered first generation. All conventional systems have two rotor blades, except for the Windstream 25, which has three.

Table 1. WIND ENERGY SYSTEMS

CONVENTIONAL SYSTEMS

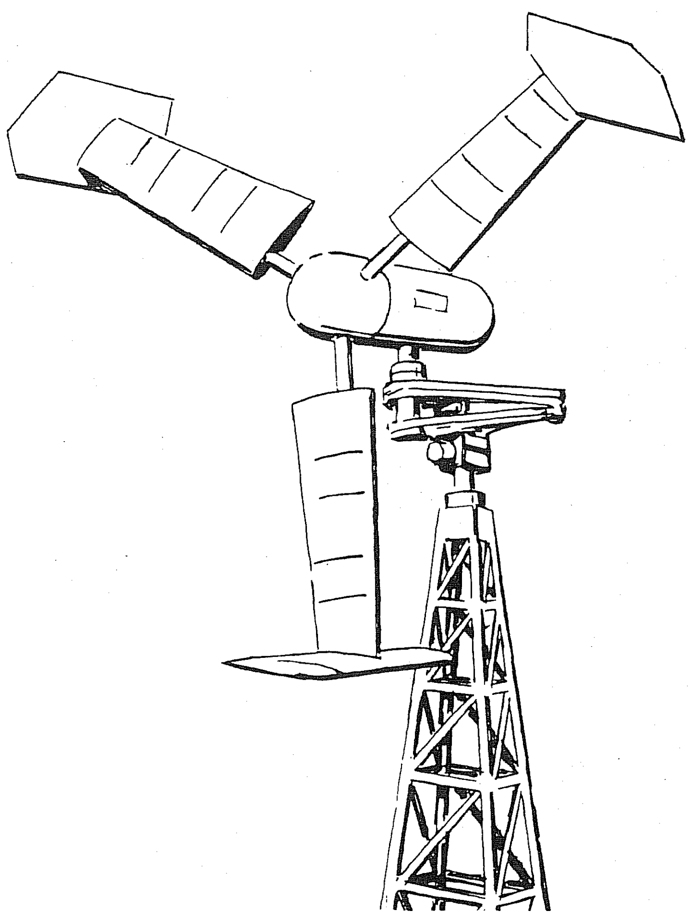
System	Diameter (feet)	Power (kW)	Builder	Status
MOD-0	125	100	NASA	Operational in Sandusky, Ohio
MOD-0A	125	200	Westinghouse	Operational in Clayton, New Mexico, and Culebra, Puerto Rico
MOD-1	200	2,000	General Electric	Operational in Boone, North Carolina
MOD-2	300	2,500	Boeing	Operation begins in 1980.
MOD-X	125	200	—	Conceptual design
Windstream 25	25	15	Grumman	Five or six have been sold.

HORIZONTAL AXIS AUGMENTED SYSTEMS

System	Researcher	Status
Dynamic inducer	AeroVironment, Inc.	12-foot diameter model tested outdoors; no augmentation achieved
Diffuser augmented wind turbine	Grumman	Up to 18-inch rotor model tested in wind tunnel; augmentation factor of 3.4 achieved
Vortex augmentor	Polytechnic Institute of New York	3-foot rotor system built; no performance data published

DYNAMIC INDUCER

The dynamic inducer can be considered a horizontal axis augmented system since tip vanes are used to obtain some of the same benefits provided by a diffuser system, without the drawbacks of a large duct. The concept was originated in 1974 by Van Holten at the Delft Institute of Technology in Holland. AeroVironment, Inc., received a contract to test the concept in 1977.[1] The contract included theoretical work, preliminary engineering estimates of costs and benefits, and field testing of a small system. Power augmentation of 50 percent is felt to be attainable by Lissaman, the principal investigator.[2] Only preliminary results have been published to date. Augmentation was not achieved, but Lissaman believes that it can be achieved with proper design and operation at the designed synchronous speed.* The dynamic inducer concept is shown in Figure 1. (This figure depicts a test of the end



Source: Victor Chase, "Energy Experts Evaluate 13 Wind Machines," *Popular Science*, September 1978.

Figure 1. DYNAMIC INDUCER

* Private communication with Dr. Lissaman.

plate or tip vane concept on a small three-bladed conventional wind turbine. Larger systems would utilize the tip vanes on conventional two-bladed wind turbines. The two-bladed version was used for the cost comparison in this project.)

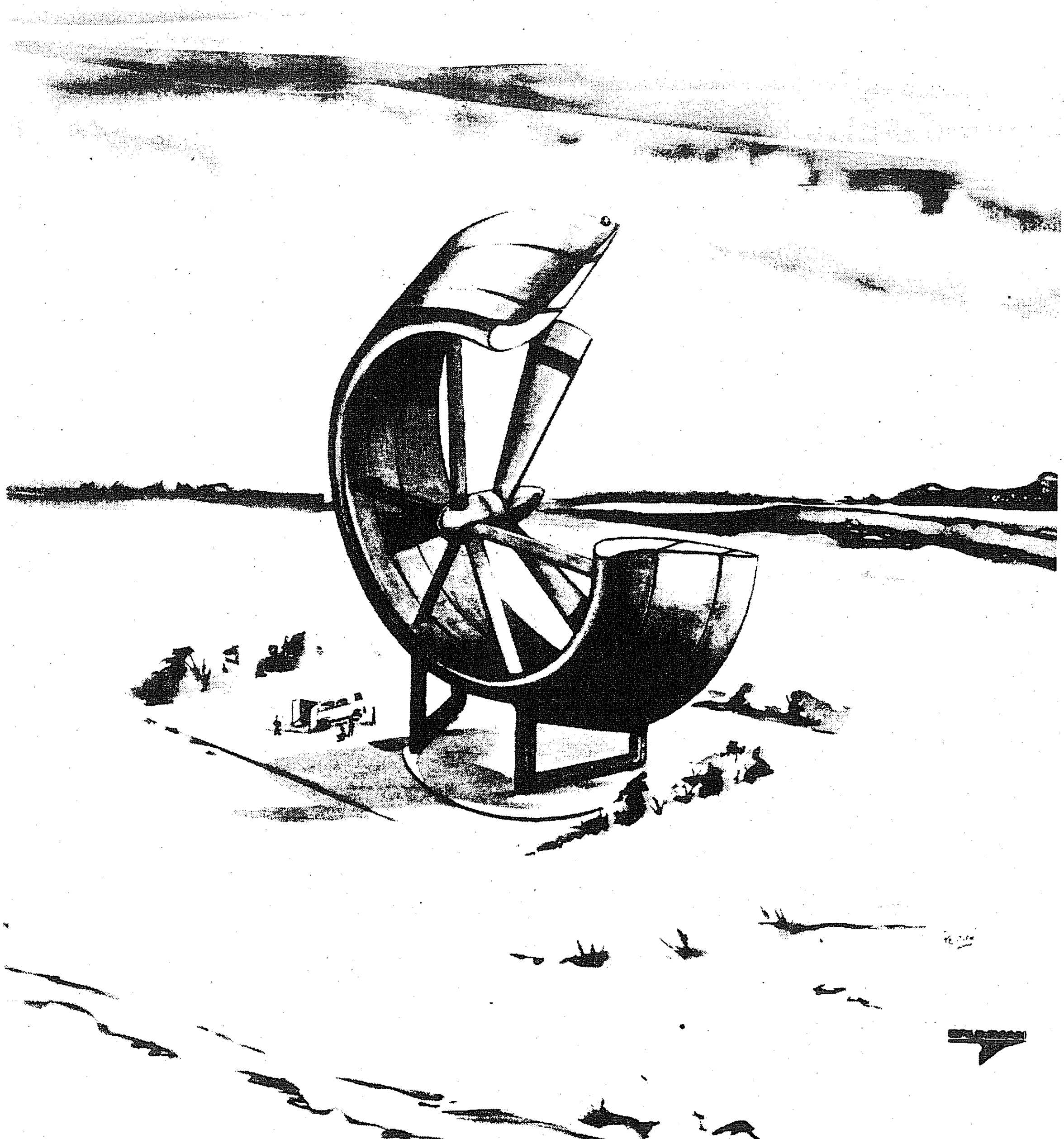
The dynamic inducer produces power augmentation by inducing increased mass flow through the turbine. The augmentor surface (the tip vanes) is much smaller than the static duct in the diffuser system (described below), but power is required to drive the tip vanes to overcome their drag. High-lift airfoils are necessary for use as tip vanes. Augmentation is achieved because the tip vanes force the flow behind the actuator radially outward, increasing the flow through the actuator.

DUCTED OR SHROUDED TURBINE CONCEPTS

Work on shrouded turbines, begun in Great Britain in the 1950s, showed that these systems can produce up to twice the power of unshrouded turbines of the same diameter.[3] More work was carried out in Israel in the 1960s.[4,5] The first work in the United States was reported at the first U.S. Wind Energy Workshop by Grumman (December 1973).[6]

Wilson carried out some aerodynamics work on ducted actuators, concluding that they could not be analyzed by any simple method.[7] Work subsequently performed by Igra in Israel showed an augmentation ratio (power output of the augmented system divided by that of an unaugmented system of the same diameter) of up to four was possible.[8] Igra presented a paper at the second U.S. Wind Energy Workshop outlining his work (September 1975).[9] Grumman also reported on its work at this conference, and has published several reports and papers since then.[10,11,12] The work has concentrated on aerodynamic performance, but includes comparative economics of the diffuser concept compared to conventional systems. A major goal of Grumman's research has been to reduce radically the size (length) of the diffuser without sacrificing performance. The cost of a large shroud would have been prohibitive; the question now is whether the shorter shroud produces a cost effective system. The diffuser augmented concept is shown in Figure 2.

The diffuser augmented wind turbine (DAWT) system consists of a shroud (static diffuser) around a more or less conventional horizontal axis rotor. The diffuser increases the mass flow through the turbine by producing a pressure considerably below atmospheric behind the rotor. The major problem has been to produce a diffuser which, while short enough to be cost effective, does not allow flow separation. The diffuser has the effect of quieting flow fluctuations, but whether the short diffuser can avoid flow separation under the influence of fluctuating atmospheric winds remains to be proved. Slots introduce external air to energize the diffuser boundary layer. An augmentation ratio of about 3.4 has been achieved with a short diffuser (length equal to one half the rotor diameter) combined with a work-ing but not optimized turbine. Grumman anticipates that an augmentation ratio of 6 or more is achievable.[13]



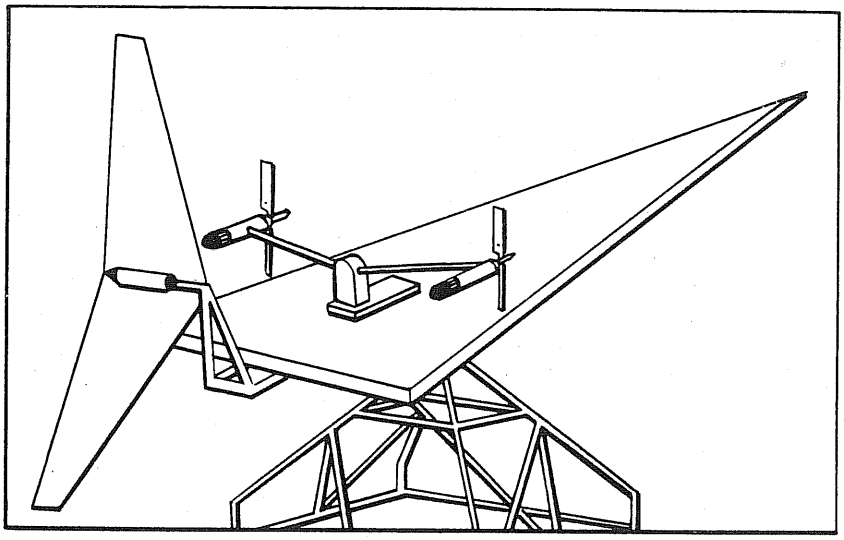
Source: R.A. Oman, K.M. Foreman, B.L. Gilbert, "A Progress Report on the Diffuser Augmented Wind Turbine," *Third Wind Energy Workshop*, September 1977, CONF 77-0921.

Figure 2. CONCEPTUAL INSTALLATION OF A DIFFUSER AUGMENTED WIND TURBINE

VORTEX AUGMENTOR

Unconfined vortex systems have been examined at both the Polytechnic Institute of New York and West Virginia University. Such systems use wing-like structures to create a vortex. A turbine is then placed in the vortex to extract power. It has been estimated that such systems can provide up to six times the power output of conventional systems of the same diameter.[14] The Polytechnic Institute of New York system uses a horizontal delta surface to create the vortex, as shown in Figure 3. Sforza has reported on the project several times.[15,16] Some data on power as a function of wind speed for a small wind tunnel model have been given, and a prototype for field testing has been constructed, but no data on this prototype have been presented. No cost data on this system have been published.*

The West Virginia University concept used a vertical wing to create the vortex, as shown in Figure 4. Loth reported on this project at the third U.S. Wind Energy Workshop.[17] He concluded that the high kinetic energy produced by the vortex is not available for energy extraction by a wind turbine. West Virginia University has since discontinued work on its vortex concept.** This system will not be discussed further in this report.



Source: U.S. Energy Research and Development Administration, "Vortex Augmentors for Wind Energy Conversion," E(49-18)-2358, December 1976.

Figure 3. VORTEX AUGMENTOR

* Private communication with Dr. Sforza.
** Private communication with Dr. Loth.

The vortex augmentor concept, if developed, would allow the use of small rotors, and if a flap on the delta surface is used to control flow, pitch change may not be necessary. Passive yaw control utilizing a vertical stabilizer is also a possibility for cutting cost. A potential problem with this concept is vortex breakdown. If the vortices break down before they reach the turbines, augmentation cannot be achieved.

Source: R.E. Walters, et. al., *Innovative Wind Machines*, West Virginia University, ERDA/NSF/00367-76/2, June 1976.

Figure 4. "VORTEX TYPE" WIND ENERGY CONCENTRATOR

SYSTEM PERFORMANCE

To calculate the performance of both conventional and augmented systems, the geometry of the system (rotor diameter, hub height, and rotor characteristics) and wind characteristics (speed, speed distribution, and variation of speed with height) must be known. The required calculations are described below. Rated power and annual energy output are determined for the dynamic inducer, DAWT, and vortex augmentor. The 2,500 kW MOD-2 wind turbine is used to illustrate the calculation of the performance of a conventional wind turbine. This system has a diameter of 91.4 meters (m) (300 feet), a hub height of 61 m (200 feet), and is designed for a 6.3 m per second (m/s) (14 miles per hour (mph)) wind speed at a height of 9.1 m (30 feet). The rated power of 2,500 kW is reached at a rated speed of 12.3 m/s (27.5 mph) at the hub; cut-in is 6.3 m/s (14 mph) and cut-out is 20 m/s (45 mph), also at the hub. The design wind speed (the point of peak power coefficient) is 8.9 m/s (20 mph) at the hub.[18]

The power in the wind is proportional to the velocity cubed:

$$P = \tfrac{1}{2} \varrho A V^3, \qquad (1)$$

where

P = power in the wind,
ϱ = density,
A = cross-sectional area, and
V = wind speed.

Power in the wind is then converted to power out of the rotor by multiplying by the rotor power coefficient. Losses from the drive train, gearbox, generator, accessory, and transformer must be subtracted. The resulting net output curve then is calculated and plotted as in Figure 5.

