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MASTER

GIROMILL OVERVIEW

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ABSTRACT

The Giromill is a vertical axis wind turbine having straight airfoils whose angles of attack are controlled so as to maximize wind energy conversion. Each airfoil is rocked during a revolution in order to maintain a constant positive angle of attack over one half revolution and a constant negative value over the other half revolution.

McDonnell Aircraft Company completed a feasibility study of the Giromill in 1976. Their initial work was followed by model tests in a wind tunnel in 1976 and 1977. Presently the Pump Division of Valley Industries, Inc., is cooperating with McDonnell Aircraft to design, build, and deliver a 40-kW (8.9-m/s) Giromill for the U.S. Department of Energy. Delivery to Rocky Flats is scheduled for the end of 1979.

In addition to describing the above work, this paper presents an evaluation of the Giromill concept in terms of some wind energy rules-of-thumb.

INTRODUCTION

Consider a rotor consisting of a set of straight vertical airfoils attached to a vertical axis. When this system is rotating in a wind stream, energy can be extracted from the stream just as it can be extracted by a Darrieus rotor. Straight airfoils, however, can be controlled so as to maximize lift throughout the rotor's revolution. Such a rotor is the vertical axis analogue of a horizontal axis wind turbine having blade pitch control.

McDonnell Aircraft Company (MCAIR) has been one of the developers of the concept [1,2]. MCAIR coined the term Giromill for their system because the theory previously developed for a powered cyclogiro airborne vehicle was readily adapted to their version of the windmill. Other straight-bladed vertical axis wind turbines are being studied in other countries [3]. In the United States, a 1-kW cycloturbine, which is similar in many ways to the Giromill, is under test at DOE's small wind systems test center at Rocky Flats [4]. A 40-kW version of MCAIR's Giromill is being designed and built by MCAIR and Valley Industries for test at Rocky Flats later this year. As a result of the cooperation of the MCAIR engineers, who are presently deeply involved in completing the project, this article will describe the MCAIR work on the Giromill design selected for test at Rocky Flats.

SERI has the task of developing techniques, including so-called rules-of-thumb, for evaluating innovative wind turbines on a consistent basis. Ratios, such as the performance-mass ratio reported recently, are useful for comparing new designs with conventional wind turbines [5]. Parametric cost equations are also being identified for innovative wind systems.

Cost-mass ratios are often used for simple cost estimates of wind turbines. By combining these parametric ratios it is possible to estimate the cost of energy produced by an innovative wind turbine. It is important not to place too much emphasis on the results of such an analysis because of the approximations involved and the resulting uncertainty in the answers. Nevertheless, the invitation to present an overview of the Giromill provides an opportunity to demonstrate the use of the evaluation techniques for the MCAIR 40-kW Giromill.

A 40 kW GIROMILL

MCAIR's Giromill Research

An early ERDA-sponsored project had as its objective the theoretical determination of the feasibility and cost effectiveness of the Giromill on the basis of a detailed design study [1]. A cyclogiro vortex theory computer program was developed to analyze parametrically Giromill configurations for devices as large as 1500 kW. The study was completed in May 1976 and verified the feasibility of the concept.

In a second study a Giromill model was tested in a wind tunnel to verify its theoretical performance [2]. The test results were not decisive, however, because two independent tunnel velocity measuring systems gave two different results. Careful scrutiny of both measuring systems failed to pinpoint the reason for the discrepancy. The conclusion was drawn, however, that even on the basis of the lower measured coefficient of performance, C_p, a full-scale Giromill would achieve a maximum C_p larger than that of a Darrieus rotor [6]. The most recent work began in September 1978 when Rockwell International, working under contract to DOE, awarded MCAIR a contract to design, build, and deliver a 40-kW Giromill [7]. Fabrication is scheduled for completion in December 1979 and testing at Rocky Flats is scheduled to begin in February 1980. In order to complete the work a teaming arrangement was made by MCAIR with the Pump Division of Valley Industries, Inc. The Aeromotor Division of this firm has successfully marketed farm windmills since 1888. Valley is participating in the design and fabrication of most of the parts and, if the windmill is successful, will market the Giromill under a license agreement.

