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SMALL WIND SYSTEMS TECHNOLOGY ASSESSMENT

State of the Art and Near Term Goals

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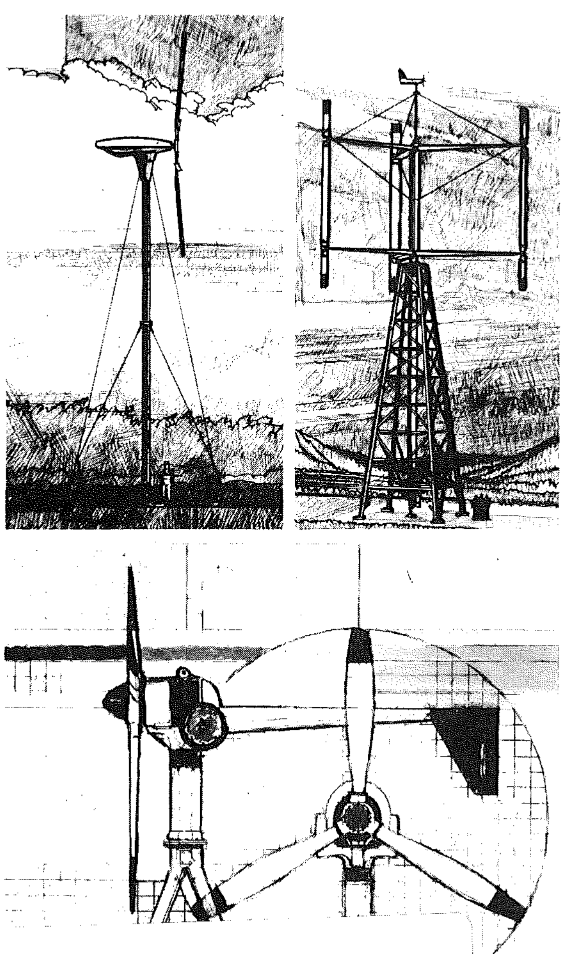

February 1980

Prepared by
Rocky Flats
Wind Systems Program

Operated by
Rockwell International
Energy Systems Group
P.O. Box 464
Golden, Colorado 80401

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ABSTRACT

Commercially available small wind conversion systems (SWECS), DOE-funded prototype SWECS, and possible second generation advanced concepts are assessed from the standpoint of several key Figures-of-Merit including cost of energy, dollars per pound, kilowatt hours per year per pound, and kilowatt hours per year per square meter of rotor area. The reliability, performance, and installation and maintenance costs of these systems are also assessed. It is concluded that current SWECS, while nearing the threshold of competitiveness with conventional energy sources, are inhibited from reaching their lowest cost potential by the use of off-the-shelf components, less than optimum rotor designs, and (in some cases) overly complicated control systems. The comparison of improved DOE prototypes and possible advanced concept SWECS shows that, in many size ranges, considerable reductions in energy cost can be achieved.

SMALL WIND SYSTEMS TECHNOLOGY ASSESSMENT

State of the Art and Near Term Goals

EXECUTIVE SUMMARY

The objective of this study was to define the current state-of-the-art for small wind energy conversion systems (SWECS) and project future SWECS characteristics and energy costs. The methodology used was to: 1) define the state-of-the-art with the aid of a series of figures-of-merit (cost of energy, dollars per pound, kilowatt hours per year per pound, and kilowatt hours per year per rotor area (square meters)); 2) project achievable, very near term improvements; 3) project further near term improvements (3-5 years) which could be made; 4) define hypothetical advanced systems incorporating these improvements; 5) define figures-of-merit (FOM) for these hypothetical systems; and 6) define Supporting Research and Technology projects which would be required to develop these systems.

For purposes of assessing the current status of SWECS, six commercially available systems (CA) and seven DOE-funded first generation prototype systems (PT-1) were used. No empirical performance data for these systems are available, since the CA units are recently developed systems (and have not been sufficiently tested at Rocky Flats) and the DOE prototypes have only been recently fabricated. In the absence of data, manufacturer estimates were used. These estimates were subjected to detailed analysis and conservatively adjusted when the analysis indicated this was necessary to produce the most accurate figures-of-merit possible.

Near term improvements have been projected by improving DOE prototypes to create second generation units (PT-2). The modifications used were proposed by the systems subcontractors or indicated by Rocky Flats analysis.

Improvements which could be realized later in the 1980's are presented in a series of Advanced Concepts (AC) for three size ranges (3-6, 6-12, and 12-25 meters) with significant potential in remote dc, utility interconnection, and direct heating applications.

Several system configurations are excluded from various stages of the analysis. All Advanced Concepts are horizontal axis systems. Several "cyclogiro" concepts were explored, but their figures-of-merit were poor. Darrieus systems were omitted from all phases of this assessment due to Rocky Flats' current inexperience with these systems.