The Weibull distribution has been found useful to represent wind speed distributions for wind energy applications. It can be expressed in terms of the probability density function (velocity frequency curve):

$$P(V)dV = (k/c)\,(V/c)^{k-1} \exp\left[-(V/c)^k\right] dV, \qquad (2)$$

where c is the scale factor and k is the shape factor. The term p(V)dV is the probability of finding a speed between V and V + dV, and has units of probability per unit speed.

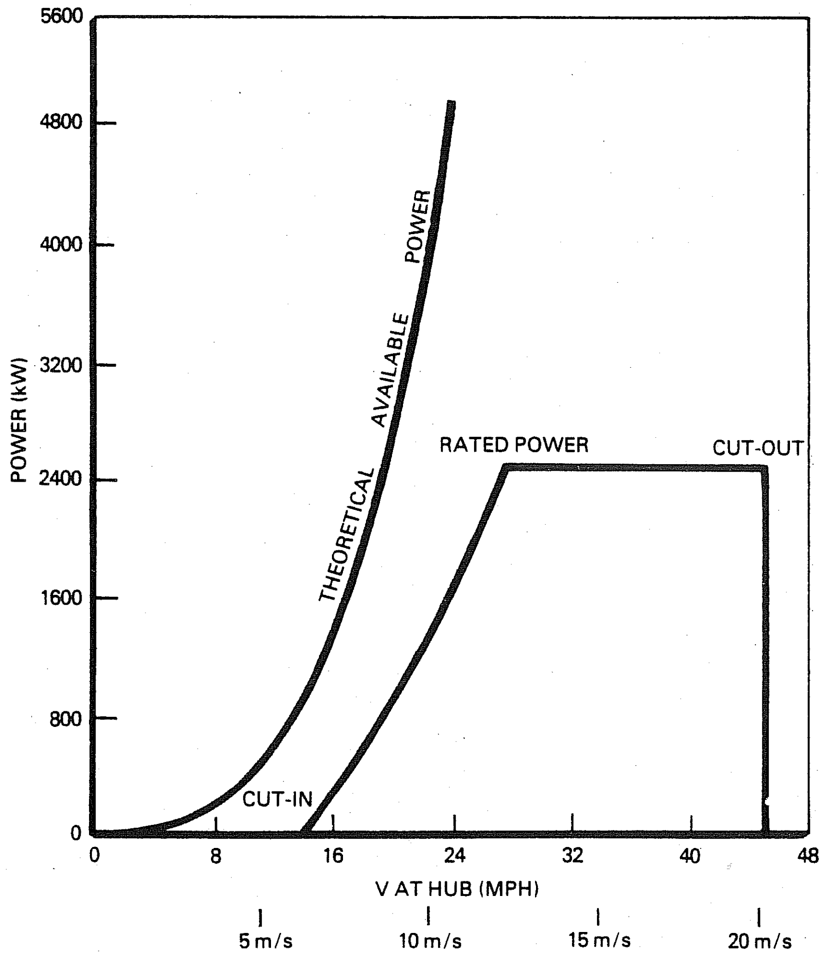


Figure 5. MOD-2 POWER OUTPUT

The wind speed distribution also can be expressed as the velocity duration curve in hours per year for which V exceeds any given value, and is expressed as:

$$H(V > V_x) = 8766 \exp[-(V_x/c)^k]. \qquad (3)$$

For this project, the velocity duration profile was specified as:

$$H = 8766 \exp\left[\frac{-\pi}{4.06}(V/\overline{V})^{2.27}\right], \qquad (4)$$

where V is the velocity, and $\overline{V}$ is the mean velocity. The shape factor therefore is 2.27, and the scale factor is $1.12\overline{V}$. At an elevation of 9.1 m (30 feet), the mean velocity $\overline{V}$ was specified as 5.4 m/s (12 mph). For a unit speed interval dV, the equivalent velocity frequency curve is:

$$H = 8766\,(2.27/1.12\overline{V})\,(V/1.12\overline{V})^{1.27} \exp[-(V/1.12\overline{V})^{2.27}]. \qquad (5)$$

The velocity frequency for an anemometer height of 9.1 m is shown in Figure 6.

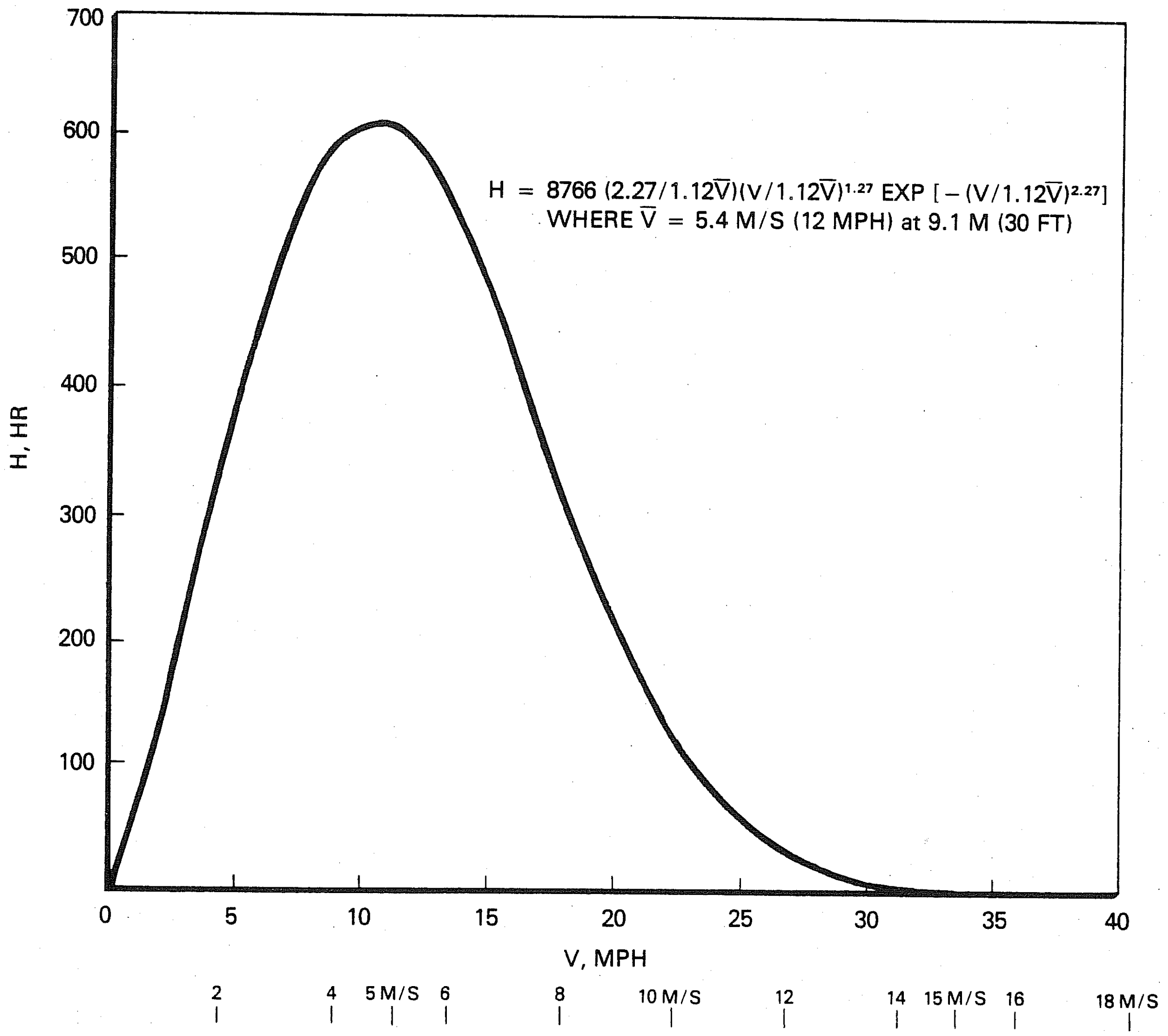


Figure 6. VELOCITY FREQUENCY CURVE

To calculate performance, the wind velocity distribution at the hub height also must be known. The mean wind speed variation with height was specified as:

$$\overline{V}_z = \overline{V}_r \frac{\ln (Z/Z_0)}{\ln (Z_r/Z_0)} , \qquad (6)$$

where

$\overline{V}_r$ = the mean wind speed at a reference elevation Z_r—5.4 m/s (12 mph) a 9.1 m (30 feet),

$\overline{V}_z$ = the mean velocity at elevation Z, and

Z_0 = the surface roughness length, specified as 0.05 m (0.16 feet).

From this equation, the mean wind speed is 7.3 m/s (16.4 mph) at 61 m (200 feet). According to Justus, the shape factor should be increased by about 25 percent in going from 30 to 200 feet, while the scale factor divided by the mean speed would change very little.[19] The velocity distribution at the hub height therefore has a mean speed of 7.3 m/s, a shape factor k of 2.84, and a scale factor of about 8.2.

The new velocity distribution can be plotted as a velocity frequency curve, similar to Figure 6, for 0.477 m/s (1 mph) increments. This curve will show the number of hours per year that the wind velocity is in each increment. For each of the velocity increments, power output can be obtained from Figure 5. Multiplying power in kW times hours in that increment gives the annual energy output contribution of that increment (in kilowatt-hours (kWh)). Summing these contributions gives the total energy in kWh produced per year. For an availability of 0.967, the annual energy output is calculated to be about 6.25 million kWh.[18] (This value is lower than NASA estimates because the extrapolation of wind speed with height specified in the subcontract results in a lower value of hub height wind speed than that used by NASA.)

AUGMENTED SYSTEMS

Performance of augmented systems usually is given in terms of an augmentation ratio, or the ratio of power output of an augmented system to that of a conventional turbine of the same diameter. Expected values of the augmentation ratio range from about 1.6 for the dynamic inducer to about 4 for the vortex augmentor, and are in the range of 4 to 8 for the diffuser augmented system.

One way of considering the augmentation ratio is to take a conventional turbine and add tip vanes, a shroud, or a delta wing to increase its power by a factor of between 1.6 and 8. Another way is to find an augmented system with a smaller diameter than a conventional system, but with the same power output. Output power is proportional to augmentation ratio, cross-sectional area, and velocity cubed:

$$P \sim \bar{r} \cdot D^2 \cdot V^3, \tag{7}$$

where

$\bar{r}$ = the average augmentation ratio,
D = the turbine diameter, and
V = the free-stream velocity.

For the same free-stream velocity and power output, the diameter of an augmented system can be smaller by the square root of the augmentation ratio. Therefore, for equivalent power, a dynamic inducer rotor can be about 20 percent smaller than a bare turbine, each of the two vortex augmentor rotors can be about 35 percent of the size of the conventional turbine, and the turbine for a diffuser augmented system can be about 35 to 50 percent of the size of a conventional turbine.

As with conventional systems, the calculation of energy output of augmented systems requires data on mean wind speed, wind speed distribution, and wind speed characteristics at the hub height. Hub height is straightforward for the dynamic inducer and the diffuser augmented system. For the vortex augmentor, however, hub height is better defined as the height of the center of the action of the augmenting surface since the flow is redirected into the turbines. This center of action has been chosen as the midpoint along the length of the tilted surface.

Capacity Factor

For a conventional wind energy system of a given power output, an augmented system of the same power output can be conceptualized. Energy output will not be the same, however, because cut-in velocity is lower, resulting in a higher capacity factor and therefore a higher energy output. The acceleration of the augmenting device may also require a lower cut-out velocity, but this effect will probably be smaller than that of lower cut-in, and may not be required if disc loading is low enough. Any differences in hub height will also cause a difference in energy output, a factor that has been ignored by some previous studies of augmented systems.[12,20]

Capacity factor is the ratio of the actual energy output of a wind turbine over a period of time divided by the energy that would have been produced if the machine had run at rated power during the same time period, such as a year. One of the equations that has been used for capacity factor is from the work of Justus:[19]

$$CF = \frac{(\overline{V} - 0.69\, V_i)}{(1.27\, V_r - 0.69\, V_i)}\,, \tag{8}$$

where

CF = the capacity factor,
$\overline{V}$ = the mean wind speed,
V_i = the cut-in wind speed, and
V_r = the rated wind speed.

All wind speeds must be in consistent units and must be at hub height. This linear relationship was intended to be used only in the range of $\overline{V}/V_r = 0.4$ to 1 (some users may not have been aware of this range limitation).* The effect of the cut-out velocity has been neglected in equation (8), a reasonable assumption for sufficiently large cut-out speeds.

Equation (8) has been superceded by a series of tabular values, also developed by Justus.[21] The newer procedure requires estimates of power coefficient at rated speed and maximum power coefficient in addition to cut-in speed, cut-out speed, rated speed, and mean wind speed at the site. Use of the older linear approximation equation instead of this procedure can cause capacity factor to be overestimated at low values of capacity factor. Use of the linear equation beyond its intended limits

* Private communication with Dr. Justus.

can result in capacity factors of 100 percent or greater, which does not make sense in the real world. The new procedure developed by Justus allows calculations over a full range of mean wind speed divided by rated wind speed.

Figure 7 shows the difference in results between the two methods. At a ratio of cut-in to rated speed of 0.5, the results vary little (bottom two curves). At a ratio of cut-in to rated speed of 0.28 (a typical value for a small conventional wind turbine such as the Grumman Windstream 25), the curves differ appreciably (top two curves), especially at low values of capacity factor. The importance for augmented systems is that cut-in velocities are low; thus the choice of methods used for estimating capacity factors is significant.

In an augmented system, flow through the turbine is accelerated from that of the free stream. The rotor therefore sees a faster speed than in the free stream. Cut-in speed of an augmented system will be lower than that of a conventional system, (by the cube root of augmentation ratio) so that its capacity factor will be somewhat higher. However, rated speed will not vary significantly. Augmented and unaugmented systems of the same diameter will reach rated power at about the same speed, but the augmented system will reach a higher power equal to the unaugmented power times the augmentation ratio. The rated speed of augmented and unaugmented systems of the same rated power will be about the same because the higher flow of the augmented system is offset by its smaller cross-sectional area.

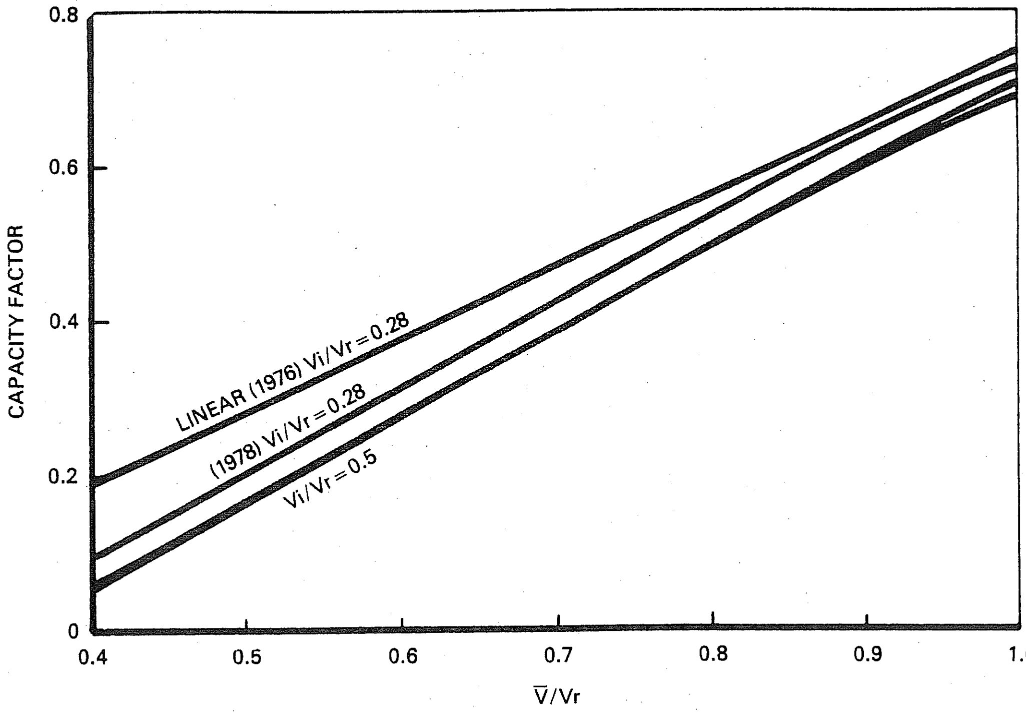


Figure 7. CAPACITY FACTOR

Capacity factors of augmented systems are unlikely to exceed those of unaugmented systems by more than 10 percent. Furthermore, augmented systems cannot produce 8 to 14 times the energy per year of unaugmented systems (augmentation ratio of 4 to 7 times capacity factor or 2), as was claimed for one augmented system.[12]

Rated Power and Annual Energy Output

Dynamic Inducer

Rated power of the dynamic inducer is a function of rated speed, hub height, rotor diameter, augmentation ratio, and rotor power coefficient (the ratio of power extracted by a wind turbine to the power in the reference area of the windstream). Rotor power coefficient was chosen as 0.36, a typical value for a second generation medium size horizontal axis turbine, such as the conceptual NASA 200 kW MOD-X. Rated speed for a wind energy conversion system usually is chosen only after a point design for a particular system has been completed. For this project, rated speed was chosen in two ways:

- based on reference mean wind speed, which allows a general calculation of power as a function of speed.
- by matching a conventional system of a specific size.

