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Richard Mitchell

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NOTICE

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Richard L. Mitchell
Solar Energy Research Institute

ABSTRACT

The Electrofluid Dynamic wind-driven generator has been investigated under government supported programs since 1975. The concept features the direct conversion of wind energy into electrical power with virtually no moving parts. Research on this concept has resulted in a detailed operational theory of electrofluid systems and a preliminary conceptual design of a full-scale generator. Analysis of the potential of this concept has established a range for the value indicators and an understanding of its optimization potential and uncertainty. A comparison is made between the value indicators for the Electrofluid Dynamic concept and those of several conventional WECS.

NOMENCLATURE

a	Dimensionless vertical spacing parameter
b	Dimensionless horizontal spacing parameter
D	Electrode diameter (m)
k	Mobility (m^2/V-s)
S_L	Horizontal electrode spacing (m)
S_T	Vertical electrode spacing (m)
U	Velocity (m/s)
V	Voltage

ELECTROFLUID DYNAMIC CONCEPT

The search for cost reduction in wind energy conversion has often led to efforts to simplify the conversion system and minimize its moving components. The Electrofluid Dynamic (EFD) wind-driven generator is one of the results of these efforts. The basic principle behind the EFD concept is the use of an aerosol particle as the active element in a drag type Wind Energy Conversion System (WECS). These particles—liquid droplets or hollow spheres (bubbles)—are charged and carried by the wind into an electrical field. This field exerts an electrical force on the particles which is opposite of the wind direction. As it responds to this field, the particles extract the kinetic energy from the wind through the drag force exerted on them. Unlike a conventional WECS that uses a mechanical coupling between the active elements and the generator, the EFD generator uses an electrical field coupling. An advantage of this arrangement is that it requires a minimum of moving parts.

This system has two main parts: the colloid charging section and the working section. As shown in Figure 1, the working section consists of an inlet/attractor electrode (item 2) and a collector electrode (item 3). The aerosol is charged with one polarity by a corona discharge wire or other charging system (item 1) and enters the working area. The wind then pushes the charged particle up the potential hill to the collector electrode. At this point the charged cloud, formed behind the EFD rig following start-up, aids the collector electrode in the collection of the charged particles. The high voltage power supply and feedback control system (items 4 and 5) ensure that the charge is drained at an adequate rate and that the field voltage is optimum for the working section. The concept typically uses very high voltage and low current (330 kV, 15 microamps/m^2).

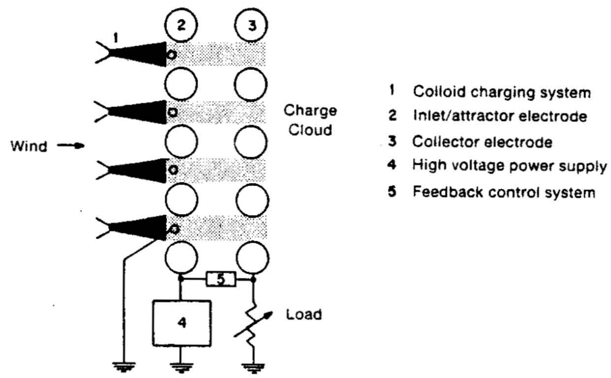

Fig. 1. Schematic of the EFD Wind-Driven Generator

Research on the Electrofluid Dynamic wind-driven generator has been underway at the University of Dayton since 1975. Initial support was provided by the National Science Foundation (NSF) (Grant No. AER75-00931), followed by support from the Department of Energy (DOE) (Contract EY-76-S-02-4130). In 1978 the technical monitoring responsibility for this and other research in the Wind Energy Innovative Systems was transferred to the Solar Energy Research Institute (SERI) (Subcontracts XH-9-8074-1 and XE-1-1291-1). These efforts have resulted in the development of analytical models for aerosol and generator performance. Wind tunnel configurations have been tested to verify the theoretical models and to establish the performance characteristics of the EFD concept (Figure 2).