The Rotor

The selected configuration is shown in Figure 1.* The Giromill has three straight 12.8-m blades attached to a long vertical column. An 18.3-m tower supports the Giromill, whose swept area center line is 22.9 m above the ground line. The symmetrical airfoil blades (NACA 0018) have a formed aluminum leading edge

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*Figure 1 was furnished by MCAIR with English units. As required by the conference guidelines, SI units will be used in the remainder of the paper.

and spar with aluminum trailing edges. All parts are riveted. The airfoil chord is 0.69 m. Horizontal support arms have been located so as to minimize the bending moment in the blades. The overall diameter of the Giromill is 17.7 m. Each arm has a streamlined steel shell to minimize drag losses and contains the electric actuator which controls the blade's angle of attack. A lightning rod, extending 38.4 m above the ground line, protects the actuator bearings from possible damage by lightning strikes on the blades.

The Giromill's vertical column is connected to the generator shaft by a speed increaser and a toothed belt, which together give an overall ratio of 54:7:1. The Giromill's nominal speed is 35 rpm. The peak electrical output is estimated to be 40 kW; an adapter kit is to be provided which would convert the machine to a mechanical output capability.

The projected electrical power versus wind speed curve is not shown but it is similar to that of a horizontal axis wind turbine. The cut-in wind speed is 4.5 m/s (10 mph) while rated net power of 40 kW is reached at 8.9 m/s (20 mph). Constant power is maintained between 8.9 m/s and the cut-out windspeed of 17.9 m/s (40 mph) by changing the blade's effective angle of attack as the windspeed changes. (All of these windspeeds refer to those measured at the centerline of the Giromill.) These performance estimates are based on MCAIR's C_p versus tip speed ratio curve, which has an estimated maximum value of 0.5. Estimates of power losses are shown in Figure 2. The power versus windspeed curve, as well as the annual energy production estimates, should therefore be considered as preliminary and, indeed, they will be evaluated further at Rocky Flats.