For the first method, rated speed was chosen as 8.9 m/s (20 mph) at 9.1 m (30 feet) for the reference wind speed of 5.4 m/s (12 mph) at the same height. Both rated and mean velocity then scale up similarly with height. Hub height was chosen as 0.75 times the diameter.

Once the power output of the dynamic inducer has been established, it can be combined with the velocity frequency curve (Figure 6) to calculate annual energy output. Figure 8 shows the result for a mean wind speed of 5.4 m/s (12 mph), a rated speed of 8.9 m/s (20 mph) at 9.1 m, and a hub height 0.75 times the rotor diameter. Energy output for the augmented system is about 67 percent higher than the conventional system for the same rotor diameter because of the augmentation ratio of 1.6, plus another 5 percent or so because of the lower cut-in speed, which results in a higher capacity factor.

In addition to this general comparison, a comparison with specific conventional systems can be made. A performance comparison of the dynamic inducer and a conventional wind turbine was conducted by Lissaman.[20] The power augmentation factor was assumed to be 1.6 for the dynamic inducer. The two conventional systems chosen by AeroVironment for comparison were the 100 kW MOD-0A and a conceptual 1,000 kW system. The 100 kW system was assumed to have a diameter of 38 m (125 feet) and a tower height of 29 m (94 feet), and the 1,000 kW system was assumed to have a diameter of 60 m (197 feet) and a tower height of 45 m (148 feet). The systems chosen were intended to be near optimal design. In addition, they were in-

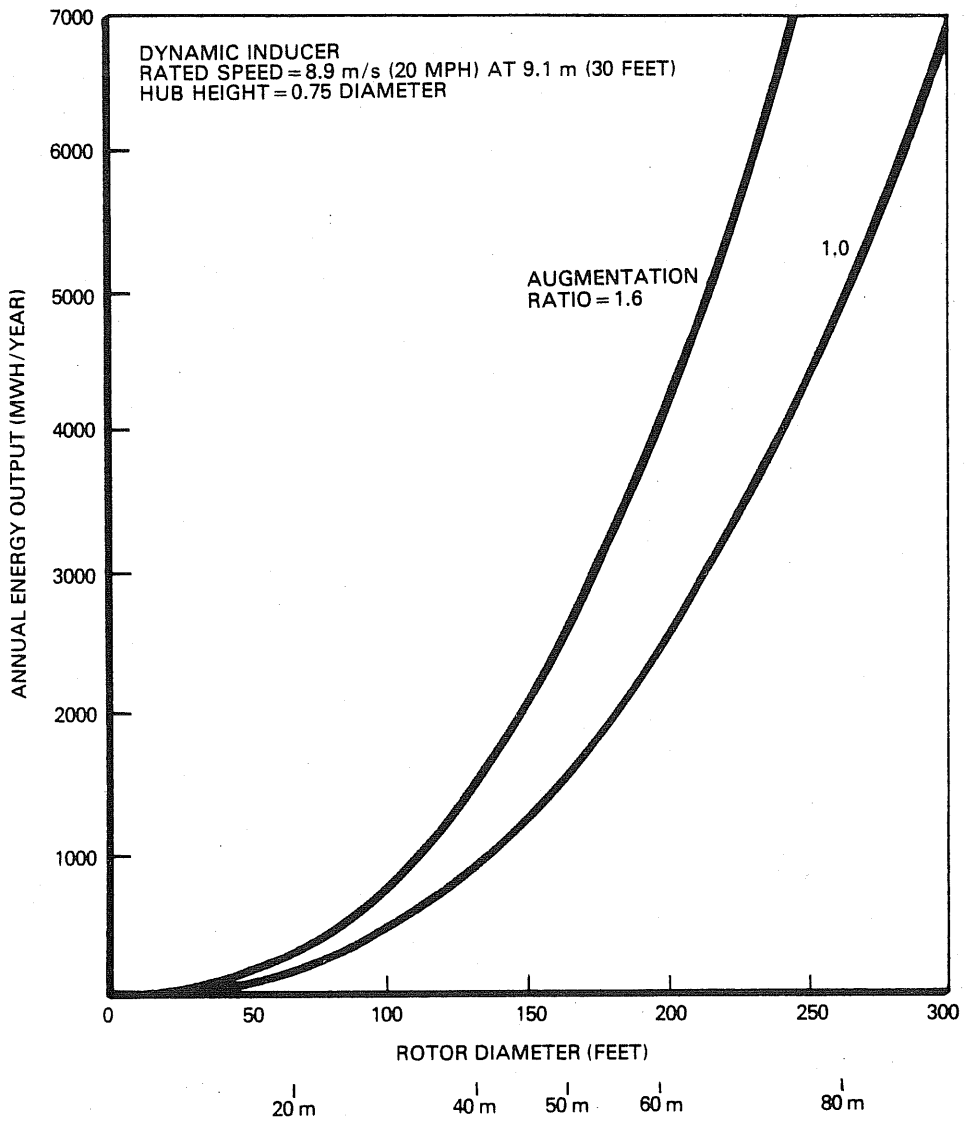


Figure 8. DYNAMIC INDUCER ANNUAL ENERGY OUTPUT

tended to operate in the vortex-synchronous state, in which induced drag is zero because the tip vane vortex system is self-cancelling in the wake. This state is defined by:

$$B = \frac{b}{R} = \frac{2\pi}{XN}, \tag{9}$$

where

B = the normalized tip vane span,
b = the tip vane span,
R = the rotor radius,
N = the number of blades, and
X = the tip speed ratio $R\Omega/u$ (Ω is the angular velocity and u is the axial velocity).

The normalized tip vane span (span divided by rotor radius), then, is a function of the number of blades and the tip speed ratio.

Several difficulties occurred in attempting to verify and update the AeroVironment work.[20] The 38 m (125 feet) 100 kW system was not optimal; 200 kW is easily achievable with this system. On the other hand, the 8 m/s (18 mph) rated speed given made their 60 m (197 feet) 1,000 kW system violate the Betz limit (a 197-foot diameter system cannot develop 1,000 kW at a speed of 18 mph), and the 38 rpm given meant it did not satisfy the vortex-synchronous state. (For 38 rpm and a wind speed of 18 mph, the tip speed ratio is about 15; for the tip vane dimensions given by AeroVironment, the tip speed ratio would need to be 10 to satisfy equation (9).) The NASA 200 kW system (MOD-X) has been chosen as the medium size system and the 2,000 kW MOD-1 as the large system for performance comparisons in this report.

The conventional 200 kW system was estimated to produce about 612,000 kWh per year for an availability of 0.9 at a 12 mph site mean wind speed. An equivalent dynamic inducer producing the same output power is a machine with a rotor smaller than the conventional system by a factor of the square root of the augmentation ratio of 1.6.

The flow this turbine sees is then higher than that of the conventional machine by a factor of the cube root of the augmentation ratio. This system produces about 588,000 kWh per year, or 4 percent less than the conventional system. This decrease is due to two opposite effects (both neglected by AeroVironment): the decrease in tower height causes a decrease in available power which more than offsets the increased capacity factor from the lower cut-in speed. Performance of the dynamic inducer is therefore less than for the conventional system; however, capital costs (analyzed in the following section) are also lower.

The conventional large (megawatt) system produces about 2.5 million kWh per year at a 12 mph site. An equivalent power dynamic inducer would produce about the same amount of energy. In this case, the increased capacity factor caused by the decrease in cut-in velocity has about the same effect as the decreased hub height. It should be noted that the MOD-1 is designed for a better wind site (8 m/s, or 18 mph) at 9.1 m (30 feet), and therefore is not a good choice for a 5.4 m/s (12 mph) site.[22]

Diffuser Augmented Wind Turbine

Grumman has carried out some performance analyses of the diffuser augmentor.[12] Variations in hub height were not considered, and the linearized equation for capacity factor was used beyond its intended range. As was discussed previously, two conclusions that do not appear justified are that capacity factor of the augmented system is twice that of a conventional system, and that the annual energy produced by the augmented system can be 8 to 14 times that of an unaugmented system.

In the current project, rated power for the diffuser augmented wind turbine was calculated in the same way as for the dynamic inducer for a 8.9 m/s (20 mph) rated speed. The range of output power considered was from about 20 kW to 200 kW. Hub height was chosen by using the Grumman design for an 18-foot system, and scaling linearly with rotor diameter. The Grumman Windstream 25, a typical small conventional wind turbine, appropriately scaled up or down, was used as the rotor, and performance curves supplied by the manufacturer were used for rotor characteristics.

Annual energy output was calculated using the turbine characteristics, a range of augmentation ratios, and an appropriate velocity frequency curve. The results are shown in Figure 9. Energy produced varies directly with augmentation ratio, with an

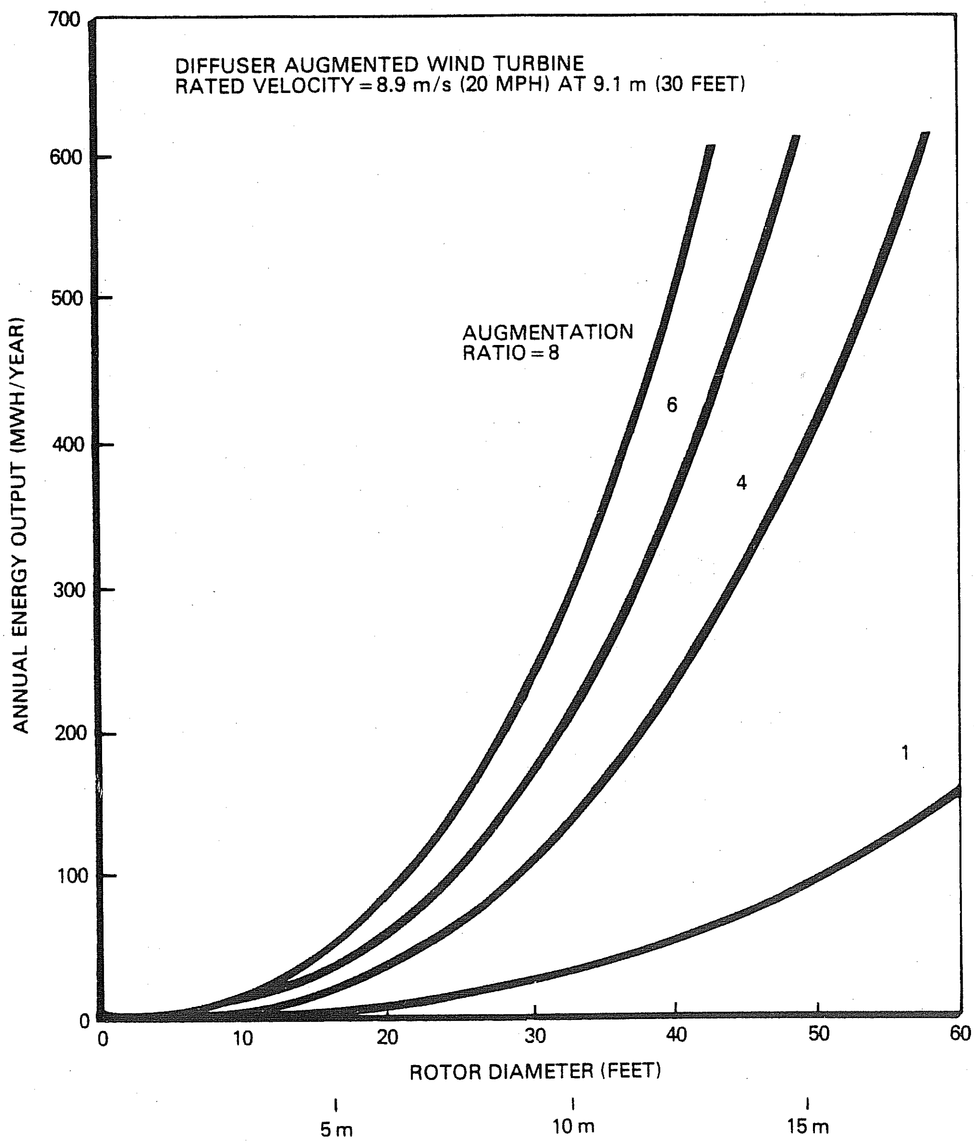


Figure 9. ANNUAL ENERGY OUTPUT OF DIFFUSER AUGMENTED WIND TURBINE

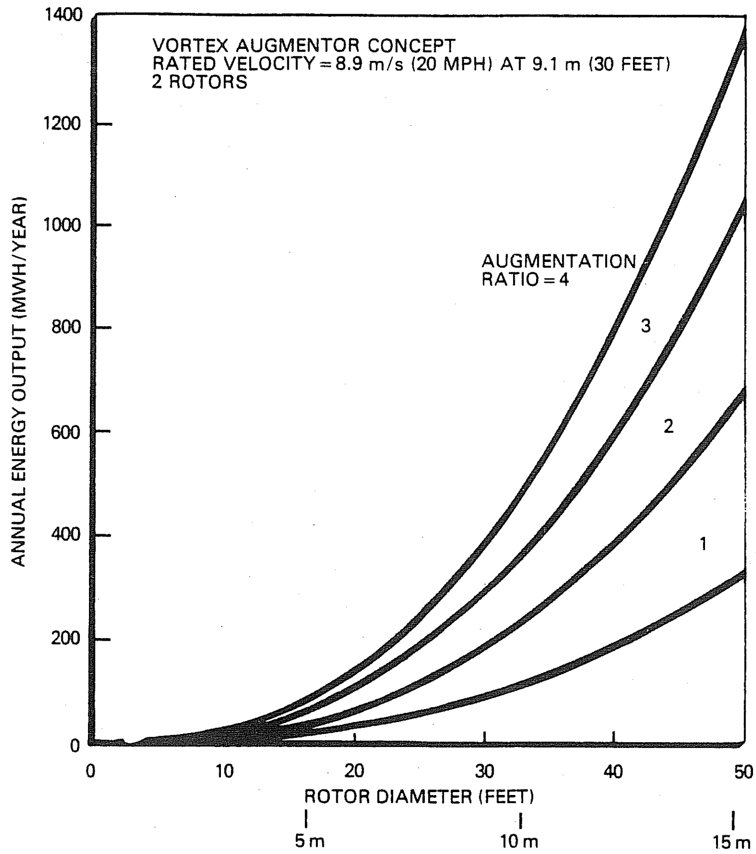


Figure 10. ANNUAL ENERGY OUTPUT OF VORTEX AUGMENTOR CONCEPT

additional benefit of up to 10 percent from the increase in capacity factor caused by the decrease in cut-in velocity of the augmented system. Energy produced increases with the square of the diameter, plus an additional increase with hub height.