Through these analyses and wind tunnel tests, researchers have developed many electrode shapes and configurations that have acceptable performance (Figures 3 and 4). As a result of these studies, it has been determined that the EFD concept has sufficient potential for a conceptual design and evaluation study.

A detailed analytical model of the EFD system including field mapping, field breakdown limits, geometric parameters, and performance characteristics was developed under the NSF grant (1). The Energy Research and Development Administration (ERDA) contract that followed [E(11-1)-4130] resulted in the construction of an EFD wind tunnel test rig, shown in Figure 2. Performance tests were then conducted to determine the operating characteristics of the concept (2). Subsequent design improvements and operational changes resulted in a power output increase of 20 times over the original measurements. This research also established the adequacy of field charging of water droplets of adequate sizes; i.e., below 4μ in diameter. With the transfer of monitoring responsibility to DOE and SERI, the theoretical model was verified, as shown in Figure 5, and a detailed study was conducted on the effects of geometry on performance (3,4).

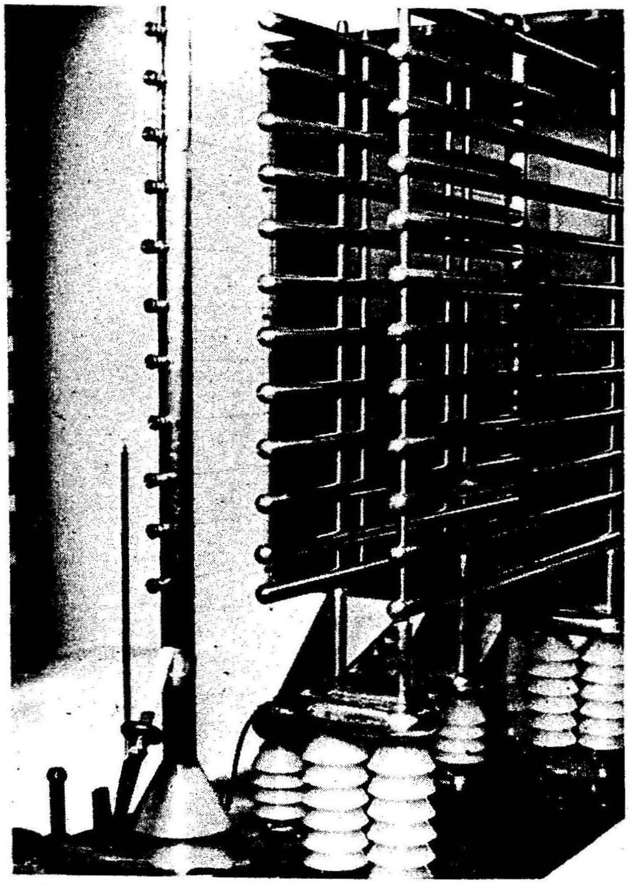

Fig. 2. Cylindrical Collector Electrode Wind Tunnel Test Rig

Wind tunnel tests have indicated that the more important parameters are particle mobility ($k = m^2/V\text{-}s$), electrode diameter (D), vertical electrode spacing (S_T), horizontal spacing (S_L), field voltage (V), and wind velocity (U). The dimensionless parameters $a = S_TD$ and $b = S_L/D$ were analyzed with regard to performance (Figure 6). As shown in Figure 7, the sensitivity of average power to changes in a is fairly pronounced for higher wind speeds and particularly in the range of a = 3.0. On the other hand, changes in parameters b and D did not cause significant changes in the average power output.

Earlier efforts demonstrated that water droplets, although good performers in an EFD concept, could not be generated with the low mobilities required for high efficiency operation. Therefore, subsequent research efforts were concentrated in the production of low mobility bubbles, which can be generated either singly or in agglomerates with the necessary mobility. Analysis of the optimum configuration for a full-size bubble generator, including pumping and charging requirements, produced encouraging results as shown in Figure 8.