SWECS State-of-the-Art

Figures-of-merit for commercially available, PT-1 and PT-2 units are shown in Figures 1-4. While specific modifications were not proposed for commercially available units, a number of strategies for improving their FOM's were identified. These include improved rotor efficiency (increased annual energy output), more reliable and material-efficient transmissions and generators, and reduced installation and maintenance costs.

The PT-1 units have FOM's which are generally better than commercially available units in the 3-6 meter size range and have figures comparable to those for 6-12 meter and 12-25 meter commercially available systems. The prototype FOM's represent figures for machines developed to meet design criteria specifications for severe environments and high reliability. These specifications are more stringent than these those to which the commercially available units were designed and this should be taken into account in comparisons.

Improved (PT-2) prototypes (with modifications to improve performance, decrease weight and reduce fabrication costs) have consistently better FOM's than the commercially available and PT-1 units.

Basic characteristics of the DOE prototype units are listed in Table I.

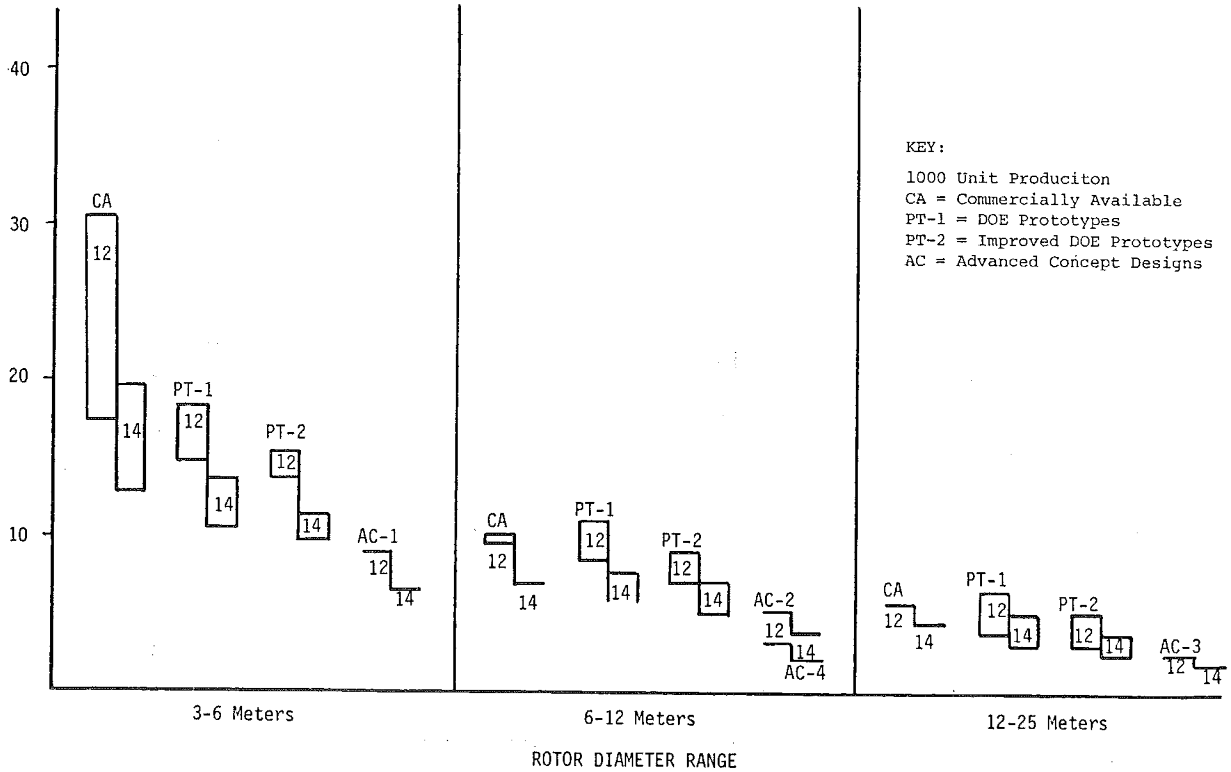


Figure 1
SWECS Cost of Energy (¢/kWh)