Vortex Augmentor

Rated power of the vortex augmentor concept depends on the diameter of the two rotors, the power coefficient of the rotors, the hub height, the augmentation ratio, and the free-stream velocity. The power coefficient of the rotors was taken as 0.34, a representative value for small simple blades such as those of the Grumman Windstream 25. Rated speed was again 8.9 m/s (20 mph) at 9.1 m (30 feet). Both the mean wind speed and rated wind speed then vary the same way with increased height.

Annual energy output of the vortex augmentor was estimated for augmentation ratios of two, three, and four as a function of rotor diameter for an 8.9 m/s site. The results are shown in Figure 10. Results are proportional to augmentation ratio, with an additional slight increase of capacity factor with augmentation ratio. Energy output also increases faster than the square of the diameter because of the increase in hub height as the system is enlarged.

COST ANALYSES

In this section, analyses were conducted to estimate the comparative capital investment and annual operations and maintenance costs of both conventional and augmented wind energy conversion systems (WECS). The costs of producing and acquiring the augmented systems at power ratings comparable to those of conventional systems were estimated. The augmented systems were scaled to the point where they could be expected to achieve the required power ratings, and their costs were estimated as a function of size (primarily weight and physical dimensions). The methodology used to estimate costs for both conventional and augmented systems is described below, and the costs of each system are presented and compared. All costs are presented in 1978 dollars. The costs estimated in this section then are used in the following section, along with the performance calculations previously presented, to provide measures of cost effectiveness.

CONVENTIONAL HORIZONTAL AXIS WIND ENERGY MACHINES

Technical data collected for the MOD-0A, MOD-X, MOD-1, and MOD-2 machines included tower heights, rotor diameters, types of towers (e.g., steel truss, pipe truss, column), blade materials, and component weights, when available. Where possible, each wind turbine system was broken down into five categories for costing purposes:

- Rotors (blades, hub, pitch control mechanism, controls)
- Drive (bearing and drive train, yaw drive, gearbox)
- Electric power generation equipment (generator, switch-gear and wiring, capacitors, sliprings, electronic control)
- Structure (tower, foundation, nacelle/structure, bedplate, bearings)
- Other (safety system, shipping/transportation, installation, site preparation and checkout, initial spares)

In some cases, subcategories were not in the categories specified above. For example, the bedplate and generator for the MOD-0A were included in the drive category. Costs could not be broken out for these two subcategories since they were incorporated within the other subcategories. Technical characteristics (including tower height and weight, rotor diameter, and materials) and cost data for each system component are contained in Tables A-1 through A-5 (Appendix A).

For all of the systems except the MOD-2, second unit costs were available. From these second unit costs, production unit or 100th unit costs were calculated using a 90 percent cost improvement curve, indicating that as the number of units doubles, the cost per unit decreases to 90 percent of the original volume cost. (A 96 to 97 percent curve was assumed for smaller turbines, based on conversations with a small system manufacturer (Grumman Energy Systems, Inc.). In the case of the MOD-2, 100th unit costs were available. Since no cost improvement curve was indicated in the Boeing report for the 25-farm-unit MOD-2 or in the NASA report for the single unit MOD-2, these costs were assumed to be based on a 90 percent curve. Hardware costs for the single unit MOD-2 were lumped into a single dollar amount with no subsystem breakout. The 25-farm-unit MOD-2 contained a more detailed cost breakout, and hardware subsystem costs were calculated as a percentage of the total system costs. To obtain subsystem costs for the single unit MOD-2, the subsystem percentages shown in Table A-4 for the 25-farm-unit MOD-2 were applied to the total hardware costs of the single unit MOD-2.

To compare blade costs among systems, all blades were costed as if constructed of steel. The original cost data for the MOD-0A reflected aluminum blades, weighing 2,350 pounds each and costing $95.70 per pound for second unit costs. If these blades were constructed with steel, they would weigh 2,500 pounds each at a second unit cost of $16.00 per pound.[23] Blade materials other than steel (i.e., wood, steel spar and rib, fiberglass, aluminum) also were costed out, as shown in Table A-6. Other materials for the MOD-2 could not be estimated due to the lack of information on the weight of the blades. The methodology and assumptions for costing the various materials for blade fabrication are explained in detail in Appendix A. Wind turbine costs presented in Tables A-1 through A-5 reflect steel blades.

For the four conventional systems, the rotor is one of the major cost elements, particularly if the blades are aluminum. For example, in the MOD-0A, a rotor consisting of aluminum blades comprises about 47 percent of total hardware costs; the blades alone are 26 percent of total hardware costs.[23] A rotor with steel blades comprises only about 32 percent of hardware costs. Fiberglass, steel spar and rib, and wood blades comprise even less of total rotor costs, indicating that these materials hold much promise for blade fabrication.

Operations and maintenance (O&M) costs for the conventional systems are based on published data from NASA and the various contractors most involved in their construction and design. Annual O&M costs for the MOD-0A, MOD-X, and MOD-1 with steel blades were calculated as 2 percent of the total turnkey costs. The O&M costs would vary depending on the other materials selected for blading. For the MOD-2 single unit, NASA estimated O&M costs at 2.2 percent of turnkey costs or $52,200.[24]

Other costs considered (presented in Appendix A) include on-site fabrication, contractor's fee, and general expenses.

AUGMENTED SYSTEMS

Cost estimates for the augmented systems are parametric estimates rather than the result of detailed engineering analyses since, with few exceptions, these systems are concepts or preliminary designs. They have not been built or even designed to the level of detail required for estimating production and fabrication costs. Sufficient data existed on the dynamic inducer to permit a more detailed analysis than for the other two systems, and the costs of its major components (rotor, tip vanes, and supporting tower) were estimated. The costs of the diffuser and delta wing vortex augmenting surfaces were estimated from their overall dimensions and factors for cost-per-unit areas of the various materials that they might comprise—aluminum, steel, or ferrocement for the shroud, and a fiberglass-encased trussing for the vortex.

Dynamic Inducer

The AeroVironment report estimated the cost effectiveness of the dynamic inducer by comparing it under the same ground rules with a conventional horizontal axis machine:

> For a given conventional horizontal machine (of near optimal design), assume that the rotor is removed and replaced with a dynamic inducer rotor designed for identical performance. Compare the costs of the two systems.[20]

Tetra Tech assumed, as did AeroVironment, that the costs for the electrical machinery, the hub and pitch control mechanism, and other equipment/installation costs are the same in both the conventional horizontal axis machine and the dynamic inducer. The major differences between the two systems are in the rotor itself, which is smaller for the dynamic inducer, and contains tip vanes and tip vane attachments; in the platform (the bedplate and supporting structure on top of the tower), which must accommodate a different overhang and clearance geometry; and in the tower. The tower can be shorter because of the smaller blading, but is not necessarily less expensive, due to the tower geometry required for greater thrust per blade.[20]

To compare the costs of the 100 kW dynamic inducer to a conventional horizontal axis machine, the MOD-0A was chosen as the baseline conventional case. The dynamic inducer was scaled up in rotor weight (blades, tip vanes, and attachments) to reflect a 200 kW machine. The MOD-1 was chosen as the baseline case for comparison of costs of the 1,000 kW dynamic inducer, which was scaled up in rotor weight to reflect a 2,000 kW machine. The methodology for scaling weights is illustrated and discussed in detail in Appendix B.

AeroVironment indicated that although the tip-vaned WECS tower is shorter, the thrust loading on the tower is higher than the conventional WECS. This results in a higher stressed tower at approximately the same cost as the comparable conventional WECS tower. For the purposes of this study, it was assumed that the costs for the conventional and the dynamic inducer towers are the same.

For platform costs, the equation AeroVironment adapted from Lockheed was used:[20]

$$C = 2.239\ R^{2.78},$$

where C is the platform cost in 1975 dollars and R is the rotor radius in meters. Since the MOD-0A platform cost was incorporated into the drive costs, this equation was used to separate the platform cost, which was then inflated to 1978 dollars. The MOD-0A platform cost was estimated at $9,660; the dynamic inducer platform cost was estimated at $5,050. The difference between these two platform costs was subtracted from the total MOD-0A drive cost to give the costs of the dynamic inducer drive system including the platform. In the case of the MOD-1, platform costs were incorporated in the category "other," under structure costs. As mentioned earlier, it was assumed that the pitch control mechanism, hub and electrical systems, and other equipment and installation costs were the same for the two conventional systems and the dynamic inducer.

Candidates for blade and tip vane materials included steel, wood, fiberglass, and aluminum; however, steel was assumed to be the tip vane attachment material in all cases. Since aluminum was the material costed in the AeroVironment report, Tetra Tech considered this material first. Total aluminum rotor cost (excluding the hub and pitch control mechanism) for the 200 kW dynamic inducer is $152,600 as compared to $194,000 for MOD-0A aluminum blades. This represents about a 21 percent savings over the MOD-0A blades. The 200 kW tip vane WEC system with aluminum rotor represents a 4.8 percent savings of the total MOD-0A WECS costs; the 2,000 kW tip vane WECS represents a 4.3 percent savings of total MOD-1 WECS costs.

With steel, wood, and fiberglass blades there is little difference in cost savings over the conventional systems: 1.5 percent and less. Fiberglass is the cheapest material for blades and tip vanes, followed by wood; aluminum is the most expensive. Regardless of the materials used, the small differences in the costs of the two systems imply that they can be considered as about equal-cost alternatives, especially when the cost uncertainties surrounding each estimate are considered. Table 2 is a summary of costs for all materials for the dynamic inducer and conventional WECS. Other cost comparisons of the MOD-0A and the 200 kW dynamic inducer and the MOD-1 and 2,000 kW dynamic inducer are contained in Appendix B.

Table 2. DYNAMIC INDUCER AND CONVENTIONAL WECS COST COMPARISONS (1978 Dollars, 100th Unit)

Power Rating Rotor Material	Conventional		Dynamic Inducer		Percent Savings of Conventional
	System Cost ($)	$/kW	System Cost ($)	$/kW	
200 kW	MOD-0A				
aluminum	961,000	4,810	915,000	4,580	4.8
steel	757,000	3,790	746,000	3,730	1.4
fiberglass	741,000	3,710	733,000	3,670	1.0
wood	743,000	3,720	735,000	3,670	1.1
2,000 kW	MOD-1				
aluminum	2,662,000	1,331	2,548,000	1,274	4.3
steel	2,194,000	1,097	2,162,000	1,081	1.5
fiberglass	2,119,000	1,060	2,098,000	1,049	1.0
wood	2,126,000	1,063	2,103,000	1,051	1.1

Diffuser Augmented Wind Turbine

Grumman conducted a cost comparison of its diffuser augmented wind turbine (DAWT) system and a conventional system in its draft report. The range of output power considered was 15 kW to about 160 kW. Steel systems were considered in the draft report, and aluminum in the unpublished supplementary material later supplied to Tetra Tech. Because no comparable design had been attempted before, Grumman established as an objective that the diffuser structure be such that it could be manufactured by a sheet metal fabricator with a minimum of special tooling or process machinery. Also, the structure was assumed to be erected at a specified site without elaborate equipment. AISI 1025 carbon steel, 36,000 psi yield strength, and standard commercial construction practices were assumed for the design.[12]

Tetra Tech considered four rotor diameter systems: 18, 25, 46, and 60 feet with power ratings up to 200 kW. Diffuser dimensions were scaled up with rotor diameters. Shroud surface area is approximately equal to the area of a truncated cone with inlet diameter D, outlet diameter 1.67 D (area ratio of 2.78), and length D/2, so that surface area, in terms of rotor diameter D, is equal to:

$$\pi\left(\frac{D + 1.67D}{2}\right)\frac{D}{2} = 2.09D^2, \tag{10}$$

where D is the rotor diameter in feet. The Grumman rotor cost was scaled by a curve fit of conventional wind turbine costs (discussed in detail in Appendix C). Originally the blade diameter of the turbine was 25 feet, and Grumman later reduced it to 18 feet by cutting back the blades. Given this procedure, the 18-foot diameter rotor would cost the same as the 25-foot diameter rotor, according to Grumman.* If the 18-foot diameter diffuser turbine was to be built in mass quantity, it would be

*Private communication with Jack Stotz, Grumman Energy Systems, Inc.

impractical to build 25-foot rotor diameter turbines and cut down the blades to 18 feet (10.5 feet of aluminum blading per turbine would be wasted). For this study, Tetra Tech costed the turbine as if it were manufactured as an 18-foot diameter rotor, except where otherwise noted.

Cost projections for the DAWT prototype with diameters of 18, 25, 46, and 60 feet are in Table D-1 (Appendix D). To find the costs of larger diffuser shrouds, the six-tenths factor was applied to the 18-foot diameter diffuser costs given by Grumman. This factor frequently is used to determine the cost of a similar piece of equipment of different capacity, and was applied to manufacturing labor costs, and shipping, assembly, and erection costs.* For example, the total area of the DAWT 18-foot shroud is 677 square feet, and the cost of materials and parts is $41,000. The area of the DAWT 25-foot shroud is 1,306 square feet. Applying the six-tenths factor:

$$\$41{,}000\left(\frac{1306}{677}\right)^{0.6} = \$60{,}800. \qquad (11)$$

$60,800 thus is the estimated cost of materials and parts for the DAWT 25 shroud.

Grumman also looked at a redesign possibility using a higher strength material of 160,000 psi yield strength steel. Manufacturing labor costs would be reduced by about 47 percent since the cost of materials and parts is reduced by over 50 percent.[12] Table D-2 in Appendix D shows the cost projections for the parametric redesign possibility. Tetra Tech applied the six-tenths factor to estimate costs of the larger diameter diffusers. Table D-3 contains estimates of DAWT costs for both the first design study and the parametric redesign possibility for quantity production.

Grumman later supplied Tetra Tech with supplementary unpublished material on DAWT cost estimates for an aluminum diffuser where costs are significantly reduced for the materials and manufacturing of the diffuser. Grumman estimated that the total cost of the aluminum shroud would be about $44,000.** This cost includes the materials and parts, and manufacturing labor costs, and the assembly, shipping, and erection of the structure (less the turbine). This estimate is an 82 percent reduction in costs from the first design (steel) DAWT prototype costs. Tables D-4 and D-5 show the supplementary Grumman costs plus Tetra Tech's estimated costs for the larger diffusers. The 60-foot diameter first-design (steel) diffuser at the

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*The indicated relationship is:

$$\frac{\text{Plant A (component A) cost}}{\text{Plant B (component B) cost}} = \left(\frac{\text{Plant A (component A) capacity}}{\text{Plant B (component B) capacity}}\right)^{x}$$

This relationship first was suggested by Lang, who suggested an average value of 0.6 for the exponent, and has been used frequently in cost estimation work.[25,26,27]

**Supplementary material from Grumman Aerospace Corporation.

100th unit is estimated to cost $3,350 per kW, compared to a MOD-0A cost at the 100th unit of $3,785 per kW. The parametric redesign 60-foot diameter diffuser would cost $1,863 per kW, which would be cheaper than the MOD-0A. If the cost estimates for the aluminum shroud design are realistic ($1,168 per kW at the 100th unit), this design would result in a cost of electricity less than one-third the cost per kW of the MOD-0A. This represents an 82 percent cost reduction from the first (steel) design, and therefore may be too optimistic.