CONCEPTUAL DESIGN

In response to the promising studies conducted to date, the current SERI-supported effort is pursuing the development of a conceptual design for an EFD wind generator having an average power output of 2.25 MW. The University of Dayton has established the operational parameters, with particular attention to the material requirements versus system performance. These parameters were used in the development of a conceptual design and performance estimate.

The wind resource for the conceptual design was chosen at 6 m/s with an assumed 1/7 power law. Since the EFD concept is considered unidirectional in this analysis, it is important to establish whether a unidirectional wind site with an annual average wind speed of 6 m/s is reasonable. The wind roses shown in Figure 9 indicate that the wind is predominantly unidirectional in more than one location. It is far more important, however, to establish an energy rose for evaluation. An analysis of the energy rose for Honolulu indicates that a site with an average wind speed of 7 m/s from the prominent wind direction and around 3 m/s from the other points will not only have an overall average of 6 m/s, but will generate an average of 6 m/s from a single compass point when the cosine law is applied to the off-axis winds. It is therefore appropriate to select a 6 m/s unidirectional wind site for the analysis of the EFD generator according to both the comparisons of yearly energy output and the probability of these sites occurring.

The parameter b was chosen to be 1.656 in order to minimize field breakdown and to maximize the operating range. The parameter a was chosen to be 3.0 using the curves shown in Figure 7 with additional consideration for drag and material requirements. The electrode diameter D was set at 0.3048 m from the evaluation of drag forces and the system performance.

POTENTIAL ANALYSIS

An analysis was performed on this design to establish the conversion efficiency at various heights with the wind speed of 6 m/s measured at 10 m, as shown in Figure 10. Under these conditions an EFD working section between 5 m and 65 m high will produce an average of 93.8 W/m^2 after