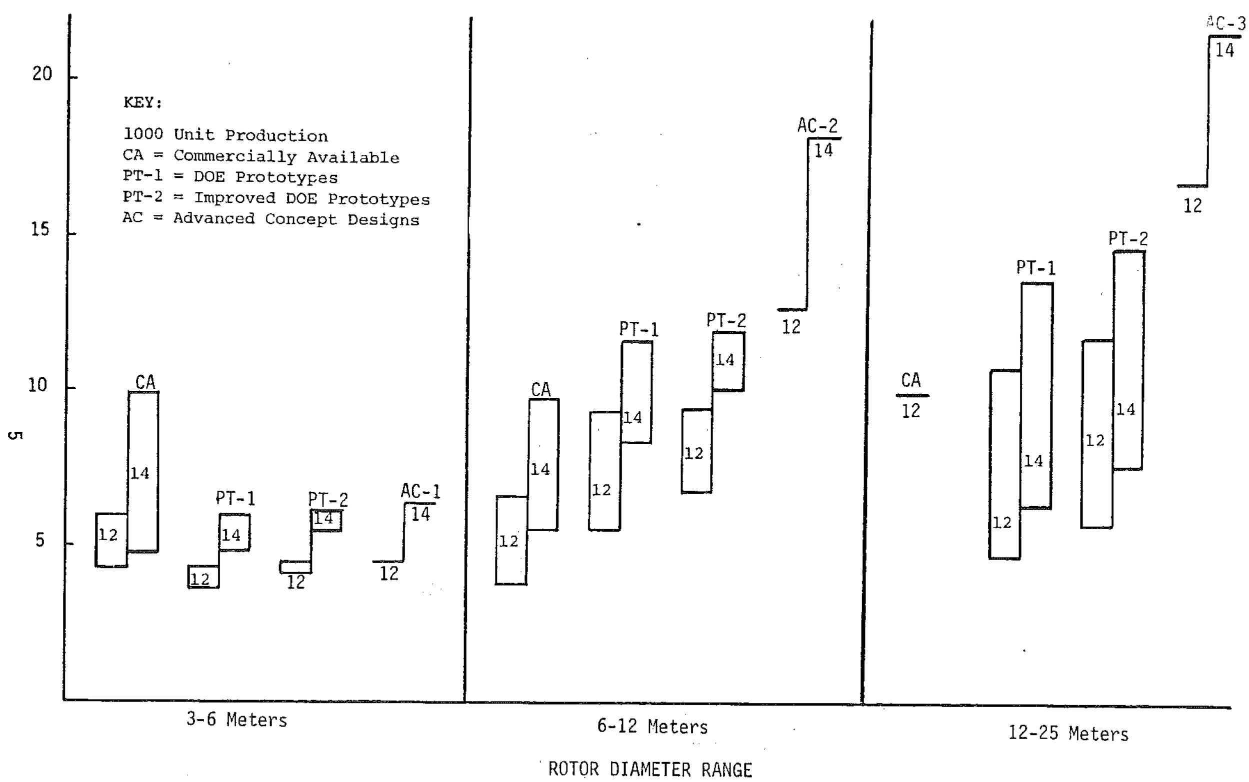
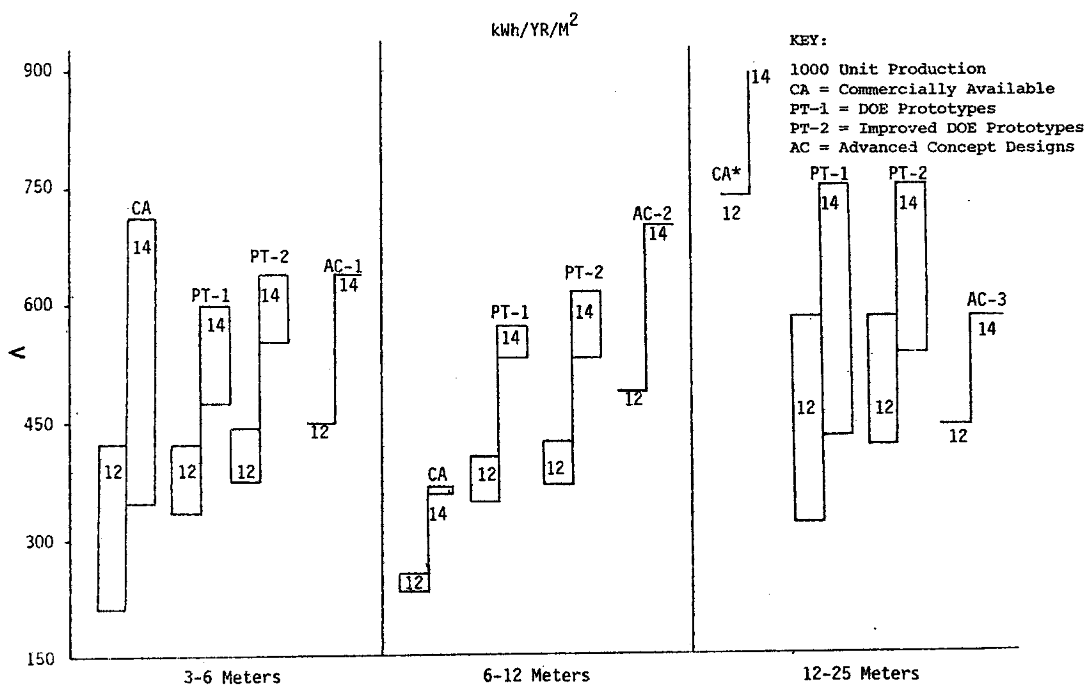


Figure 2
SWECS Performance vs System Weight (kWh/yr/lb)



ROTOR DIAMETER RANGE

Figure 3
System Efficiency

* - Extremely high figures indicate manufacturer's data are unreliable.