In addition to steel and aluminum materials for shrouds, Tetra Tech considered the possibility of a ferrocement shroud. Complete DAWT structures may be constructed of ferrocement subassemblies made in factories, or constructed completely at the installation site. Ferro Boat Builders in Maryland, a company experienced in the designing and costing of ferrocement boat hulls, assisted Tetra Tech in this effort. Since they normally deal with large boat structures, Ferro Boat Builders costed out a 30,000-square foot shroud. The six-tenths factor then was applied to scale these costs down to the smaller diameter shrouds. Table D-6 shows the rough estimates for the 30,000-square foot shroud as given by Ferro Boat Builders; Table D-7 gives the estimated cost for the smaller diameter shrouds. According to these estimates, a ferrocement shroud is about 37 percent cheaper than an aluminum shroud (Table D-8). The cost for the 60-foot diameter, 200 kW diffuser with a ferrocement shroud is estimated to be $996 per kW, which is less expensive than the MOD-0A.

Fiberglass also would be an attractive material for shroud construction, and its cost probably would be between those of the ferrocement and aluminum shrouds. Lack of good cost data prevented an estimate of the fiberglass system cost. Table 3 is a summary of DAWT cost estimates for all materials costed for the shroud.

Of the augmented systems examined, the diffuser augmented wind turbine with a ferrocement, fiberglass, or aluminum diffuser appears the most promising. While the estimates are somewhat crude, and the scaling laws not well-known, the results justify a closer look at the economics of ferrocement shrouds. Although fiberglass costs for the diffuser were not established, they could be cost effective, and further research is recommended. Steel shrouds for the diffuser augmented system apparently are not cost effective in any size group.

Vortex Augmentor

Although the Polytechnic Institute of New York has continued work on the vortex augmentor concept for four years, no cost analysis has been published. A draft report that included economics had been expected during this project. Since this report was not forthcoming, an independent analysis was conducted to determine the cost of the system.

Table 3. DAWT COST ESTIMATES FOR 100th UNIT[a] (In Thousands of 1978 Dollars)

System	Turbine Cost[b,c]	Shroud Cost: Steel First[d] Design Study	Shroud Cost: Steel Redesign[d] Possibility	Shroud Cost: Aluminum	Shroud Cost: Ferrocement[e]	Total System Cost: Steel First Design Study	Total System Cost: Steel Redesign Possibility	Total System Cost: Aluminum	Total System Cost: Ferrocement
DAWT 18	9.8	124.7	54.7	21.9	13.8	134.5	64.4	31.8	23.5
DAWT 25	20.0	185.0	81.1	32.4	20.4	205.0	101.1	52.4	40.4
DAWT 46	78.1	385.0	168.6	67.4	42.5	464.0	247.0	145.6	120.6
DAWT 60	140.8	529.0	232.0	92.8	58.4	670.0	373.0	234.0	199.2

[a] All costs except the turbine are based on a 90 percent cost improvement curve; turbine costs are based on a 97 percent cost improvement curve.
[b] Supplementary material from Grumman Aerospace Corporation.
[c] Private communication with Jack Stotz, Grumman Energy Systems, Inc.
[d] K. M. Foreman and B. L. Gilbert, *Further Investigations of Diffuser Augmented Wind Turbines,* Draft Final Report, Grumman Aerospace Corporation, CO2-2616-78/1, December 1978.
[e] Ferro Boat Builders, Maryland.

For the two turbines placed in the vortex to extract power, four rotor diameters were considered: 5.5, 8, 11, and 15 m (18, 26, 36, and 49 feet). The delta wing and its supporting tower then were scaled accordingly. The detailed scaling methodology for the vortex augmentor concept is contained in Appendix E. Table E-1 shows the specifications for the turbines and the turbine support towers, and for the delta wing and its support tower.

The delta wing augmentor was costed in four sections: the delta wing, the delta wing support tower, the turbines, and turbine support towers. Fabrication and construction costs for the delta wing structure were estimated based on a combination of methods since structures of this size and function usually do not fall into a single, easily categorized group. Construction materials considered for the delta wing structure were steel, aluminum, ferrocement, and metal and fiberglass combination structures.

For the larger 2,230 m^2 (24,000-square foot) triangular assembly (49 m by 91 m or 161-foot base by 300-foot height), ferrocement and steel were not considered as structure materials, principally due to the excessive overall weight-to-stress relationship. For practical cost, construction, and operational reasons, the entire structure should be fabricated as a flexible aerodynamic frame since the operating wind forces imposed on this assembly will be large and fluctuating, resulting in large changing stresses. A rigid frame assembly for this device would be prohibitively heavy and relatively difficult to deploy. Hence, in estimating costs, consideration was given to a combination lightweight aluminum space frame and aluminum or fiberglass skin type of an assembly.

Production costs for the delta wing were based on recently produced welded space frame assemblies, having relatively loose overall tolerances and high flexibility. It was assumed that this assembly is a cantilevered, triangular shape supported on a single point with 360 degrees freedom horizontal pivot, and a radial roller thrust-bearing assembly (cost is included in the delta wing support structure discussed below). Approximate costs in 1978 dollars for the delta wing structure range from $35 to $42 per square foot of assembly surface. This cost range does not include engineering design, dynamic testing, erection, and special mechanical devices or instrumentation required for stress monitoring and attitude control.

The 65.5 m (215 foot) height by 35 m (115 foot) base delta wing structure could be manufactured in quantity for approximately $2.30 to $3.00 per m^2 ($25 to $32 per square foot) of surface area, assuming similar construction materials and generally the same support and operational constraints. The above costs assume a relatively simple jig-type manufacturing process. For the smaller delta wing, these costs then were reduced linearly with area and 5 to 6 percent engineering costs added.

Costs for the delta wing support structures (i.e., mounting towers) are generally easier to establish since their structural frame configuration is relatively common and similar to water tank towers and other vertical support structures. However, variable cost aspects such as height of the structure, the weight of the delta wing and turbines, foundation conditions, and the nature and extent of the anticipated wind-induced dynamic loads make cost estimation difficult. Since these factors have not been determined at this point, a specific in-place cost is difficult to postulate. For purposes of this analysis, a cost of \$18.60 per m^2 (\$200 per square foot) (including pivot assembly costs) of the tower horizontal section was assumed. The methodology for costing the two turbines and the two turbine towers is discussed in Appendix E.

For the 5.5, 8, and 11 m (18, 26, and 35 foot) rotor diameter systems, the dominant cost component is the delta wing support tower, followed by the delta wing structure. For the 15 m (49 foot) diameter rotor system, the delta wing structure costs more than the tower. Cost estimates can be found in Tables E-2 and E-3.

SYSTEM COMPARISON

For each wind energy system considered, the performance calculations and cost data have been combined to yield a measure of cost effectiveness—the cost of electricity in dollars per kWh. The cost of electricity for both conventional and augmented systems is determined below.

CONVENTIONAL SYSTEMS

Table 4 shows, for three conventional wind turbines, the annual energy output, total capital cost, annual cost, and the cost of electricity. The cost of electricity, as a function of output power, was calculated for the MOD-0A, MOD-1, and the single unit MOD-2 using the equation specified by SERI:

$$COE = \frac{(IC)\,(FCR) + (AOM)}{(AKWH)}, \tag{12}$$

where

COE = cost of electricity,
IC = initial or "turnkey" cost,
FCR = fixed charge rate (0.18/yr),
AOM = uniform annual operations and maintenance cost; and
AKWH = total annual kWh produced using the wind speed duration profile and including planned outages.

In dollars per kWh, the cost of electricity at sites with mean speeds of 18 to 12 mph varies from 3.5 to 6.6 cents per kWh for the MOD-2; from 6.5 to 18.0 cents per kWh for the MOD-1, and from 13.7 to 23.7 cents per kWh for the MOD-0A. Figure 11 summarizes these costs.

Table 4. SUMMARY OF ANNUAL ENERGY OUTPUT, COSTS, AND COST OF ELECTRICITY FOR MOD-0A, MOD-1, AND MOD-2 WIND TURBINES

Turbine	Annual Energy Output at 12 mph Mean Wind Site at 30 Feet (MWh); 90% Availability	Total Capital Cost 1978 Dollars 100th Unit	Annual Cost 1978 Dollars 100th Unit	Cost of Electricity (Cents per kWh)
MOD-0A	~ 640	757,000	151,400	23.7
MOD-1	~ 2,440	2,194,000	439,000	18.0
MOD-2	~ 7,030	2,279,000	462,000	6.6

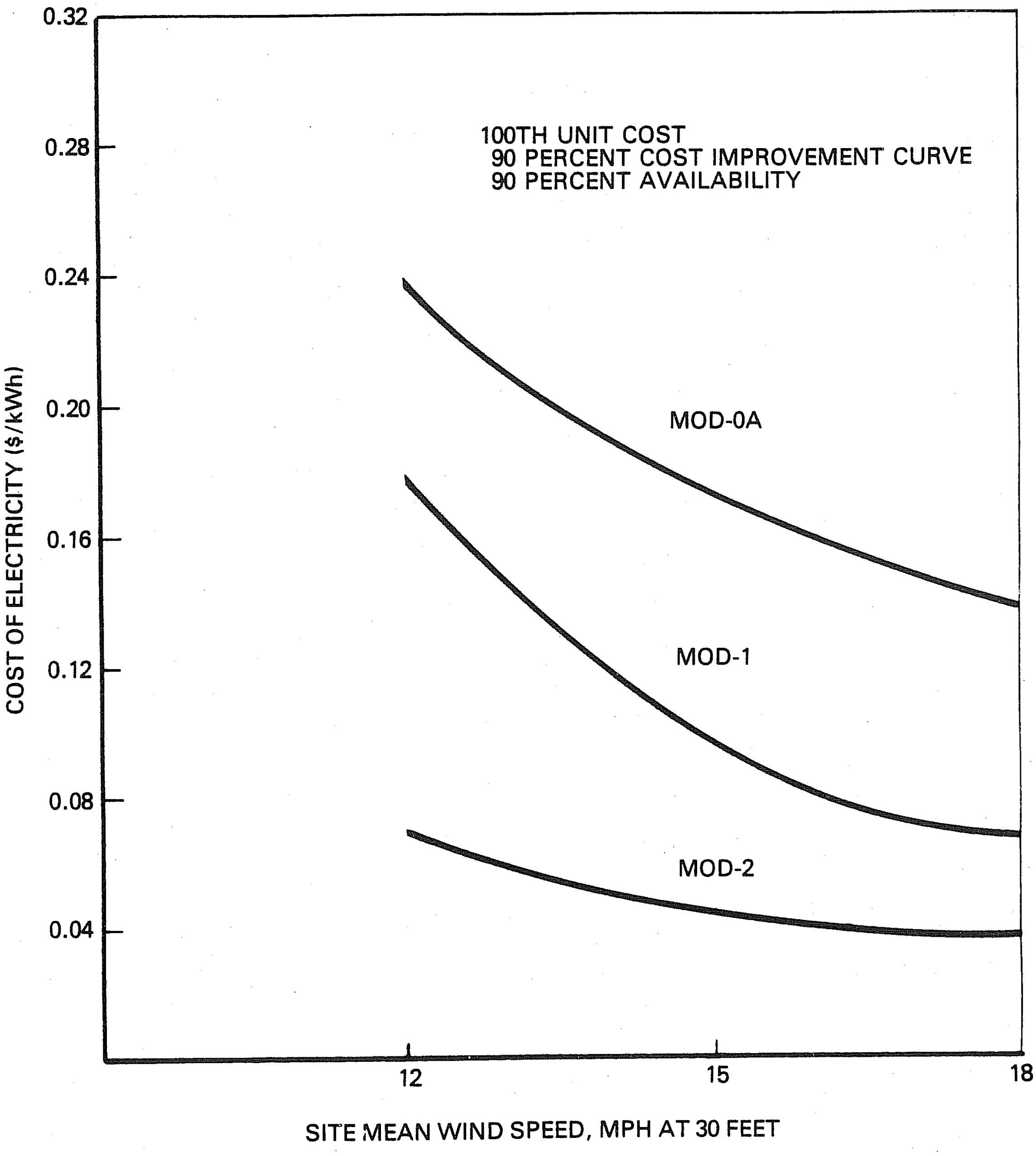

Figure 11. COST OF ELECTRICITY OF CONVENTIONAL WECS

AUGMENTED SYSTEMS

The cost of electricity for the augmented systems was calculated from the yearly energy output, initial capital costs, and an assumed annual operations and maintenance cost. Different augmentation factors were assumed for each system.

Dynamic Inducer

An augmentation factor of 1.6 was assumed in calculating yearly energy output for the dynamic inducer. Annual operations and maintenance costs were assumed to be the same as for a conventional system (2 percent of the initial cost). For a 200 kW system with aluminum, steel, fiberglass, or wood blades, the cost of electricity for the dynamic inducer was found to be virtually the same as for the conventional system. The prime reason for this similarity is that the 1 to 5 percent lower cost of the dynamic inducer is offset by the approximately 4 percent lower energy output. For a 2,000 kW system, the dynamic inducer cost of electricity was calculated to be about 1.2 to 4.3 percent less than for the conventional system. The 4.3 percent value is for aluminum blades and 1.2 percent is for steel, fiberglass, or wood blades; future blades are expected to be made of steel, fiberglass, or wood.

The dynamic inducer appears to offer a 4 percent cost effectiveness advantage, at most. This difference is insignificant because of the uncertainties in the cost estimates. In addition, this system has yet to be tested successfully in terms of producing power and augmentation. Also, the weight, and therefore the cost, of the tip vanes assumed by AeroVironment seems very low. Assuming both the rotor blades and the tip vanes are flat plates, the area of both can be calculated from the AeroVironment data.[20] The area of the tip vane is about 1.75 times that of the blade, yet its weight was assumed to be less than one-third of the blade weight by AeroVironment.[20] While centrifugal and lift forces may tend to cancel on the tip vane, it still seems hard to believe that the weight per area of the tip vane would be less than one-fifth that of the blade.

Diffuser Augmented Wind Turbine

The performance of the diffuser augmented wind turbine was calculated using an augmentation ratio of 6. This value may be optimistic, but Grumman believes it can be even higher. Also, a shroud length of one-half of the rotor diameter was used; Grumman believes the shroud can be even shorter, and therefore less expensive.

The cost of electricity for steel, aluminum, and ferrocement diffuser systems is shown as a function of rated power in Figure 12. Uncertainty of the cost estimate increases as the rated power increases. The cost of electricity for steel-shrouded systems at the lower power ratings is higher than that of the conventional Windstream 25; it is not expected that a steel shroud would be cost effective in this size range. The cost of electricity for this system at 200 kW is less than that of the expensive MOD-0A, but still is likely to be more than that of an advanced conventional system, such as the MOD-X. It is not expected that steel diffuser systems will be cost effective.

Aluminum diffusers may be cost effective. Using primarily the Grumman data, the cost of electricity with aluminum diffusers appears to be less than that for conventional systems. More work is needed to determine if aluminum shrouds actually could be this inexpensive.