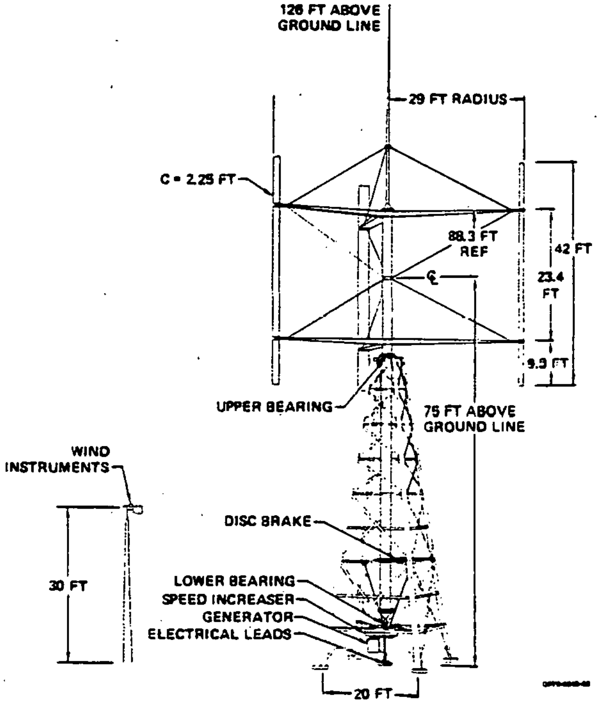

Figure 1. Selected Configuration for the 40-kW Giromill

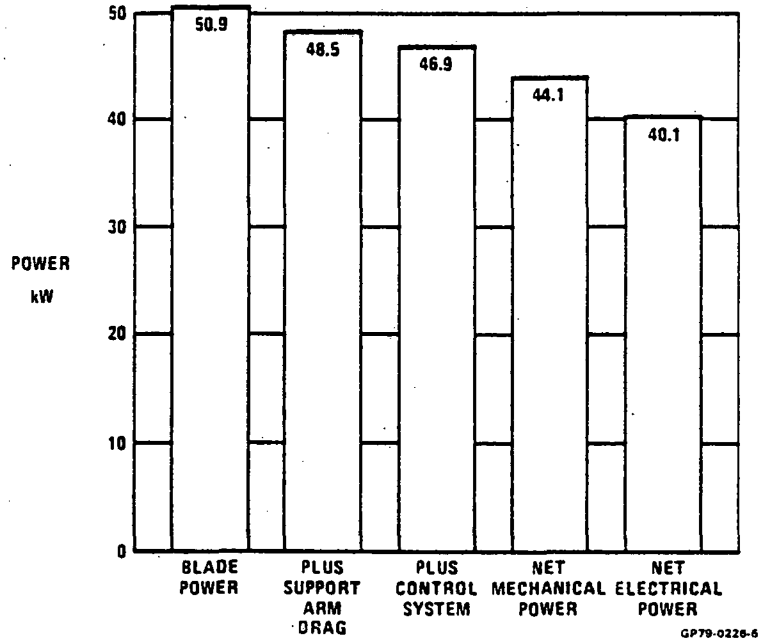

Figure 2. Estimated Power Losses for Giromill

Actuator Controls

The details of rocking the Giromill's blades during a revolution have been presented previously [2]. In simple terms the effective angle of attack is kept constant, -12° for winds below 8.9 m/s, over one half revolution while, for the same winds, a +12° angle of attack is maintained over the other half revolution. The blade rocking angle, also measured with respect to the chord line, is therefore a complex function of blade position in one revolution, wind direction, and windspeed. At a windspeed of 17.9 m/s, the effective angle of attack is ±3°. Blade flip occurs twice in each revolution, when the blade chord is parallel with the wind.

Various mechanisms have been studied by MCAIR for rocking the blades during rotor revolution. The 2.1-m diameter by 1.5-m span wind tunnel model used a central cam and three push-rod and bell crank assemblies [2]. Hydraulic control mechanisms also have be considered. The selected actuator control for each blade is a d.c. motor connected to the blade's pivot axis by a toothed drive belt. Power for the d.c. motor comes from a 24V battery, alternator, and voltage regulator set. Control signals for the actuators are provided from the wind instruments shown in Figure 1. As noted in Figure 2, 1.6 kW, which is about 3% of peak power, is the estimated average power consumption for the actuator controls.

Design Criteria

The Giromill is designed to withstand a 56 m/s (125 mph) peak gust. It must survive ice, hail, lightning, dust, and coastal extremes as well as temperatures ranging from -40° C to 60° C (-40° F to 140° F). The fatigue life of the Giromill is to be at least 30 years.

These constraints affect the selection of materials and components used in the Giromill; this effect becomes clearer when the details of the design criteria are known. Details of the ice criteria, which happen to be stringent, can serve as an example. In operation the blades must survive an 8.9-m/s wind with 13 mm of ice on the leading edge. When the Giromill is stopped, the blades must withstand 76 mm (3 in) of ice over one half of their surface simultaneously with the occurrence of a 56-m/s (125-mph) wind. Similar requirements must be met for the support arms, central column, and the fixed tower. When the loads are known for each of these situations, a safety factor of 1.5 has been specified to determine dimensions of the various components.

These criteria are related to the endurance of the Giromill when exposed to extreme environmental conditions. Operating criteria also have a significant impact on the Giromill design. An important example is related to the Giromill's actuated blades. The hinge point for the blade is 22% of the chord away from the leading edge, and the blade center of gravity has been specified at 23.25% from the leading edge. The location of the center of gravity is significantly different from that of an extruded blade for a Darrieus rotor. (The largest Darrieus rotor built, the Magdalen Island machine, has its blade's center of gravity at 44% chord). Thus, the Giromill blade has 4-mm thick aluminum sheet metal in the leading edge and spar, while the trailing edge thickness is 0.5 mm. In addition some ballast is needed to obtain the desired c.g. location. As a result, the blades make up 6% of the total system weight and account for 16% of the cost.

Another important operating criterion is, of course, that the Giromill produce 40 kW_e in an 8.9-m/s wind. All of these design criteria determine the dimensions and consequently the mass (weight) of the Giromill's components.

ELEMENTARY EVALUATION CONSIDERATIONS

Energy Output Estimates

SERI is interested in simple cost evaluation techniques for innovative wind energy systems. A useful parameter in these studies has been an estimate of the electrical energy produced by a wind energy system of a given size, in one year, at a site having given wind characteristics. The evaluation is made, not surprisingly, in terms of a comparison with the characteristics of conventional horizontal and vertical axis wind turbines. Because of the approximations necessary to make the comparisons, there is considerably more uncertainty in such results than there is in results derived from field comparisons of machines.

Consider a wind turbine site having an annual average wind speed of 6.7 m/s (15 mph) as measured at a height of 9.1 m (30 ft). Assume the site has a wind height profile with an exponent of approximately 0.13, a Rayleigh distribution for the wind speeds, and a standard air density of 1.23 kg/m^3 (0.076 lb/ft^3). (See Ref. 8 for further discussion on wind profile and wind distribution). The electrical energy output of several machines has been estimated using wind site characteristics similar to these (see Table 1). All of the calculations assume 90% availability of the machines when the wind is above cut-in speed. As shown in Figure 2, engineering estimates have been made for drive train and generator losses. The energy estimate for the Hütter machine is based on its measured power curve (11), the assumptions given above for wind site characteristics, and Golding's energy/peak power graphs (14).