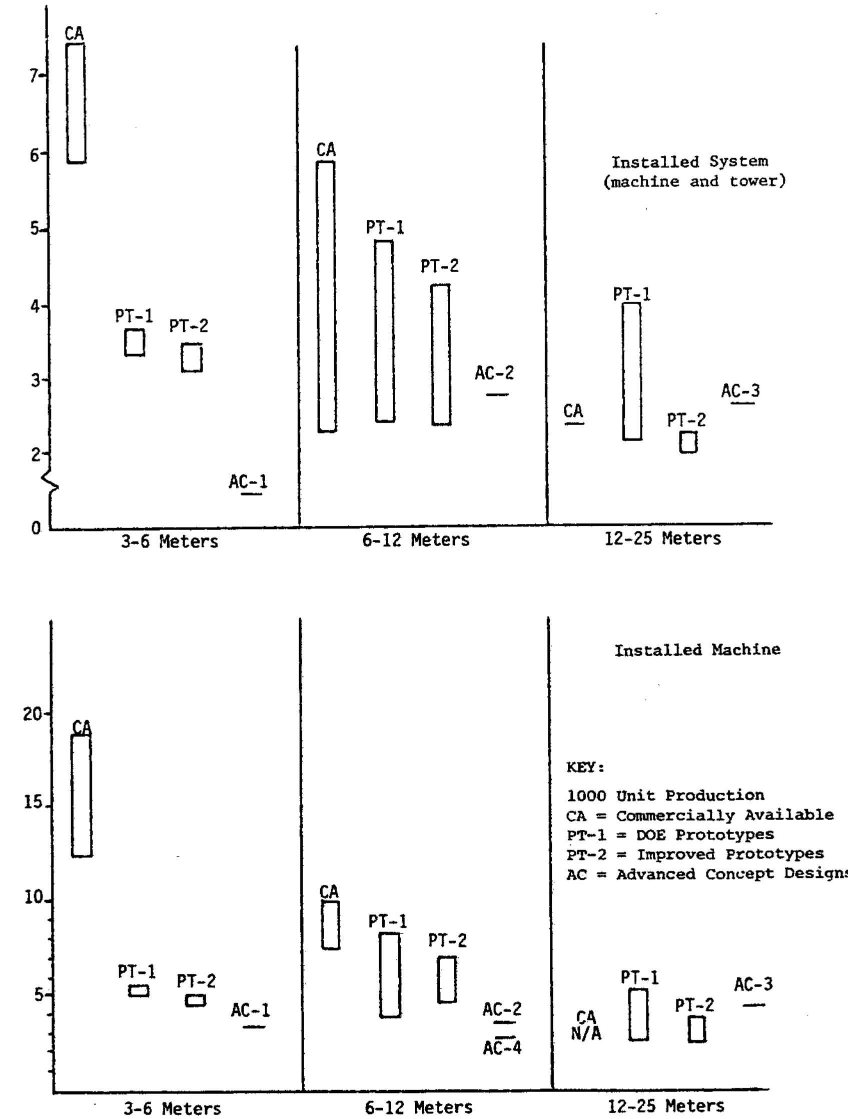


Figure 4
SWECS Cost per Pound ($/lb)

TABLE I

Prototype System Characteristics

MACHINE	ROTOR SIZE	RATED OUTPUT (9.0 m/s)	ROTOR CONFIGURATION	APPLICATIONS
North Wind	5 m	2 kW	2 blade, downwind horizontal axis	Remote battery charger
Enertech	5 m	2 kW	3 blade, upwind horizontal axis	Remote battery charger
UTRC	9.5 m	8 kW	2 blade, downwind horizontal axis	Utility inter-connection
Windworks	10 m	8.5 kW	3 blade, downwind horizontal axis	Utility inter-connection
Grumman	10 m	11 kW	3 blade, downwind horizontal axis	Utility inter-connection
Kaman	19.5 m	40 kW	2 blade, downwind horizontal axis	Utility/ mechanical
McDonnell	18.5 m	40 kW	3 blade, vertical axis giromill	Utility/ mechanical

Four Advanced Concept systems in 3-6, 6-12, and 12-25 meter size ranges have dramatically better FOM's than the other units evaluated. These systems are hypothetical designs which incorporate passive system controls; dynamically "soft" components; custom-designed gearboxes, generators, housings, and towers; and features which allow ease of maintenance and reduction of maintenance requirements.

Basic characteristics of the AC units use are listed in Table II.

SRT Requirements

Supporting Research and Technology (SRT) projects required to develop AC units would include systems integration studies to prioritize development work; analysis and development of the "delta-three" hinged rotor and other concepts to reduce fabrication costs and increase performance; work on new integral transmission and gearbox subassemblies; development and testing of appropriate field modulated induction generators and heat churn power converters; and development of aesthetic, lightweight, freestanding "soft" towers designed to reduce installation costs and be compatible with "soft" rotor and drive systems.