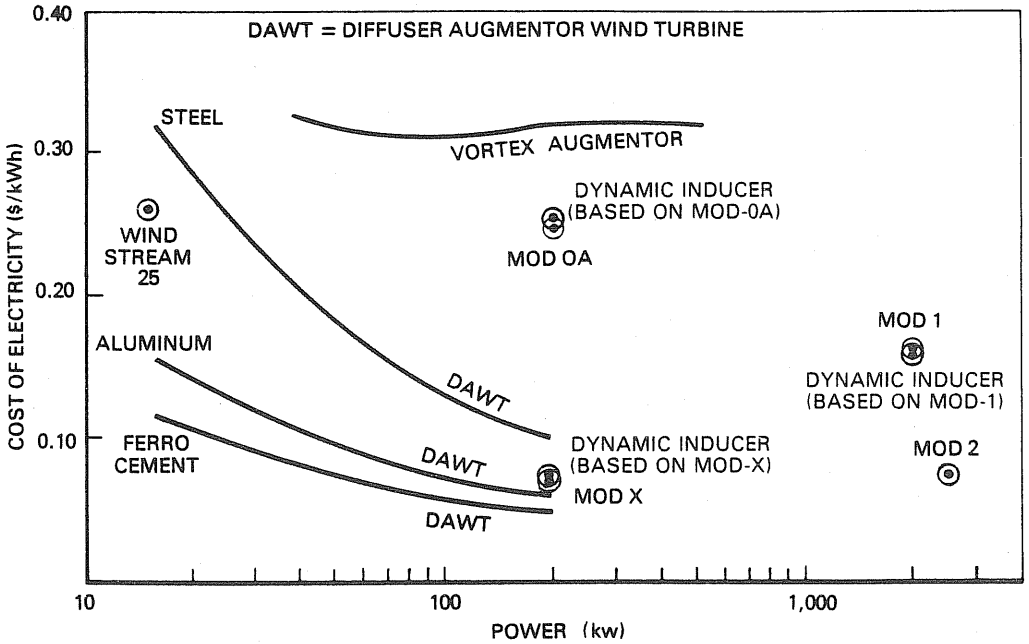

Figure 12. COST OF ELECTRICITY

Ferrocement shroud cost of electricity values may be even lower than the estimates for aluminum. Ferrocement costs were derived from the cost of building boats of this material. While the estimates are somewhat crude, and the scaling laws are not well-known, the results appear promising enough so that a closer look at the economics of ferrocement shrouds is justified. (As was mentioned previously, fiberglass costs for the diffuser were not established. However, further work to investigate cost effectiveness of fiberglass diffusers appears justified.)

Vortex Augmentor

To calculate cost of electricity for the vortex augmentor, an augmentation ratio of four was assumed. Since performance data still is lacking on this system, this is only a rough estimate. The cost of electricity for this concept, shown in Figure 12, appears to be too high to be competitive with the conventional systems. In addition, the cost of electricity does not decrease with size because the augmentor surface will be more difficult to build in the larger sizes.

SUMMARY AND CONCLUSIONS

The cost of electricity for the dynamic inducer might be slightly less than that of a conventional system at the larger (megawatt) sizes, if an augmentation ratio of 1.6 were achieved. However, augmentation has not been achieved, and tip vanes may be heavier and therefore more expensive than has been assumed. The choice of material does not appear to affect this conclusion. The dynamic inducer does not appear to be a promising approach to augmented systems development.

Of the augmented systems examined, the diffuser augmented wind turbine with a ferrocement, fiberglass, or aluminum diffuser appears the most promising. Steel shrouds for the diffuser augmented system do not appear to be cost effective in any size range. More work is needed to establish the augmentation ratio achievable. To date, augmentation ratios of about 3.5 have been achieved in wind tunnel tests, but reaching values of 6 or more depends on several trends and assumptions. A test of the best diffuser, combined with an appropriately designed turbine running at the proper tip speed ratio, is desirable. Unless this test is successful, testing a system in the real wind environment is not recommended. More work on the economics of diffusers built of ferrocement, fiberglass, or aluminum also is recommended. Some of these materials may have real promise, but not enough is known yet to reach firm conclusions on their cost effectiveness.

Performance data on the vortex augmentor concept are scarce, so that quantifying cost effectiveness is difficult. It appears, however, that the system requires too large and therefore too expensive an augmentation surface and support structure, especially for medium to large sizes. Unless forthcoming data show very high augmentation ratios, further work on medium or large size units is not justified.

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APPENDIX A

CONVENTIONAL HORIZONTAL AXIS WIND ENERGY MACHINE (MOD-0A, MOD-X, MOD-1, MOD-2) COSTS

METHODOLOGY FOR COSTING BLADES

Tables A-1 through A-5 in this Appendix present the results of calculating rotor blade costs as if they were all constructed of steel. Other materials, including wood, steel spar and rib, fiberglass, and aluminum, also were examined (Table A-6). The only costs available for these other materials were given for the MOD-X; aluminum costs also were available for the MOD-0A. Since the blade lengths were the same for both the MOD-X and MOD-0A, the cost per pound and weight for each of the materials was assumed to be the same for both conventional machines if constructed of the same material. With these costs given, the four various material costs can be estimated for MOD-1 blades. (Rated speed for the MOD-1 is higher than for the MOD-0A, but they are both first generation machines, and their cut-out speeds are similar.) These material costs include manufacturing labor costs and are complete fabrication costs. The methodology used is described below.

Wood blades for the MOD-0A cost about \$7.50 per pound at the 100th unit. Since the weight of the steel blades increased by a factor of 7.20 from a MOD-0A to a MOD-1, it was assumed that the weight of wood blades would increase by the same factor. MOD-0A wood blades weigh 4,000 pounds, hence MOD-1 wood blades would weigh 28,800 pounds. Using the six-tenths factor (a rule for determining the cost of a similar piece of equipment but of different capacity) to find the cost of MOD-1 wood blades, would result in:

$$\$30{,}000\left(\frac{28{,}000}{4{,}000}\right)^{0.6} = \$98{,}067 \qquad \text{(A-1)}$$

where:

\$30,000 = the total cost of wood blades for the MOD-0A at \$7.50 per pound;
28,800 = the weight (pounds) of MOD-1 wood blades;
4,000 = the weight (pounds) of MOD-0A wood blades; and
\$98,067 = the resulting total cost of MOD-1 wood blades, costing \$3.41 per pound at the 100th unit.

Utilizing the same methodology and assumptions, the costs of steel spar, fiberglass, and aluminum blades for the MOD-1 can be estimated. Table A-6 shows the cost of materials for the MOD-0A and MOD-1. Fiberglass, steel spar and rib, and wood appear to be attractive materials from a cost standpoint for blade fabrication.

Table A-1. 200 kW MOD-0A SYSTEM COSTS (1978 Dollars)

Component	Weight (Pounds)	100th Unit 90 Percent LC (Dollars)	Percent Total
Rotor	13,800	245,000	32
(steel blades)		(44,000)	(5.8)
Drive			
gearbox, generator, and hub support	26,800	144,000	19
yaw mechanism	3,900	43,000	5.7
Electrical			
electronic control		39,000	5.2
electrical system		39,000	5.2
Structure			
tower	45,000	50,000	6.6
foundation		33,000	4.4
Other			
safety system		12,000	1.6
shipping		10,000	1.3
installation		142,000	18.8
Total (includes G&A and profit (27 percent))	90,000	757,000	
$/kW		3,785	
O&M (2 percent)		15,140	
$/kW		76	
Annualized cost		151,400	

Characteristics

tower height 93 feet
rotor diameter 125 feet
pipe truss tower
steel blades 5,000 pounds

Source: Second unit costs and weights for the MOD-0A were found in NASA/Lewis Research Center, "200 kW Wind Turbine Generator Conceptual Design Study," DOE/NASA/1028-79/1, January 1979.

Table A-2. 200 kW MOD-X SYSTEM COSTS—FULL PITCHABLE ROTOR (1978 Dollars)

Component	Weight (Pounds)	100th Unit 90 Percent LC (Dollars)	Percent Total
Rotor			
blades (steel)	5,000	38,640	26
hub	2,800	10,819	7
PCM	1,700	6,624	4
controls	200	4,968	3
Drive-gearbox	15,000	19,872	13
Electrical			
generator	2,500	3,588	2
switchgear and wiring	1,600	4,195	3
capacitors	1,300	276	0.2
sliprings	100	497	0.3
Structure			
tower	41,500	34,362	23
bedplate	1,500	1,242	1
bearings		3,312	2
foundation		2,208	1
Other			
safety	20	1,104	1
shop assembly and test		9,936	7
shipping		1,656	1
installation and checkout		2,484	2
installations		4,554	3
Subtotal	73,220	150,337	
15 percent G&A		22,549	
15 percent profit		25,933	
Total		198,819	
$/kW		994	
O&M (2 percent)		3,976	
$/kW		20	
Annualized cost		39,763	

Characteristics

tower height 96 feet
rotor diameter 125 feet

cantilevered cylinder
rotating tower

steel blades 5,000 pounds

Source: Second unit costs and weights for the MOD-X were found in NASA/Lewis Research Center, "200 kW Wind Turbine Generator Conceptual Design Study, "DOE/NASA/1028-79/1, January 1979.

Table A-3. 2,000 kW MOD-1 SYSTEM COSTS (1978 Dollars)

Component	Weight (Pounds)	100th Unit 90 Percent LC (Dollars)	Percent Total
Rotor			(25.8)
blades (steel)	36,000	166,000	7.6
hub	41,200	202,100	9.2
torque control	42,600	95,400	4.3
controls	8,100	102,600	4.7
Drive			
bearing, drivetrain	73,400	182,600	8.3
yaw drive system	51,300	158,900	7.2
Electrical			
power generating equipment	70,100	171,900	7.8
Structure			
nacelle/structure	73,900	187,300	8.5
tower	352,700	213,500	9.7
Other			
assembly and test site		348,000	15.9
preparation, erection, and checkout		365,300	16.7
Total (including G&A, and fee)	749,300	2,193,600	
$/kW		1,097	
O&M (2 percent)		43,872	
$/kW		22	
Annualized cost		438,720	

Characteristics

tower height ≈ 128 feet
rotor diameter 200 feet

steel truss tower

steel blades 36,000 pounds

Source: General Electric Company, "MOD-1 Wind Turbine Generator Analysis and Design, Executive Summary," NAS 3-20058, December 1978, and General Electric Company, "MOD-1 Parametric Trade Study," Draft Final Report, 30 March 1978.

Table A-4. 2,500 kW MOD-2 (BOEING) SYSTEM COSTS (1978 Dollars)

Component	Weight (Pounds)	100th Unit 90 Percent LC (Dollars)	Percent Total
Rotor	170,000	353,400	21
Drive	100,000	407,110	24
Structure			
nacelle	70,000	197,650	12
tower	260,000	291,100	17
Other			
site preparation		174,020	10
transportation		31,150	2
erection		147,161	9
initial spares		37,600	2
non-recurring costs		37,600	2
Subtotal	600,000	1,676,791	
Fee (10 percent)		167,679	
Total		1,844,470	
$/kW		738	
O&M		16,113	
$/kW		6	
Annualized cost		348,118	

Characteristics

tower height 193 feet
rotor diameter 300 feet

steel shell tower
steel blades

25 unit cluster totaling 62.5 MW

Source: Boeing Engineering and Construction, "2,500 kW Wind Turbine System for Electric Power Generation," 8 January 1979.

Table A-5. 2,500 kW MOD-2 (NASA SINGLE UNIT) SYSTEM COSTS (1978 Dollars)

Component	100th Unit (Dollars)	Percent Total
Rotor	393,918	21
Drive	453,659	24
Structure		
nacelle	220,295	12
tower	324,842	17
Other		
site preparation	194,159	10
transportation	33,605	2
erection	164,288	9
initial spares	41,072	2
non-recurring costs	41,072	2
Total installed equipment	1,866,910	
Contingency (10 percent)	186,691	
	2,053,601	
AFDC	18,261	
Fee (10 percent)	207,186	
Total	2,279,048	
$/kW	912	
O&M	52,205	
$/kW	21	
Annualized cost	462,434	

Source: NASA/Lewis Research Center, "Wind Turbines for Electric Utilities: Development Status and Economics," 19 December 1978.

Table A-6. COST OF BLADE MATERIALS (1978 Dollars)

System	Material	Total Blade Weight (Pounds)	Production Unit ($/Pound)	Total Blade Costs (Dollars)
MOD-0A—MOD-X	Aluminum	4,700	41.28	194,016
	Fiberglass	4,400	6.36	27,984
	Steel spar and rib	7,000	3.71	25,970
	Wood	4,000	7.50	30,000
	Steel[a]	5,000	8.80	44,000
MOD-1	Aluminum	33,840	18.74	634,216
	Fiberglass	31,680	2.89	91,476
	Steel spar and rib	50,400	1.68	84,893
	Wood	28,800	3.41	98,067
	Steel[b]	36,000	4.61	166,000

[a]MOD-0A steel cost taken from Table A-1.
[b]MOD-1 steel cost taken from Table A-3.

Source: NASA/Lewis Research Center, "200 kW Wind Turbine Generator Conceptual Design Study," DOE/NASA/1028-79/1, January 1979, and material presented at Conference on Large Horizontal Axis Wind Turbines and Their Market Potential.

APPENDIX B

DYNAMIC INDUCER WECS COSTS

The methodology for scaling rotor weights is illustrated in Tables B-1 through B-12 for the various blade materials, and discussed in detail below.

Taking the conventional 100 kW machine (Table B-1) used in the AeroVironment study, the total blade weight of 1,660 pounds was divided into the total weight of the MOD-0A blades (the blades for both conventional machines are aluminum), yielding a factor of 2.83. To scale the dynamic inducer rotor up to 200 kW, the blade, tip vane, and tip vane attachment weights, as reported by AeroVironment, were multiplied by this factor, resulting in a total rotor weight of 4,044 pounds. The cost of aluminum blades for the MOD-0A at the 100th unit (90 percent cost improvement curve) is $41.28 per pound (as reported in Table A-6, Appendix A). Since in this case the blades and tip vanes for the dynamic inducer are aluminum, this cost per pound was used, resulting in a cost of $148,691. If the MOD-0A blades were steel, the cost would be $8.80 per pound at the 100th unit. This cost per pound was used for the steel tip vane attachments and resulted in a cost of $3,890. Therefore, the total rotor cost (excluding the hub and pitch control mechanism) is $152,581 for the 200 kW dynamic inducer (Table B-2).

Table B-1. SPECIFICATIONS OF 100 kW AND 200 kW WEC SYSTEMS WITH ALUMINUM ROTOR

Parameter	AeroVironment Conventional 100 kW	AeroVironment Tip Vaned 100 kW	MOD-X	MOD-0A 200 kW	Scaled up Tip Vaned 200 kW
Rotor diameter	125 ft	99 ft	125 ft	125 ft	99 ft
Blade weight (2) (aluminum)	1,660 lb	962 lb	4,700 lb	4,700 lb	2,724 lb
Tip vane weight (2) (aluminum)	—	310 lb	—	—	878 lb
Tip vane attachment (2) (steel)	—	156 lb	—	—	442 lb
Tower height	94 ft	74.5 ft	96 ft	93 ft	74.5 ft

To scale: 4,700 lb ÷ 1,660 lb = 2.8313

dynamic inducer blades: 962 lb × 2.8313 = 2,724
tip vanes: 310 lb × 2.8313 = 878
tip vane attachments: 156 lb × 2.8313 = 442
total weight 4,044 lb

Table B-2. 200 kW DYNAMIC INDUCER AND MOD-0A SYSTEM COST COMPARISON (Aluminum Rotor) (1978 Dollars)

Component	MOD-0A (100th unit) (Dollars)	Dynamic Inducer (100th unit) (Dollars)
Rotor	449,000	407,581
blades (aluminum)	194,000	112,447
tip vanes (aluminum)	—	36,244
attachments (steel)	—	3,890
hub, PCM	255,000	255,000
Drive (includes platform)	187,000	182,391
Electrical	78,000	78,000
Structure	83,000	83,000
tower	50,000	50,000
other	33,000	33,000
Other equipment/installation	164,000	164,000
System cost	961,000	914,972
$/kw	4,805	4,575
O&M	19,220	18,299
$/kw	96	92
Annualized cost	192,200	182,994

Note: The 200 kW tip vane WEC system represents a 4.8 percent savings of the total MOD-0A WECS costs, or $46,028.