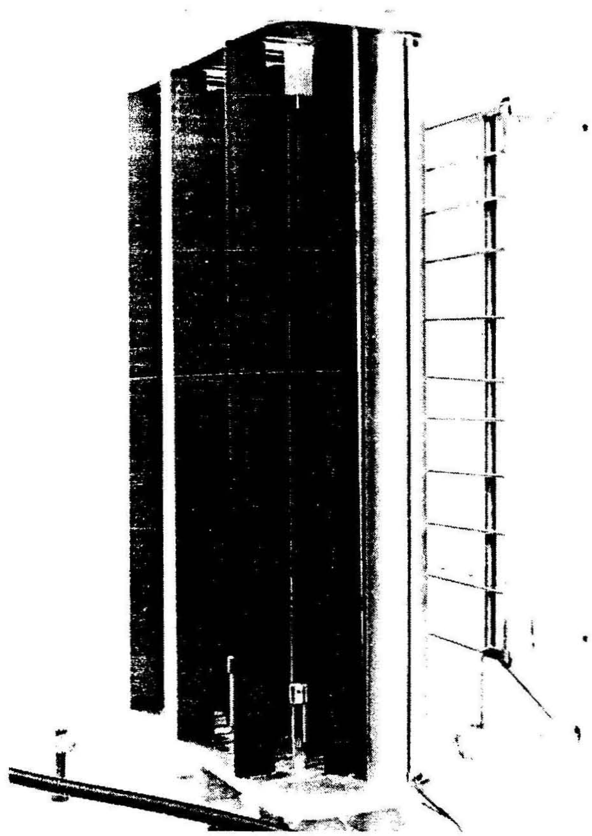

Fig. 3. Large Electrode Geometry Wind Tunnel Test Rig

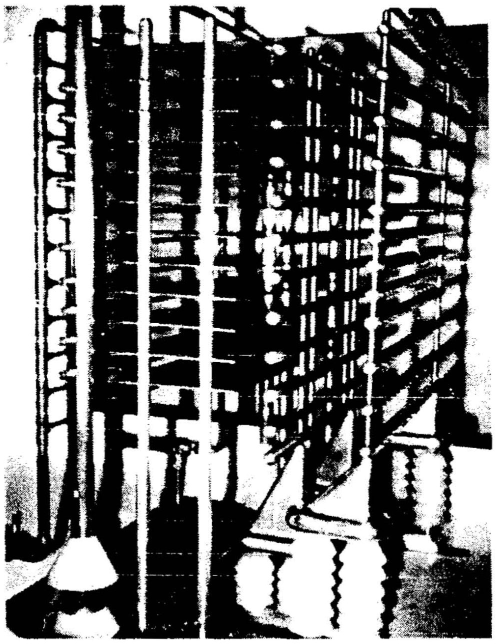

Fig. 4. Multistage Electrode Configuration Wind Tunnel Test Rig

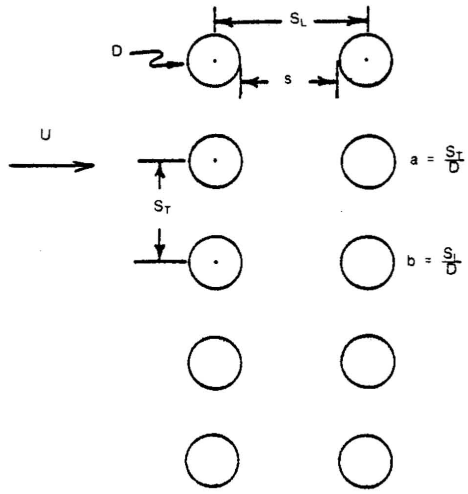

Fig. 6. Electrode Spacing Notation for the EFD Generator

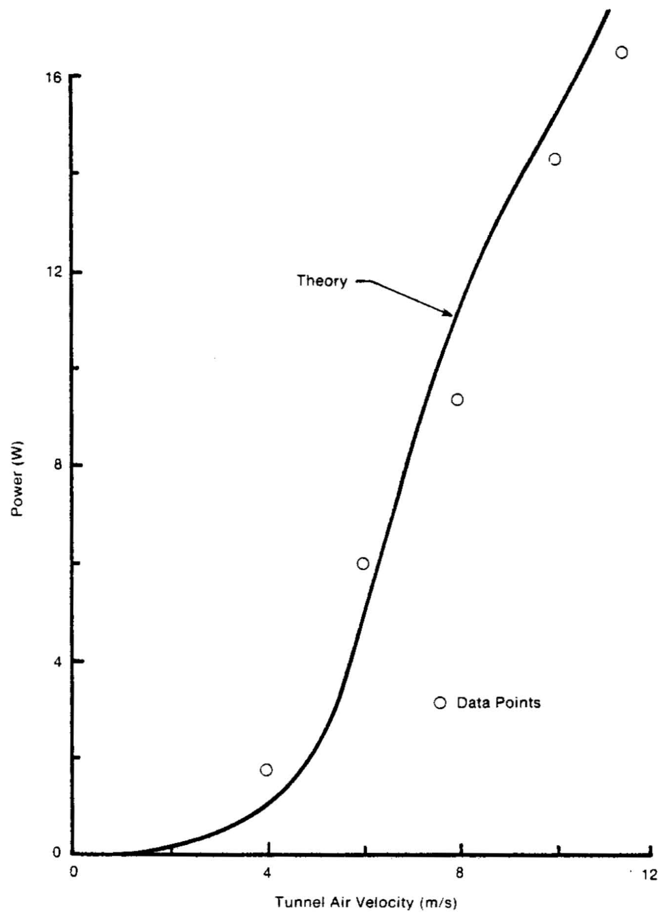

Fig. 5. Comparison of EFD Wind Tunnel Test Data with Theory