Conclusions

The study concluded that significant cost of energy improvements can be made in SWECS of all size ranges. These improvements can be realized primarily by simplified controls, increases in performance (annual energy output), and the development of components specifically designed for SWECS (through increased reliability, longer system life, and lower hardware cost).

Projected production schedules for the units in this study using a doubling of production rates every 3-5 years (from an initial run of 1,000 units) and a 95% learning curve, indicated the achievable energy costs for the year 1990 listed in Table III.

TABLE II

Advanced Concept SWECS

AC	ROTOR DIA. rated output	ROTOR/HUB	ROTOR CONTROLS	TRANSMISSION ASSEMBLY	POWER CONVERSION	TOWER	APPLICATION	kWh/Yr 12-14 mph
1	5 m (2 kW)	Plastic injection molded (soft downwind 3 blade rotor	Centrifugal (weights in blade)	Integrated Hub/Trans/ Generator (RT drive)	Alternator (single output)	Wood utility pole (guyed)	Battery Charger (DC output)	8,820 12,500
II	10 m 8-10 kW	2 blade downwind rotor; figerglass pultruded blades (twisted, flapping)	Delta-3 passive hinge	Integrated Hub/Trans/ Generator (RT drive)	Field Modulated induction generator	Free standing sectional pultruded	Utility Interconneciton	38,400 55,200
III	19.5 m	2 blade downwind wood lay up modes (twisted, flapping)	Delta-3 passive hinge	Integrated Hub/Trans/ Generator (RT drive)	Field Modulated Induction generator	Tripod (3 wood utility poles)	Utility Interconnection	130,000 166,000
IV	10 m 8-10 kW	2 blade downwind fiberglass pultruded blades (twisted, flapping)	Delta-3 passive hinge	RT drive	Heat Churn tower mounted	Free Standing flared fiberglass (pre-impregnated)	Direct heating	44,600 64,000

TABLE III

Achievable Energy Costs by 1990

SIZE RANGE	1990 COST OF ENERGY*(1980 dollars)			
	COM.AVAIL.	PT-1	PT-2	AC
3-6 meter	10.8	9.1	8.5	5.8
6-12 meter (electrical)	8.6	5.1	4.1	3.3
6-12 meter (mechanical)	---	---	---	2.2
12-25 meter	none	2.8	2.2	1.8

*Calculated with Fixed Charge Rate Formula.

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SMALL WIND SYSTEMS TECHNOLOGY ASSESSMENT

State of the Art and Near Term Goals

1.0 INTRODUCTION

After eight years of development by private industry and three years of federally sponsored development efforts, the present generation of small wind energy conversion systems (<100 kW) is approaching the threshold of competitiveness with conventional energy sources in the United States. The objective of this document is to define the current status of small wind energy conversion systems (SWECS) with respect to the gains which have been made and can be made in the near future. It is beyond the scope of this report to define the expense required to achieve these gains. This report defines what can be achieved and provides a general summary of the technical and development efforts required.

The data used in this report are a combination of empirical fact and estimates derived from careful engineering judgment. This combination is unfortunate but necessary and, in itself, indicates a great deal about the fluid SWECS state-of-the-art. Future revisions will incorporate additional empirical data as they become available.

It is the conclusion of this assessment that significant gains can be realized in the near future. The state-of-the-art is not sufficiently advanced for SWECS to be widely competitive in today's energy market, even though the technology appears superior to most other solar technologies. However, the threshold of widespread competitiveness has been approached. It can be surpassed with concerted development efforts within three to five years if these efforts are supported with component and subsystem development projects. Such gains can be achieved with an adequately funded program which should not require a significant increase over past efforts. Further, since the technology is already competitive in many situations, development efforts can be concurrent with planned federal commercialization activities. Such commercialization activities will help develop the market for SWECS while the last steps required to make the technology widely competitive are made.

This report documents the results of a SWECS technology assessment and projects future SWECS characteristics and energy costs. The methodology used was to: 1) define the state-of-the-art through a series of Figures-of-Merit (such as cost of energy, dollars per pound and kilowatt hours per year per pound); 2) project achievable, near term improvements possible with the current DOE prototype machines; 3) project further improvements which could be made through innovations within conventional configuration horizontal-axis and cyclogiro SWECS, 4) define hypothetical advanced systems incorporating these improvements; 5) determine Figures-of-Merit for these hypothetical systems by defining their weights, costs, and performance; and 6) define Supporting Research and Technology (SRT) projects which would be required to apply the innovations to the development of new systems.

This assessment, while it has long been necessary, has been performed at the earliest possible time. Fabrication of the first generation DOE prototypes has just been completed and offers an ability to determine improvements which can be made. However, since prototype tests are just beginning, these improvements must be considered subject to change. It is expected that this assessment will be revised periodically to consider advances in commercially available systems, DOE prototype test data, and the results of more detailed advanced concept analyses.