The cost of aluminum blades for the MOD-1 would be $18.74 per pound at the 100th unit; steel costs, $4.61 per pound (as reported in Table A-6). Tables B-3 and B-4 show the scaling methodology and the detailed costs for the MOD-1 and the 2,000 kW dynamic inducer.

MOD-0A and MOD-1 costs were estimated as if the blades were steel, because steel was the blade material used for all conventional systems discussed in the cost section of the report. Tables B-5 and B-6 give the weight specifications used to scale the dynamic inducer up to 200 kW and 2,000 kW with an all-steel rotor, and Tables B-7 and B-8 show the detailed costs for each system. The cost of steel for MOD-0A blades at the 100th unit is $8.80 per pound; for MOD-1 blades, $4.61 per pound.

Applying the same methodology for scaling the dynamic inducer rotor, and using the price per pound of wood and fiberglass from Table A-6, the dynamic inducer cost with wood and fiberglass blades was estimated and compared to that of the MOD-0A and MOD-1. Tables B-9 through B-12 show the scaling methodology and blade costs for wood and fiberglass for the 200 kW and 2,000 kW dynamic inducer. (For the conventional WECS blade costs, refer to Appendix A.) All other systems costs and parameters remain the same unless otherwise specified.

Table B-3. SPECIFICATIONS OF 1,000 kW AND 2,000 kW WEC SYSTEMS WITH ALUMINUM ROTOR

Parameter	AeroVironment Conventional 1,000 kW	AeroVironment Tip Vaned 1,000 kW	MOD-1 2,000 kW	Scaled up Tip Vaned 2,000 kW
Rotor diameter	197. ft	156 ft	200 ft	156 ft
Blade weight (2) (aluminum)	4,978 lb	3,334 lb	33,840 lb	22,664 lb
Tip vane weight (2) (aluminum)	—	782 lb	—	5,316 lb
Tip vane attachment (2) (steel)	—	440 lb	—	2,991 lb
Tower height	147.6 ft	116.8 ft	128 ft	116.8 ft

To scale: 33,840 lb ÷ 4,978 lb = 6.7979

dynamic inducer blades:	3,334 lb × 6.7979 = 22,664
tip vanes:	782 lb × 6.7979 = 5,316
tip vane attachments:	440 lb × 6.7979 = 2,991
total weight	30,974 lb

Table B-4. 2,000 kW DYNAMIC INDUCER AND MOD-1 SYSTEM COST COMPARISON (Aluminum Rotor) (1978 Dollars)

Component	MOD-1 (100th unit) (Dollars)	Dynamic Inducer (100th unit) (Dollars)
Rotor	1,034,262	938,234
blades (aluminum)	634,162	424,723
tip vanes (aluminum)	—	99,622
attachments (steel)	—	13,789
hub, PCM, other	400,100	400,100
Drive	341,500	341,500
Electrical	171,900	171,900
Structure	400,800	383,006
tower	213,500	213,500
other (including platform)	187,300	169,506
Other equipment/installation	713,300	713,300
System cost	2,661,762	2,547,940
$/kw	1,331	1,274
O&M	53,235	50,959
$/kw	27	25
Annualized cost	532,352	509,588

Note: The 2,000 kW tip vane WEC system represents a 4.3 percent savings of the total MOD-1 WECS costs, or $113,822.

Table B-5. SPECIFICATIONS OF 100 kW AND 200 kW WEC SYSTEMS WITH STEEL ROTOR

Parameter	AeroVironment Conventional 100 kW	AeroVironment Tip Vaned 100 kW	MOD-X	MOD-0A 200 kW	Scaled up Tip Vaned 200 kW
Rotor diameter	125 ft	99 ft	125 ft	125 ft	99 ft
Blade weight (2)	1,660 lb (aluminum)	962 lb (aluminum)	5,000 lb (steel)	5,000 lb (steel)	2,898 lb (steel)
Tip vane weight (2)	—	310 lb (aluminum)	—	—	934 lb (steel)
Tip vane attachment (2) (steel)	—	156 lb	—	—	470 lb
Tower height	94 ft	74.5 ft	96 ft	93 ft	74.5 ft

To scale from aluminum blades to steel blades: 5,000 lb ÷ 1,660 lb = 3.012

dynamic inducer blades: 962 lb × 3.012 = 2,898
tip vanes: 310 lb × 3.012 = 934
tip vane attachments: 156 lb × 3.012 = 470
total weight 4,302 lb

Table B-6. SPECIFICATIONS OF 1,000 kW AND 2,000 kW WEC SYSTEMS WITH STEEL ROTOR

Parameter	AeroVironment Conventional 1,000 kW	AeroVironment Tip Vaned 1,000 kW	MOD-1 2,000 kW	Scaled up Tip Vaned 2,000 kW
Rotor diameter	197 ft	156 ft	200 ft	156 ft
Blade weight (2)	4,978 lb (aluminum)	3,334 lb (aluminum)	36,000 lb (steel)	24,111 lb (steel)
Tip vane weight (2)	—	782 lb (aluminum)	—	5,655 lb (steel)
Tip vane attachment (2) (steel)	—	440 lb	—	3,182 lb
Tower height	147.6 ft	116.8 ft	128 ft	116.8 ft

To scale from aluminum blades to steel blades: 36,000 lb ÷ 4,978 lb = 7.2318

dynamic inducer blades: 3,334 lb × 7.2318 = 24,111
tip vanes: 782 lb × 7.2318 = 5,655
tip vane attachments: 440 lb × 7.2318 = 3,182
total weight 32,948 lb

Table B-7. 200 kW DYNAMIC INDUCER AND MOD-0A SYSTEM COST COMPARISON (Steel Rotor) (1978 Dollars)

Component	MOD-0A (100th unit) (Dollars)	Dynamic Inducer (100th unit) (Dollars)
Rotor	245,000	238,857
blades (steel)	44,000	25,502
tip vanes (steel)	—	8,219
attachments (steel)	—	4,136
hub, PCM	201,000	201,000
Drive (includes platform)	187,000	182,391
Electrical	78,000	78,000
Structure	83,000	83,000
tower	50,000	50,000
other	33,000	33,000
Other equipment/installation	164,000	164,000
System cost	757,000	746,248
$/kw	3,785	3,731
O&M	15,140	14,925
$/kw	76	75
Annualized cost	151,400	149,250

Note: The 200 kW tip vane WEC system represents a 1.4 percent savings of the total MOD-0A WECS costs, or $10,752.

Table B-8. 2,000 kW DYNAMIC INDUCER AND MOD-1 SYSTEM COST COMPARISON (Steel Rotor) (1978 Dollars)

Component	MOD-1 (100th unit) (Dollars)	Dynamic Inducer (100th unit) (Dollars)
Rotor	566,060	551,991
blades (steel)	165,960	111,152
tip vanes (steel)	—	26,070
attachments (steel)	—	14,669
hub, PCM, other	400,100	400,100
Drive	341,500	341,500
Electrical	171,900	171,900
Structure	400,800	383,006
tower	213,500	213,500
other (including platform)	187,300	169,506
Other equipment/installation	713,300	713,300
System cost	2,193,560	2,161,697
$/kw	1,097	1,081
O&M	43,871	43,234
$/kw	22	22
Annualized cost	438,712	432,339

Note: The 2,000 kW tip vane WEC system represents a 1.5 percent savings of the total MOD-1 WECS costs, or $31,863.

Table B-9. SPECIFICATIONS OF 100 kW AND 200 kW WEC SYSTEMS WITH WOOD ROTOR

Parameter	AeroVironment Conventional 100 kW (Pounds)	AeroVironment Tip Vaned 100 kW (Pounds)	MOD-0A 200 kW (Pounds)	Scaled up Tip Vaned 200 kW (Pounds)
Blade weight (2)	1,660 (aluminum)	962 (aluminum)	4,000 (wood)	2,318 (wood)
Tip vane weight (2)	—	310 (aluminum)	—	747 (wood)
Tip vane attachment (2) (steel)	—	156	—	376

To scale from aluminum blades to wood blades: 4,000 lb ÷ 1,660 lb = 2.41

dynamic inducer blades:	962 lb × 2.41 = 2,318
tip vanes:	310 lb × 2.41 = 747
steel tip vane attachments:	156 lb × 2.41 = 376
total weight	3,441 lb

wood = \$7.50 per lb
steel = \$8.80 per lb

Blade Costs for Dynamic Inducer (100th unit):

2,318 lb × \$7.50 per lb =	\$17,385 blades
747 lb × \$7.50 per lb =	5,603 tip vanes
376 lb × \$8.80 per lb =	3,309 attachments
	\$26,297 total blades

Table B-10. SPECIFICATIONS OF 100 kW and 200 kW WEC SYSTEMS WITH FIBERGLASS ROTOR

Parameter	AeroVironment Conventional 100 kW (Pounds)	AeroVironment Tip Vaned 100 kW (Pounds)	MOD-0A 200 kW (Pounds)	Scaled up Tip Vaned 200 kW (Pounds)
Blade weight (2)	1,660 (aluminum)	962 (aluminum)	4,400 (fiberglass)	2,550 (fiberglass)
Tip vane weight (2)	—	310 (aluminum)	—	822 (fiberglass)
Tip vane attachment (2)	—	156	—	414

To scale from aluminum blades to fiberglass blades: 4,400 lb ÷ 1,660 lb = 2.65

dynamic inducer blades: 962 lb × 2.65 = 2,550
tip vanes: 310 lb × 2.65 = 822
steel tip vane attachments: 156 lb × 2.65 = 414
total weight 3,786 lb

fiberglass = \$6.36 per lb
steel = \$8.80 per lb

Blade Costs for Dynamic Inducer (100th unit):
2,550 lb × \$6.36 per lb = \$16,218 blades
822 lb × \$6.36 per lb = 5,228 tip vanes
414 lb × \$8.80 per lb = 3,643 attachments
\$25,089 total blades

Table B-11. SPECIFICATIONS OF 1,000 kW AND 2,000 kW WEC SYSTEMS WITH WOOD ROTOR

Parameter	AeroVironment Conventional 1,000 kW (Pounds)	AeroVironment Tip Vaned 1,000 kW (Pounds)	MOD-1 2,000 kW (Pounds)	Scaled up Tip Vaned 2,000 kW (Pounds)
Blade weight (2)	4,978 (aluminum)	3,334 (aluminum)	28,800 (wood)	19,287 (wood)
Tip vane weight (2)	—	782 (aluminum)	—	4,524 (wood)
Tip vane attachment (2) (steel)	—	440	—	2,545

To scale from aluminum blades to wood blades: 28,800 lb ÷ 4,978 lb = 5.79

dynamic inducer blades:	3,334 lb × 5.79 =	19,287
tip vanes:	782 lb × 5.79 =	4,524
steel tip vane attachments:	440 lb × 5.79 =	2,545
	total weight	26,356 lb

wood = \$3.41 per lb
steel = \$4.61 per lb

Blade Costs for Dynamic Inducer (100th unit):

19,287 lb × \$3.41 per lb =	\$65,769	blades
4,524 lb × \$3.41 per lb =	15,427	tip vanes
2,545 lb × \$4.61 per lb =	11,732	attachments
	\$92,928	total blades

Table B-12. SPECIFICATIONS OF 1,000 kW AND 2,000 kW WEC SYSTEMS WITH FIBERGLASS ROTOR

Parameter	AeroVironment Conventional 1,000 kW (Pounds)	AeroVironment Tip Vaned 1,000 kW (Pounds)	MOD-1 2,000 kW (Pounds)	Scaled up Tip Vaned 2,000 kW (Pounds)
Blade weight (2)	4,978 (aluminum)	3,334 (aluminum)	31,680 (fiberglass)	21,218 (fiberglass)
Tip vane weight (2)	—	782 (aluminum)	—	4,977 (fiberglass)
Tip vane attachment (2) (steel)	—	440	—	2,800

To scale from aluminum blades to fiberglass blades: 31,680 lb ÷ 4,978 lb = 6.36

dynamic inducer blades: 3,334 lb × 6.36 = 21,218
tip vanes: 782 lb × 6.36 = 4,977
steel tip vane attachments: 440 lb × 6.36 = 2,800
total weight 28,995 lb

fiberglass = $2.89 per lb
steel = $4.61 per lb

Blade Costs for Dynamic Inducer (100th unit):
21,218 lb × $2.89 per lb = $61,320 blades
4,977 lb × $2.89 per lb = 14,384 tip vanes
2,800 lb × $4.61 per lb = 12,908 attachments
$88,612 total blades

APPENDIX C

CONVENTIONAL TURBINE AND TOWER COST ESTIMATING RELATIONSHIPS

Each of the horizontal axis augmented wind energy conversion systems analyzed in this project includes a conventional wind turbine, supporting tower, and an augmentor; system costs include the costs of these subsystems. The augmented systems contain turbines and towers whose characteristics differ from those of the conventional systems discussed earlier. Consequently, the initial investment costs of these alternative subsystems differ as well.

Equations to estimate the costs of major components comprising turbines and towers had been developed in other studies, but the limited data made available to Tetra Tech on the characteristics of the augmented systems precluded their use. Therefore, equations were developed to estimate the costs of the wind turbines used in the different types of augmented systems. Because of the small data base, Tetra Tech was limited to only one or two variables for estimating cost. Consequently, it was not possible to capture the impact of different design approaches or technology (i.e., different types of hubs and rotor control systems).

Three equations were developed. The first equation estimates the initial costs of the turbine itself and includes the costs of the rotor, rotor control, drive mechanism, generator, and platform. The second equation estimates the cost of the tower that supports the turbine. The third and final equation estimates the tower height required to support a turbine of any given rotor diameter. The third equation was developed for use in cases where a turbine's tower height was not available or could not be calculated from other criteria.

TURBINE COSTS

The initial investment costs of a conventional turbine with steel blades can be estimated from the equation:

$$WTC = 0.00431 \cdot D^{2.2158} \cdot N, \qquad \text{(C-1)}$$

where:

WTC = the 100th-unit investment cost in thousands of 1978 dollars,
D = the rotor diameter (in feet) of that turbine; and
N = the number of blades contained in the turbine.

Equation (C-1) was developed from log-linear regression analyses of the costs and characteristics of the Grumman Windstream 25, MOD-0A, and MOD-1 conventional (horizontal axis, first generation) wind turbines. The data that were used are shown in Table C-1.

Table C-1. CONVENTIONAL WIND TURBINE COSTS AND CHARACTERISTICS (In Thousands of 1978 Dollars)

System	100th-Unit Cost[a]	Rotor Diameter (Feet)	Number of Blades
Windstream 25	16.0	25	3
MOD-0A	401.6	125	2
MOD-1	1,040.0	200	2

[a]Costs are manufacturing costs and exclude site-specific costs, transportation, contractor's burden, and fee. Rotor blades are fabricated from steel.

The equation that best fits these data and from which equation (C-1) was derived is:

$$\ln(WTC/N) = -5.447 + 2.2158\,(\ln D), \qquad \text{(C-2)}$$

where ln (WTC/N) is the natural logarithm of WTC divided by N; and WTC, D, and N are the same as in equation (C-1).