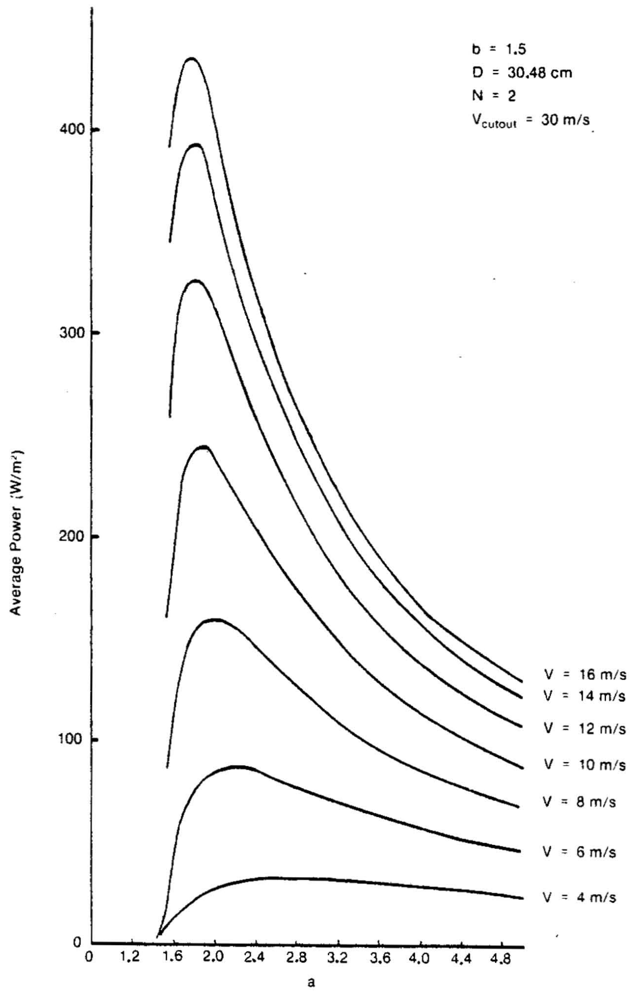

Fig. 7. Average Power Density Versus Vertical Electrode Spacing as a Function of Wind Speed

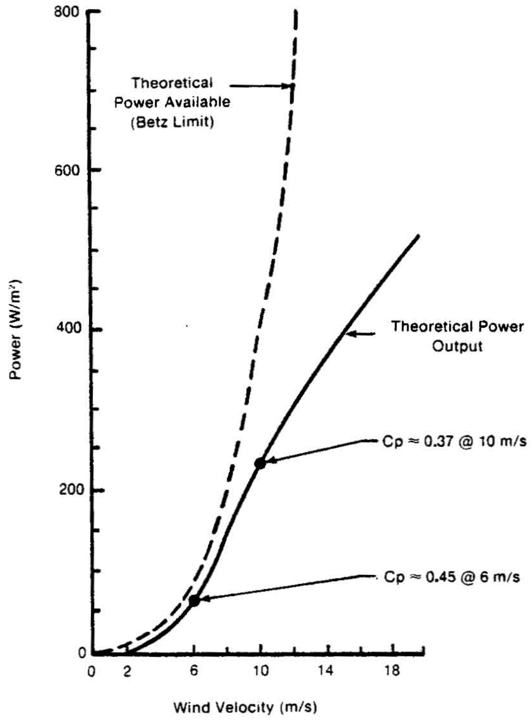

Fig. 8. Theoretical EFD Power Output Density Versus Wind Speed for a Full-Sized Generator

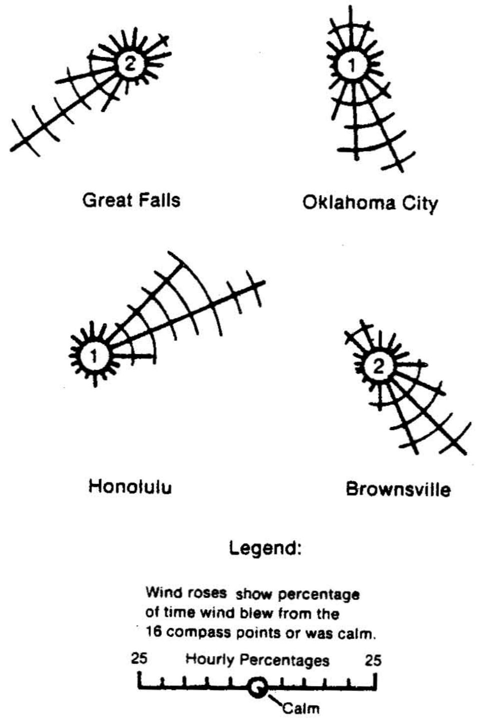

Fig. 9. Sample Wind Roses Based on Hourly Observations (1951 - 1960)