2.0 FIGURES OF MERIT - PRESENTATION OF FINDINGS

2.1 Figures of Merit

Throughout this report, Figures-of-Merit (FOM's) are used to illustrate SWECS status and potential improvements. The selected FOM's are: 1) cost-of-energy (expressed in cents per kilowatt-hour); 2) kilowatt-hours per year per pound; 3) kilowatt hours per year per square meter of rotor swept area; and 4) dollars per pound. SWECS referenced in these figures are commercially available, DOE prototype, and advanced concept designs. These systems are briefly discussed in Section 2.2.

Cost-of-Energy (Figure 1) is the most widely recognized economic measure for wind systems. A fixed charge rate formula developed by JBF Scientific Corporation was used in all cost of energy calculations. This was done to make these calculations comparable with those provided for Darrieus systems (Sandia Labs) and large WECS (NASA-Lewis Research Center). However, it is recognized that the fixed charge rate has several limitations which tend to inflate costs. (Life cycle costing methods have been developed at Rocky Flats which consistently indicate lower, "levelized" costs for SWECS.) All costs in this report are in 1980 dollars. FOB costs for commercially available and DOE prototype systems were obtained from the manufacturers, as were the performance figures necessary for cost-of-energy calculations. Installation and maintenance costs for the DOE prototypes were also obtained from the manufacturers. All other costs were derived from consistent formulas which are detailed at the end of this report. In some instances, manufacturer-supplied data which were inconsistent with known characteristics of specific machines or components were modified. These instances are noted and explained in the text.

Kilowatt-hours per year* per pound (kWh/yr/lb) (Figure 2) give an indication of the efficiency of material use relative to energy output. The FOM illustrates the benefits derived from reduced rotor loading as systems are improved. However, this FOM is, at best, an imperfect indicator of merit. Numerous examples can be cited of a design change which decreases cost-of-energy while decreasing energy yield per pound of system.

Kilowatt-hours per year per square meter of rotor swept area (kWh/yr/m^2) (Figure 3) is an indication of system efficiency. It also serves as a believability factor. For example, the highest value for a horizontal-axis DOE prototype was approximately 430 at 12 mph (5.4 m/s). Though values greater than 430 kWh/yr/m^2 are certainly achievable, values over

* SWECS performance (kWh/yr) was determined for all systems at 12 mph and 14 mph annual average wind sites (measured at 30 feet) using the Rayleigh distribution. All performance figures were calculated at hub height, using the 1/7th power law.