Equation (C-2) was significant at the 95 percent confidence level and explained over 99 percent of the variation observed in ln(WTC/N).

The fit of equation (C-1) in estimating the costs in Table C-1 was:

System	Actual	Estimate	Percent Difference
Windstream 25	16.0	16.2	−1.2
MOD-0A	401.6	381.8	4.9
MOD-1	1,040.0	1,081.6	−4.0
Root Mean Square Error (MSE) =			−1.5

Tower Costs

The initial investment cost of conventional towers was estimated from the equation:

$$TC = 3.439 \cdot 1.032^{H} \cdot 0.993^{(H \cdot \sigma COL)}, \qquad \text{(C-3)}$$

where:

TC = the 100th-unit investment cost in thousands of 1978 dollars;

H = the tower height in feet; and

σCOL = a dummy variable that equals one for cylindrical, columnar towers, and zero otherwise.

The data that were analyzed to develop equation (C-3) are shown in Table C-2.

Table C-2. WIND TURBINE TOWER COSTS AND CHARACTERISTICS (In Thousands of 1978 Dollars)

System	100th Unit Cost (Dollars)	Tower Height (Feet)	Type of Tower
MOD-0A	65.4	93	Truss
MOD-1	183.0	128	Truss
MOD-2	371.1	193	Column[a]
MOD-X	34.4	96	Column[a]

[a]σCOL equals one for these towers.

The equation that best fits the tower cost data is:

$$\ln TC = 1.2352 + 0.0313H - 0.0071\,(H \cdot \sigma COL), \qquad \text{(C-4)}$$

where TC, H, and σCOL are the same as in equation (C-3).

Equation (C-4) was significant at the 95 percent level of confidence and explained over 99 percent of the variation observed in ln TC.

The fit of equation (C-3) for estimating tower costs was:

System	Actual	Estimate	Percent Difference
MOD-0A	65.4	63.0	2.4
MOD-1	183.0	188.1	−5.1
MOD-2	371.1	367.3	3.8
MOD-X	34.4	35.1	−0.7

Root Mean Square Error (MSE) = −0.1

TOWER HEIGHT

In cases where tower height is not specified, it can be estimated as a function of rotor diameter by the equation:

$$H = 1.576 \bullet D^{0.841}, \qquad \text{(C-5)}$$

where H is the tower height in feet, and D is the rotor diameter in feet.

Equation (C-5) was derived from analysis of the data shown in Table C-3.

Table C-3. TOWER HEIGHT DATA

System	Tower Height (Feet)	Rotor Diameter (Feet)
Windstream 25	17.7[a]	18
MOD-0A	93.0	125
MOD-1	128.0	200
MOD-2	193.0	300

[a]Height used in DAWT system.

Equation (C-5) was derived from the log-linear equation:

$$\ln H = 0.4451 + 0.841 \bullet \ln D, \qquad \text{(C-6)}$$

where H and D are the same as in equation (C-5).

Equation (C-6) was significant at the 95 percent level of confidence and explained over 99 percent of the variation observed in ln H.

The fit of equation (C-5) in estimating turbine tower height was:

System	Actual	Estimate	Percent Difference
Windstream 25	17.7	17.73	−0.2
MOD-0A	93.0	90.45	2.7
MOD-1	128.0	134.28	−4.9
MOD-2	193.0	188.83	2.2
Root Mean Square Error (MSE) =			−0.1

APPENDIX D

DIFFUSER AUGMENTED WIND TURBINE COSTS

Table D-1. FIRST DESIGN (STEEL) DAWT COST PROJECTIONS FOR PROTOTYPE (In 1978 Dollars)

Description	Diameter (Feet)	Area (Square Feet)	Material and Parts	Turbine	Manufacturing Labor Costs	Assembly, Shipping, Erection	System Cost	Annual O&M	Annualized Cost
First design study (36,000	18	677	41,000	11,959	113,000	97,000	262,959	5,259	52,592
psi Y.S. steel) diffuser	25	1,306	60,813	24,480	167,607	143,874	396,774	7,935	79,354
weight ~ 44,000 pounds	46	4,422	126,416	95,636	348,415	299,082	869,549	17,391	173,910
	60	7,524	173,900	172,311	479,286	411,422	1,236,919	24,738	247,384

Note: The total area of the DAWT-18 shroud is 677 square feet. The cost of material and parts is $41,000. The area of the DAWT-25 shroud is 1,306 square feet. Using the six-tenths factor:

$$\$41{,}000\left(\frac{1306}{677}\right)^{0.6} = \$60{,}813$$

where: $60,813 is the cost of materials and parts for the DAWT-25.

Table D-2. PARAMETRIC REDESIGN (STEEL) DAWT COST PROJECTIONS FOR PROTOTYPE
(In 1978 Dollars)

Description	Diameter (Feet)	Area (Square Feet)	Material and Parts	Turbine	Manufacturing Labor Costs	Assembly, Shipping, Erection	System Cost	Annual O&M	Annualized Cost
One parametric redesign	18	677	20,000	11,959	60,000	30,000	121,959	2,439	24,392
possibility (160,000 psi	25	1,306	29,665	24,480	88,995	44,497	187,637	3,753	37,527
Y.S. steel) diffuser weight	46	4,422	61,666	95,636	184,999	92,499	434,800	8,696	86,960
9,000 pounds	60	7,524	84,829	172,311	254,488	127,244	638,872	12,777	127,774

Table D-3. DAWT COST PROJECTIONS FOR 100th UNIT

	(In 1978 Dollars)						
Diameter (Feet)	Materials and Parts	Turbine[a]	Manufacturing Labor Costs	Assembly, Shipping, Erection	System Cost	Annual O&M	Annualized Cost
First Design Study							
18	20,377	9,771	56,161	48,209	134,518	2,690	26,904
25	30,224	20,000	83,301	71,505	205,030	4,101	41,006
46	62,829	78,135	173,162	148,644	462,770	9,255	92,554
60	86,428	140,778	238,205	204,477	669,888	13,398	133,978
Parametric Redesign Possibility							
18	9,940	9,771	29,820	14,910	64,441	1,289	12,888
25	14,744	20,000	44,231	22,115	101,090	2,022	20,218
46	30,648	78,135	91,945	45,972	246,700	4,934	49,340
60	42,160	140,778	126,481	63,240	372,659	7,453	74,532

[a]All costs are based on a 90 percent cost improvement curve with the exception of the turbine. Turbine costs for DAWT-25 are based on estimates for production unit given by Grumman via several telephone conversations. Cost improvement curve appears to be about 97 percent for the turbine.

Table D-4. REVISED (ALUMINUM) DAWT COST ESTIMATES FOR PROTOTYPE (In 1978 Dollars)

Description	Diameter (Feet)	Shroud	Turbine[a]	System Cost		Annual O&M	Annualized Cost
Stressed aluminum	18	44,000	25,000	69,000	Grumman	1,380	13,800
	25	65,262	25,000	90,262		1,805	18,052
	46	135,666	95,636	231,302	Tetra Tech	4,626	46,260
	60	186,625	172,311	358,936		7,179	71,787

[a]Grumman assumed costs for the 18 and 25 foot diameter turbines to be the same since the blades of the 25 foot diameter turbine was cut back to an 18-foot diameter turbine. In this case, Grumman assumed a 90 percent cost improvement curve for turbines.

Table D-5. REVISED (ALUMINUM) DAWT COST ESTIMATES FOR 100th UNIT (In 1978 Dollars) (90 Percent Cost Improvement Curve)

Diameter (Feet)	Shroud	Turbine[a]	System Cost	Annual O&M	Annualized Cost
18	21,868	12,425	34,293	686	6,859
25	32,435	12,425	44,860	897	8,972
46	67,426	47,531	114,957	2,299	22,991
60	92,753	85,639	178,392	3,568	35,678

[a]Grumman assumed costs for the 18- and 25-foot diameter turbines to be the same since the blades of the 25-foot diameter turbine was cut back to an 18-foot diameter turbine. In this case, Grumman assumed a 90 percent cost improvement curve for turbines.

Table D-6. COSTS FOR A 30,000 SQUARE FOOT (702,500 POUND) DIFFUSER SHROUD WITH A 1½ INCH THICK SKIN (Prototype)

1. Light weight aggregate mortar

   105 pounds per foot^3 or 393,750 pounds
   $6 per foot^3 or 5.71¢ per pound

   Total cost = $22,500

2. Steel

   82,500 pounds of steel of which one-third is mesh and two-thirds is reinforcing bar.

   mesh - 27,500 pounds at $2 per pound = $55,000
   rebar - 55,000 pounds at $0.22 per pound = $12,100

   Total cost = $67,100

3. Total material costs = $89,600

4. Labor costs (including manufacturing, assembly, shipping, and erection) = $180,000.

5. Total cost of shroud = $269,600 ($8.99 per foot^2) excluding 20 percent general contractors fee.

Table D-7. FERROCEMENT DIFFUSER COST ESTIMATES

	In 1978 Dollars					
Diameter (Feet)	Material	Turbine[a]	Manufacturing Labor Costs, Assembly, Shipping, Erection	System Cost	Annual O&M	Annualized Cost
			Prototype			
18	9,213	11,959	18,508	39,680	794	7,936
25	13,666	24,480	27,455	65,601	1,312	13,120
46	28,407	95,636	57,069	181,112	3,622	36,222
60	39,076	172,311	78,500	289,887	5,798	57,977
			Ferrocement Diffuser—100th Unit (90 Percent Cost Improvement Curve)			
18	4,579	9,771	9,198	23,548	471	4,710
25	6,792	20,000	13,645	40,437	809	8,087
46	14,118	78,135	28,363	120,616	2,412	24,123
60	19,421	140,778	39,015	199,214	3,984	39,843

[a]Turbine costs are based on Grumman estimate via telephone conversations, for 25 foot diameter and scaled accordingly. Cost improvement curve appears to be about 97 percent for the turbine.

Table D-8. REVISED DAWT ALUMINUM SHROUD AND FERROCEMENT SHROUD COST COMPARISONS (100th UNIT, 1978 DOLLARS)

		Shroud		Total Cost	
	Turbine[a]	Aluminum	Ferrocement	Aluminum	Ferrocement
DAWT-18	9,771	21,868	13,777	31,839	23,548
DAWT-25	20,000	32,435	20,437	52,435	40,437
DAWT-46	78,135	67,426	42,481	145,561	120,616
DAWT-60	140,778	92,753	58,436	233,531	199,214

[a]All costs except the turbine are based on a 90 percent cost improvement curve. Turbine costs are based on a 97 percent cost improvement curve.

APPENDIX E

VORTEX AUGMENTOR CONCEPT COSTS

SYSTEM SCALING AND COSTING METHODOLOGY FOR THE VORTEX AUGMENTOR CONCEPT

Turbine and Turbine Support Tower

Rotors were considered in 18, 26, 35, and 49 foot diameters. Heights for the two towers supporting the turbines were scaled from the turbine tower equation, discussed in Appendix C:

$$H = 1.576 \bullet D^{0.841}, \qquad \text{(E-1)}$$

where H is the tower height in feet, and D is the rotor diameter in feet.

Since the two towers that support the turbines are slanted, the result of equation (E-1) was applied to equation (E-2) to find the angled height:

$$SH = \sqrt{2} \bullet H, \qquad \text{(E-2)}$$

where SH is the slanted tower height in feet, and H is the tower height in feet from equation (E-1).

Turbine costs were estimated from the turbine cost equation discussed in Appendix C:

$$WTC = 0.00431 \bullet D^{2.2158} \bullet N, \qquad \text{(E-3)}$$

where:

WTC = the 100th-unit investment cost in thousands of 1978 dollars,
D = the rotor diameter in feet, and
N = the number of blades (in this case, three per turbine).

Since there are two turbines, the result of equation (E-3) was doubled, and G&A and fee (25 percent) were added to give the fully burdened turbine costs.

Turbine tower costs were estimated by the tower cost equation discussed in Appendix C:

$$TC = 3.439 \bullet 1.032^{H} \bullet 0.993^{(H \bullet \sigma COL)}, \qquad \text{(E-4)}$$

where:

TC = the 100th-unit investment in thousands of 1978 dollars;
H = the tower height in feet; and
σCOL = a dummy variable that equals one for cylindrical, columnar towers, and zero otherwise (in this case, equals one).

Equation (E-4) gives the cost of one turbine tower, so the result was doubled for two towers, and G&A and fee (25 percent) were added to the final cost to give fully burdened turbine tower costs.

Delta Wing and Delta Wing Support Tower

Tetra Tech scaled the delta wing structure from the 18-foot long delta surface prototype built by the Polytechnic Institute of New York. Specifically:

$$L = 6.1D, \qquad \text{(E-5)}$$

where L is the length of the delta wing in feet, and D is the rotor diameter in feet; and

$$W = 3.3D, \qquad \text{(E-6)}$$

where W is the width of the delta wing in feet, and D is the rotor diameter in feet. Equations (E-5) and (E-6) give the dimensions of the delta wing structures for rotor diameters of 18, 26, 35, and 49 feet.

The 35-foot rotor diameter delta wing structure has a power output of 200 kW. The height of the tower that supports this delta wing was determined to be comparable to the height of the tower for a 200 kW conventional wind machine. From this, the heights of the towers supporting the other delta wing structures and their turbines were scaled according to equation (E-7):

$$H = 2.43D, \qquad \text{(E-7)}$$

where H is the tower height in feet, and D is the rotor diameter in feet.

The base of the delta wing tower was scaled according to equation (E-8):

$$B = \tfrac{1}{2}H, \tag{E-8}$$

where B is the tower base in feet, and H is the tower height in feet from equation (E-7).

Table E-1 gives the specifications for the vortex augmentor concept, and Tables E-2 and E-3 show the cost estimates for the prototype and the 100th unit.

Table E-1. SPECIFICATIONS OF THE VORTEX AUGMENTOR CONCEPT

Rotor Diameter (Feet)	Turbine Tower Height (Feet)	Delta Wing Structure (Feet)	Delta Wing Support Structure (Feet)
18	25.1 each	½ (110 × 59) or (3,245 ft^2)	½ (43.74 × 21.87) or (478.3 ft^2)
26	34.2 each	½ (160 × 86) or (6,880 ft^2)	½ (63.18 × 31.59) or (997.9 ft^2)
35	43.9 each	½ (215 × 115) or (12,362 ft^2)	½ (85.05 × 42.53) or (1,808 ft^2)
49	58.3 each	½ (300 × 161) or (24,150 ft^2)	½ (119 × 59.54) or (3,542.6 ft^2)

Table E-2. VORTEX AUGMENTOR COST ESTIMATES FOR PROTOTYPE (In 1978 Dollars)

Rotor Diameter (Feet)	Turbine Cost	Turbine Tower Cost	Delta Wing	Delta Wing Support Structure	Total Cost
18	39,320	31,972	53,240	192,475	317,007
26	88,813	39,960	239,340	401,569	769,682
35	171,604	50,664	704,430	727,565	1,654,263
49	361,676	72,052	1,973,650	1,425,594	3,832,972

Table E-3. VORTEX AUGMENTOR COST ESTIMATES FOR 100th UNIT (90 Percent Cost Improvement Curve) (In 1978 Dollars)

Rotor Diameter (Feet)	Turbine Cost	Turbine Tower Cost	Delta Wing	Delta Wing Support Structure	Total Cost
18	19,542	15,890	26,459	95,660	157,551
26	44,140	19,860	118,954	199,580	382,534
35	85,287	25,180	350,101	361,600	822,168
49	179,753	35,810	980,905	708,520	1,904,988

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