pumping and charging requirements. A 65-m-high EFD wind generator having an average power output of 2.25 MW would then require a 400-m width, as shown in Figure 11, resulting in a wind energy conversion area of 24,000 m^2. The working section (Figure 12) is supported by guy wires and steel angles (Figure 13) and has the collector electrode at 300 kV and the attractor electrode at -30 kV. An EFD system in this configuration will produce an annual energy output (AEO) of 13,000 MWh at a predominantly unidirectional wind site with a 6 m/s average wind.

The lack of yaw capability and the unidirectional wind site raise questions about the validity of the EFD AEO prediction. In order to establish whether the 13,000 MWh AEO prediction is realistic, a comparison should be made with a conventional WECS such as a MOD-2 system. Such a comparison shows a large discrepancy in the wind profiles experienced by the WECS as a result of the height difference of the extraction elements in each system. For purposes of establishing the validity of the AEO, we assume that the EFD system has been raised to a comparable hub height of 61 m. This comparison, however, does not represent the EFD conceptual design; it only aids in validating the AEO estimate for the conceptual design. The MOD-2 has an AEO of 9,750 MWh in a 6.3 m/s mean annual wind speed at a hub height of 9.15 m. This gives the MOD-2, with a swept area of 6,570 m^2, an AEO/m^2 of 1,485 kWh/m^2 (5). By comparison, the EFD system average power density is 118 W/m^2 if its midpoint is raised to the MOD-2 hub height of 61 m (Figure 10). With this assumption the EFD machine has an annual energy output per unit area of 1,055 kWh/m^2 or 71% of the MOD-2 prediction of 1,485 kWh/m^2. Note that the actual energy rose for a given site may change the percentage of differences by a significant amount. However, considering the unidirectional wind site of the EFD system and its lack of yaw capability, the EFD AEO estimates appear to be reasonable.

Many pertinent parameters aid in the comparison and evaluation of a WECS. One of these parameters, although not necessarily the most important, is cost. Because it operates differently from other WECS, the EFD concept may have benefits that overshadow its cost of construction. One benefit may be a minimum of moving parts, which may reduce O&M costs. In order to examine this parameter, cost estimates of this EFD conceptual design were performed at SERI. This costing effort was developed using a detailed estimate of material and labor requirements for the EFD conceptual design (Figures 11, 12, and 13) from "Richardson Process Plant Construction Estimating Standards" and information from manufacturers of special equipment. We

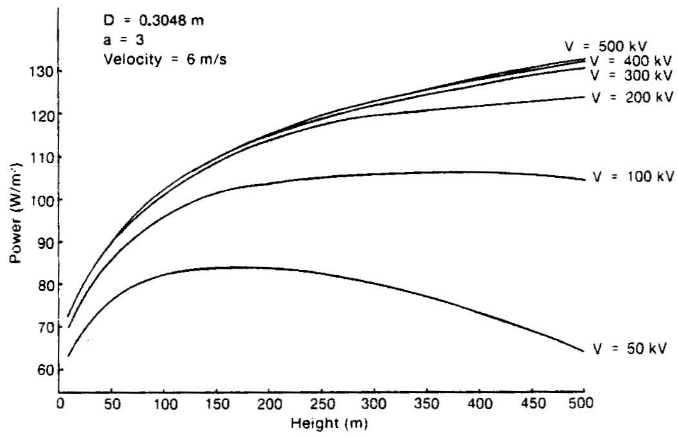

Fig. 10. Average EFD Generator Power Density Versus Height

estimated the cost of a single unit constructed on site without making provisions for land cost and without incorporating manufacturing or learning curves. The results, shown in Table 1, include all construction overhead and profit.