System Masses

Some of the parameters shown in Table 1, when combined with the total wind turbine system mass, appear to rank the systems in terms of their mass efficiency. Mass ratios are expected to be important because many approximate correlations exist between component masses and component costs. Peak kilowatt ratios may have some use as they tend to indicate effective or ineffective utilization of rotors and drive trains designed for high power. Such ratios are often called "rules of thumb" and should be used with care because of the approximations necessary for their application. Table 2 presents some ratios, suggested by other wind energy researchers, for the systems of Table 1. These ratios are annual energy/mass [5], mass/swept area [15], annual energy/peak power [14], and peak power/swept area [11].

The system masses shown in Table 2 include (approximately) all component masses located above the tower foundations. "Approximately" is placed in parentheses because of slight differences; for example, some quoted total system masses include electrical controls and some do not. Utility components such as transformers, however, are not included. The uncertainties associated with these discrepancies are estimated to be small since completed designs or built systems are being considered. The Giromill has an additional uncertainty in its weight estimate because the design has only recently been completed and is subject to review. An earlier estimate of 8,165 kg (18,000 lb) was only recently revised to be 9,072 kg (20,000 lb) [7]. Other uncertainties exist for some of the annual energy estimates (due, for example, to different assumed wind profiles) so that the overall uncertainty in the energy to mass ratio is probably between ±10% to ±20%.

It is important to note that different materials, typically steel and aluminum, make up the total mass. Aluminum accounts for about 6% of the total Mod OA and Giromill masses and from 20% to more than 30% of the Darrieus rotors' masses. About 13% of the Hütter machine mass was contained in the fiberglass reinforced plastic blades. The majority of the mass is steel, however, for each of the systems in Table 2.

Another caveat has to be made for Table 2 because of slight differences in the design criteria for the various sytems. Fatigue life, safety factors, special wind gust conditions, temperature and environmental extremes are not uniform for the systems of Tables 1 and 2. The Giromill has perhaps the most severe ice loading criteria. The Hütter machine was required to withstand a 60 m/s (134 mph) wind with the blades stopped but in normal operating position [11]. However, the Mod X must survive a slightly lower wind speed of 54 m/s (120 mph) with the blades feathered [13]. The Darrieus rotors are required to withstand similar high winds, 67 m/s (150 mph) for the Sandia Darrieus, but the winds are incident on the blade planform (the so-called buckling case). As mentioned previously, the design criteria affect the thickness, structure, and consequently the mass of the system components. Ideally, all of the systems, or at least all generic systems, must have the same design criteria before comparisons are made.

TABLE 1

ANNUAL WIND ENERGY ESTIMATES

Wind System	Swept Area (m^2)	Wind Shear Exponent	Peak Power (kW_e)	Rated Wind Speed (m/s) (center line height)	Annual Electrical Energy (MWh)	Reference
Sandia Darrieus (A)*	84	0.17	30	13.4	60	9
Giromill	226	0.14	40	8.9	190	7
Sandia Darrieus (K)	279	0.17	120	15.0	221	9
Magdalen Islands Darrieus	595	0.13	224	15.0	387	10
Hütter	915	0.13	90	9.0	365	11
Mod OA	1,140	0.13	200	9.5	892	12,13
Mod X	1,140	(Ref. 8)	200	9.5	950	13

* (A) denotes a point design completed by Alcoa Laboratories for Sandia Laboratories while (K) refers to a point design completed by A.T. Kearney.

TABLE 2

MASS AND WIND ENERGY RATIOS

Wind System	Mass (Mg)	Weight (lb)	Energy/mass (Wh/g)	Mass/swept area (kg/m^2)	Peak Energy/yr/power (kWh/yr/kW)	Peak Power/m^2 (W/m^2)
Sandia Darrieus (A)	3.82	(8,417)	15.7	45.7	2,000	357
Giromill	9.07	(20,000)	20.9	40.1	4,750	177
Sandia Darrieus (K)	11.51	(25,383)	19.2	41.3	1,842	430
Magdalen Islands Darrieus	22.00	(48,500)	17.6	37.0	1,728	376
Hütter	13.15	(29,000)	27.8	14.4	4,056	98.4
Mod OA	40.37	(89,000)	22.1	35.4	4,460	175
Mod X	33.08	(72,920)	28.7	29.0	4,750	175