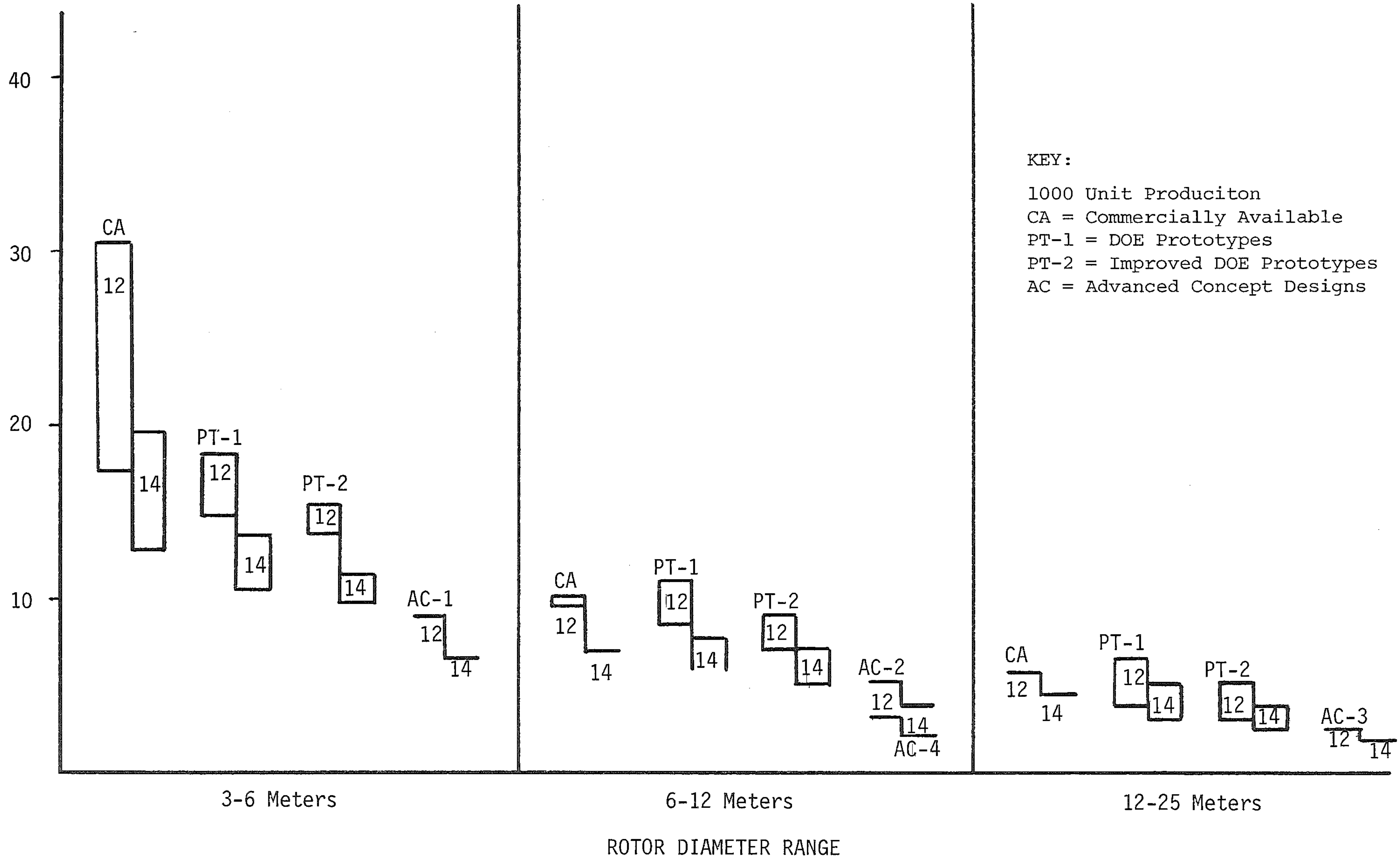


Figure 1

SWECS Cost of Energy (¢/kWh)

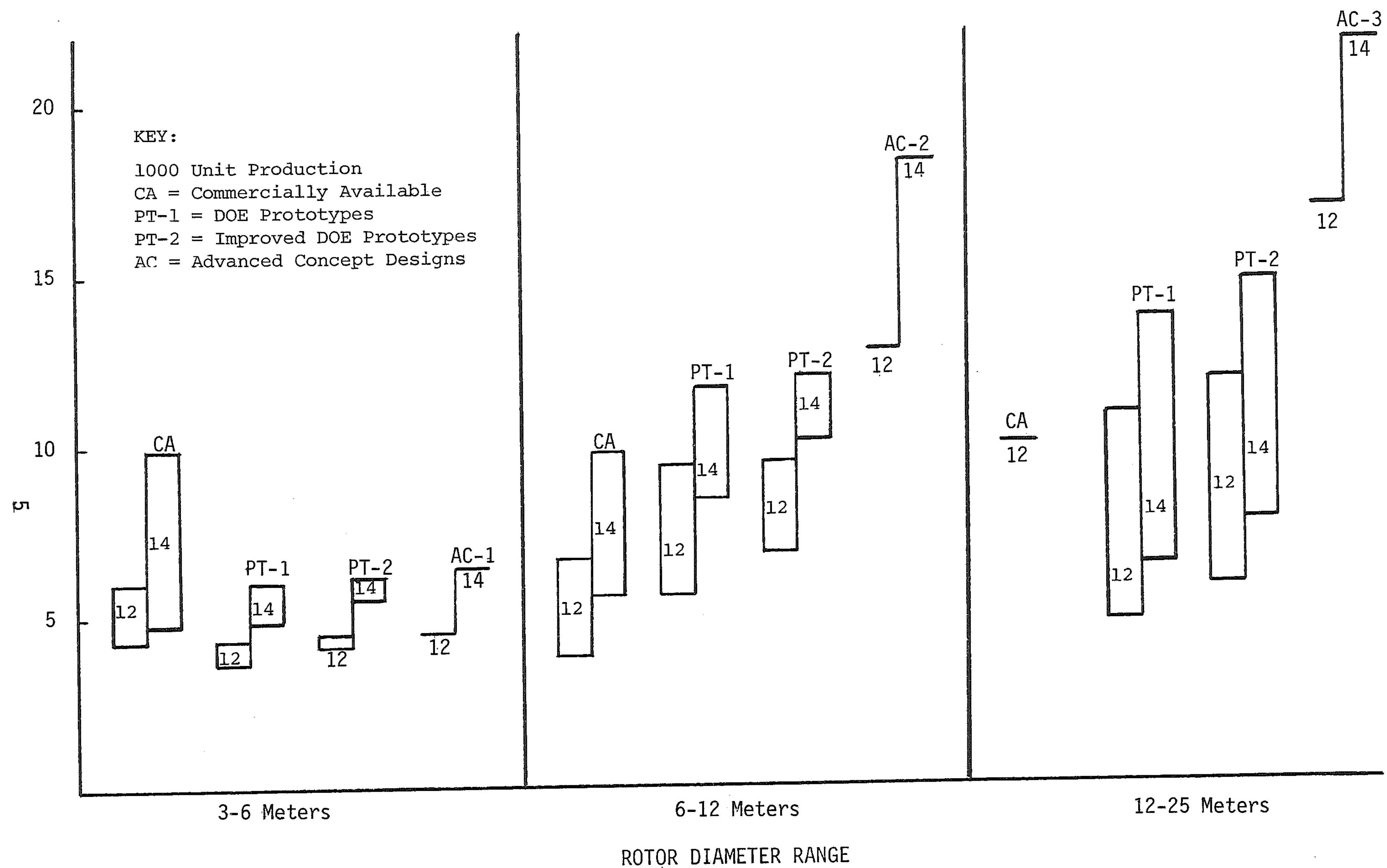


Figure 2

SWECS Performance vs System Weight (kWh/yr/lb)