Table 1. Total Capital Cost for a Single (Conceptual Design) EFD Wind Generator

Foundation	$ 56,000
Structural steel and rigging	8,750,000
Aluminum tubing foil plates	10,841,000
Insulators	288,000
Pumping and piping systems	3,138,000
Total Capital Cost	$23,073,000

Using the DOE Cost of Energy equation, the annualized cost of energy (COE) of the EFD system is:

$$COE_{annual} = \frac{\$23,073,000 \times 0.18}{13,000,000 \text{ kWh}} = 31.9¢/\text{kWh} . \quad (1)$$

Since no value has been established for the lack of moving parts, the O&M costs have not been included in this calculation.

A more realistic evaluation of the EFD system can be made if the 100th unit manufactured is costed. The modular nature of the EFD conceptual design is conducive to the application of manufacturing processes. With these assumptions it is estimated that an EFD generator having an average power output of 2.25 MW would cost $15,724,000 with an annualized cost of energy of:

$$COE_{annual} = \frac{\$15,724,000 \times 0.18}{13,000,000 \text{ kWh}} = 21.8¢/\text{kWh} . \quad (2)$$

The estimates for cost reduction are considered far from optimistic because of the operational characteristics of the system. However, the preliminary nature of the design studies are not detailed enough to establish a definitive range for a cost reduction. Our projection is that reductions could range from very modest to well below the previous prediction.

Due to the variances in costing estimates, it is useful to look at other parameters such as the mass and wind energy value indicators shown in Table 2 (7,8). As shown, the EFD concept is within the range of most wind systems with respect to kWh/m^2 but is extremely material intensive. This material intensity could be compensated for if the kWh/m^2 value were not at the lower end of the range. However, these values will have a negative impact on the system potential if they cannot be improved upon.

Current SERI-supported efforts on the EFD concept are purely theoretical. Very little design optimization has occurred as compared to that demonstrated by the construction of large conventional WECS. Therefore, the EFD value indicators presented in Table 2 could be modified by a factor of three or more with regard to mass and to a much smaller degree with regard to energy output. The materials of construction and design could significantly affect the mass per square meter of conversion area. Note also that the O&M costs that have been neglected in this analysis, and are assumed to be a very positive factor, may instead be significant considering the material corrosion within the working section. It is also anticipated that further site-specific optimization of electrode spacing could significantly increase the energy/mass value indicator. In general, operational characteristics that have been demonstrated indicate that a great deal of optimization

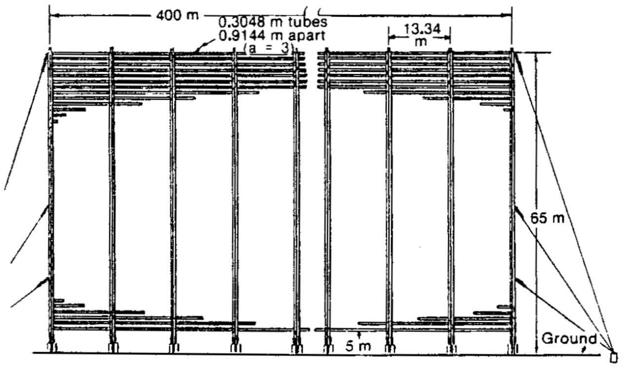

Fig. 11. Frontal View of the EFD Generator Conceptual Design

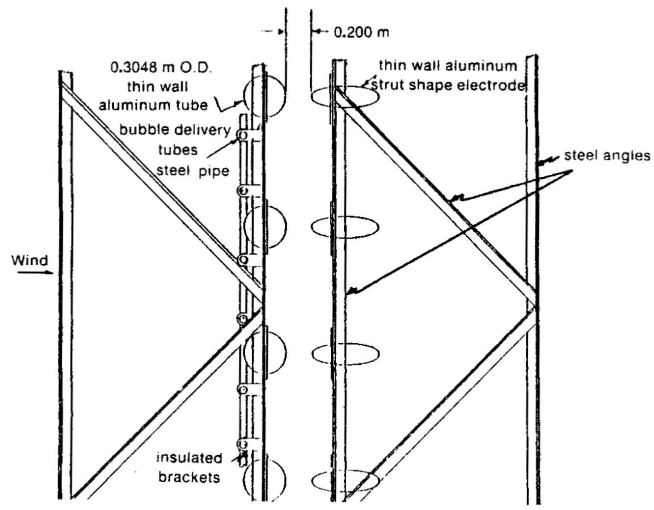

Fig. 12. Detailed Side View of the Towers and Electrodes for the EFD Generator Conceptual Design