Despite the assumptions and uncertainties associated with the results of Table 2, the table does allow an evaluation to be made of the potential for the selected Giromill configuration. The energy-mass ratio of 20.9 Wh/g is higher than that for the conventional vertical axis turbines as one would expect for a more aerodynamically efficient design. The ratio, however, is less than those estimated for the horizontal axis wind machines which, admittedly, are second and third generation turbines. The mass efficiency of the Giromill, as determined by this ratio, is good since it is similar to that of the conventional machines. Note that the DOE goals of 25 to 40 kWh/lb correspond to about 55 to 88 Wh/g [5].

The mass-swept area ratio of the Giromill is one of the higher values in Table 2. This is perhaps the result of stringent design criteria but is also partially a result of choosing a three-bladed configuration. The use of three blades increases the rotor's solidity. The Hütter machine is outstanding in this respect because its mass-swept area ratio is two to three times smaller than those of the other systems.

The next ratio, annual energy per unit of peak power, is related to the system load factor, an engineering measure of the effective utilization of the system. Dividing each ratio by 8760, the number of hours in a year, gives directly the system load factor. The Giromill ratio is one of the highest, partly as a result of its relatively high C_p.

The last column in Table 2 provides a measure partially related to the load factor, but a low value also gives an indication that the system will perform well in wind sites having lower average wind velocities [11]. The Giromill value of 177 W/m^2 is about average for the group.

In general, the Giromill ratios are reasonably good when compared with those of advanced low cost designs (Mod X, Sandia Darrieus) as well as with those of built machines (Mod OA, Magdalen Islands Darrieus, the Hütter machine). An important item to verify for the Giromill is the power versus wind speed curves which form the basis for the annual energy estimate. The recommendation is based on the high value estimated for the annual energy-peak power ratio. The conclusion of this elementary comparative evaluation is that the selected Giromill configuration has a potential for producing cost-competitive energy equal to that of the comparison systems.

Cost Considerations

The following discussion indicates, in a general way, the cost considerations necessary for the Giromill and other wind systems. In addition, since the Giromill costs are not presently available, an estimate will be made of its total installed cost and, consequently, its cost of energy. Note that these preliminary cost estimates are our own and are subject to revision by MCAIR as their design efforts continue.

Several major cost areas have been identified to ensure equitable evaluation cost estimates. First the costs have to be normalized in terms of dollars of a particular year (1979), and in terms of how many units will be produced (100). Second, the costs need to be complete, although research and development costs are excluded. Table 3 is a list of cost considerations with their definitions. Table 4 gives some rules-of-thumb for cost items in Table 3 based on a review of DOE-funded design studies. Table 4 will be used to estimate the capital costs of the Giromill.

It is important to note that the ratios used to calculate the cost of the Giromill are preliminary and require further refinement. Several problems do exist within the current database (see references noted in Table 4). One discrepancy is that components are grouped in different ways; that is, electrical and control component costs are sometimes included in generator cost. Another area of concern is that it is often difficult to separate direct field costs from indirect field costs. The wide ranges for the ratios shown in Table 4 are a result of these discrepancies as well as the previously mentioned differences in materials and designs. SERI expects to update these and other cost ratios as more cost information for new machines becomes available.

The Giromill blades and arms, together, have a total mass of about 1100 kg. Assume a rotor cost ratio of $10/kg, simply to avoid the most optimistic value noted in Table 4. The tower mass is about 4,100 kg and $2/kg ratio will be

TABLE 3

COST CONSIDERATIONS FOR INSTALLED WIND SYSTEMS

Item	Definition
Manufactured Equipment	Total of wind system components
Wind Generator	Rotor and drive
Drive	Speed increaser, shafts
Rotor	Blades, hub, pitch and yaw system
Electrical	Generator, power conditioning
Controls	rpm control system, safety systems
Enclosure	e.g., fairings
Tower	Support structure, tie downs, etc.
Site Specific Costs	Land, transmission lines, access roads
Foundation	Concrete, anchors
Materials	Transport, fencing, lights, conduit, wire, site preparation
Installation	All labor costs to site assemble, erect and check out the system
Manhours	Labor hours for installation
Site Preparation	Excavation, cleaning, dewatering, fill
Total Direct Field	Sum of all direct costs, which is everything above
Indirect Field	Indirect field and office costs accrued during installation; e.g., temporary construction facilities, craft benefits, payroll burdens, construction equipment
Interest	Cost of capital during installation
Spares	Initial replacement parts
Contingency	Reserve fund
Fee	Fee for installation firm
Total Capital	Total of all of costs
Operations and Maintenance (O&M)	Normal and unscheduled maintenance plus normal operating costs
Levelized O&M	Annuitized O&M costs, 30 year life
Carrying Charges	Annual financial charges on total capital
Total Annual	Total of carrying charges and O&M