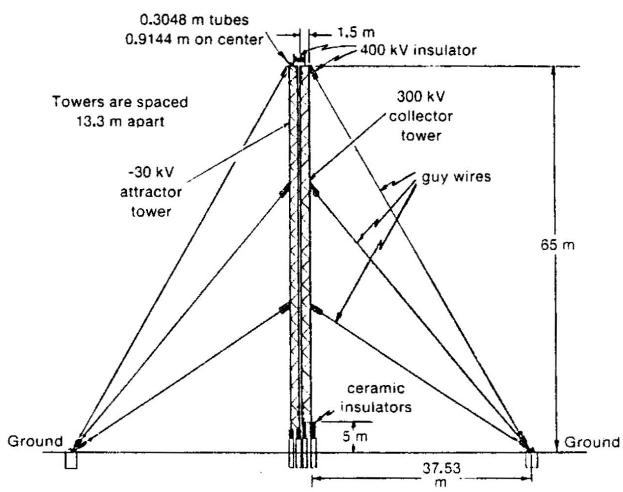

Fig. 13. Side View of the EFD Conceptual Design

Table 2. Mass and Wind Energy Value Indicators

Wind System	Mass (mg)	Energy/Mass (kWh/kg)	Mass/ Conversion Area (kg/m^2)	kWh/m^2
Sandia Darrieus (1)	3.82	15.7	45.7	717.5
Giromill	9.07	20.9	40.1	838.1
Sandia Darrieus (2)	11.51	19.9	41.3	821.9
Magdalen Island Darrieus	22.00	17.6	37.0	651.2
Hutter	13.15	27.8	14.4	400.3
MOD-OA	40.37	22.1	35.4	782.3
MOD-X	33.08	28.7	29.0	832.3
EFD	1,721.50	7.5	71.7	539.9
MOD-1	297.00	15.0	102.0	1530.0

potential exists for the EFD concept. The value indicators range from very marginal to acceptable for a conventional WECS. We feel that further research on the Electrofluid Dynamic WECS is needed to establish value indicators that have a narrower range. This research could establish whether this concept is a viable alternative to conventional wind energy conversion.

REFERENCES

1. Minardi, J.E., Lawson, M.D., Williams, G., "Electrofluid Dynamic (EFD) Wind Driven Generator," COO/4130-77/1, Oct. 1976, NSF.

2. Minardi, J.E., Lawson, M.D., "Annual Progress Report on the Electrofluid Dynamic Wind Driven Generator," COO/4130-77/2, July 1977, U.S. ERDA.

3. Minardi, J.E., Lawson, M.D., Wattendorf, F.L., "Third Annual Progress Report on the Electrofluid Dynamic Wind Generator," COO-4130-2, May 1979, U.S. Dept. of Energy.

4. Minardi, J.E., Lawson, M.D., Wattendorf, E.L., "Fourth Annual Progress Report on the Electrofluid Dynamic Wind Generator," UDR-TR-80-108, May 1981, University of Dayton Research Institute.

5. NASA, "MOD-2 Wind Turbine System Concept and Preliminary Design Report," DOE/NASA 0002-80/2, July 1979, NASA.

6. "Selected Climatic Maps of the United States," 1977, National Climatic Center, Ashville, N.C.

7. McConnell, R.D., "Giromill Overview," SERI/TP-35-263, May 1979, Solar Energy Research Institute.

8. McConnell, R.D., "A Screening Method for Wind Energy Conversion Systems," SERI/TP-731-649, June 1980, Solar Energy Research Institute.