assumed because it is a slightly modified tower concept. Assume a \$5/kg ratio for the remainder of the mass. Then the Giromill system cost is estimated to be \$38,500. Note that DOE's estimated goal for mature wind machines is between \$4 and \$7/kg [5] so that \$38,500 may be considered optimistic but not completely unrealistic for a mature Giromill. An additional \$6,000 is estimated for foundations (20 m^3 of concrete). The Total Direct Field Cost is therefore estimated at about \$53,400.00. The Cost of Energy, COE, is calculated by [13]:

$$\text{COE} = \frac{(0.18)\,(\text{Total Capital}) + \text{Levelized O\&M}}{\text{Annual energy production}}$$

A summary of the Giromill COE estimation is shown in Table 5.

The Giromill's COE, 8.2¢/kWh, is illustrative only because of the generalizations involved in the system costing and the assumptions made for the Total Direct Field Cost modular factor of Table 4. Wind systems having similar mass-energy ratios, like the Sandia Darrieus or the Mod OA, will have similar costs of energy, a fact which indicates the weakness of the technique. More specifically, it is possible but unlikely that three so dissimilar systems — the Giromill, the Sandia Darrieus (K) and the Mod OA — would have about the same Cost of Energy. To improve these simple costing techniques it appears that some measure is needed to represent the complexity of a wind turbine system. Perhaps the number of moving parts needs to be known so that correlations can be established between that number and system costs and O&M costs. Another problem is the lack of

TABLE 4

COST ESTIMATIONS [9,13,16,17,18]

Item	Estimates
Rotor	\$5 to \$37/kg
Drive	\$3 to \$11/kg
Electrical	\$5 to \$22/kg
Controls	\$24 to \$79/kg
Enclosure	\$1 to \$13/kg
Tower	\$1 to \$4/kg
Foundations	\$300/m^3
Total Direct Field	Larger of {Wind Generator cost X 2.5 Manufactured Equipment X 1.2}
Indirect Field	16% of Total Direct Field
Interest	2% of Total Direct and Indirect Field
Spares	3% of Wind Generator Cost
Contingency	10% of Total Direct Field
Fee	10% of Total Direct Field and Spares Cost
Total Capital	Total of Direct Field, Indirect, Interest, Spares, Contingency and Fee
Annual O&M	2% of Total Direct Field
Levelized O&M	2 X Annual O&M
Carrying Charges	0.18 X Total Capital
Total Annual	O&M plus carrying charges

validation for both energy estimating and simplified cost estimating techniques. Comparisons need to be made between field results and design estimates. In any case, simple cost estimating techniques cannot replace detailed costing techniques because of these discrepancies. The justification for contracting a detailed cost analysis of a wind system will, however, depend on the results of simplified techniques such as the one outlined in this section.

CONCLUSION

A 40-kW Giromill, a vertical axis wind turbine with vertical modulated airfoils, is being designed and fabricated by McDonnell Aircraft Company and Valley Industries Inc. The Giromill is to be delivered to Rocky Flats in late 1979 for tests in early 1980.

An evaluation of the selected Giromill configuration, in terms of wind energy system ratios, indicates that the Giromill has the potential for producing energy at a cost equivalent to or lower than the energy costs of some conventional horizontal axis and vertical axis wind turbines.

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TABLE 5

GIROMILL COST ESTIMATION

	$ (1979)
Giromill System Cost	38,500
Foundations	6,000
	44,500
Total Direct Field	53,400
Indirect Field	8,544
Interest	1,239
Spares	550
Contingency	5,340
Fee	5,395
Total Capital	74,468
Annual O&M	1,068
Levelized O&M	2,136

$$\text{COE} = \frac{(74{,}468)(0.18) + 2{,}136}{190{,}000 \text{ kWh}}$$

$$= 0.082/\text{kWh}$$

$$= 8.2¢/\text{kWh}$$

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