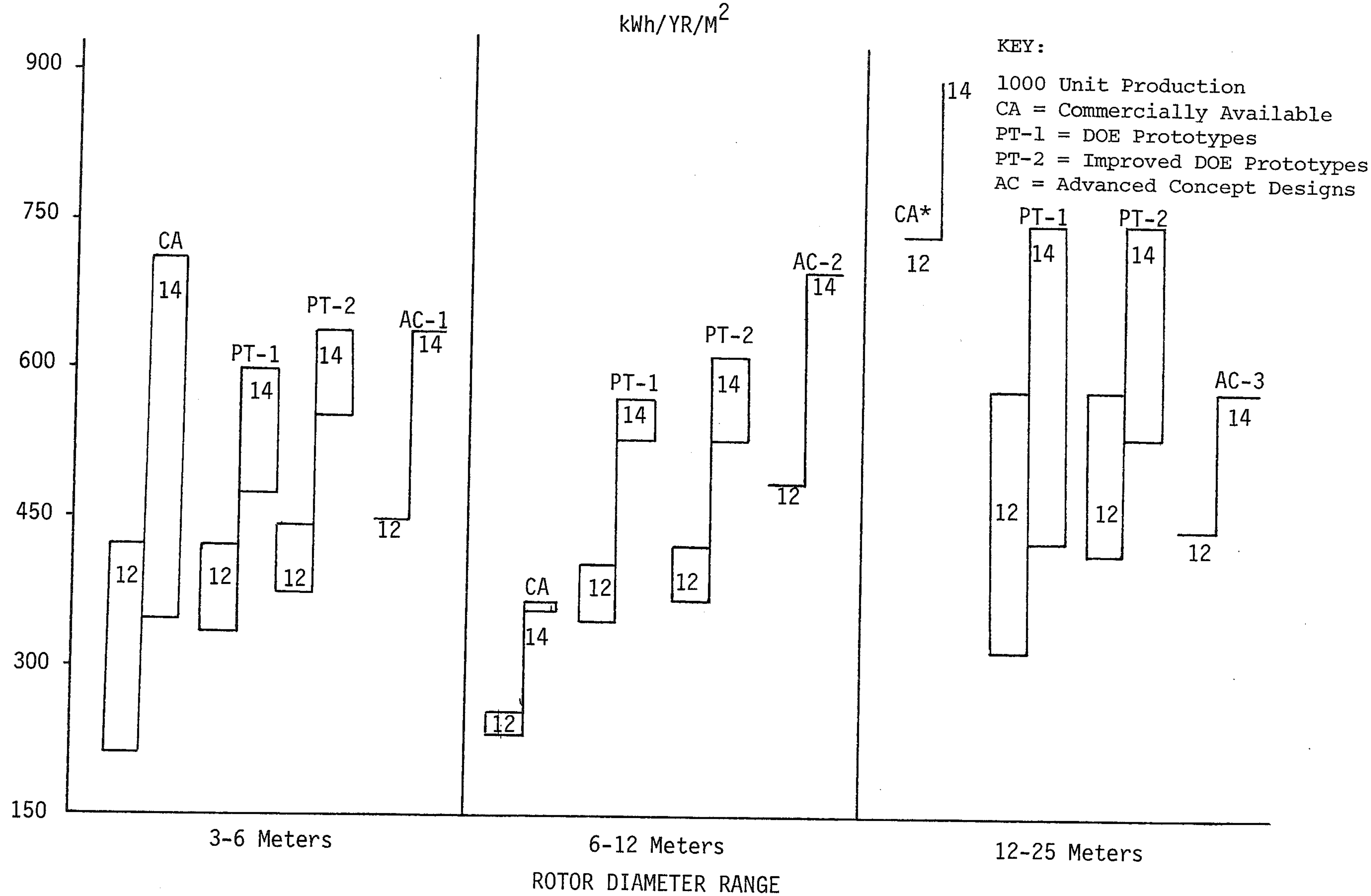


Figure 3
System Efficiency

* - Extremely high figures indicate manufacturer's data are unreliable.

600 (electrical system) at this wind speed would be considered an indication that performance estimates were unreliable.

Dollars per pound ($/lb) (Figure 4) are an indication of system complexity and provide another believability factor. Dollars per pound figures below $1.50 (for an electrical output system) would indicate that systems were underpriced or that contractor cost estimates were unreliable.

A number of figures of merit are needed because no single FOM is a sufficiently comprehensive, accurate or reliable basis for comparison. The reader must exercise caution to avoid reaching conclusions from comparisons based upon one or a few FOM's. Rather, all of the available data must be understood, weighed to eliminate apparent contradictions, and balanced before making a decision regarding future action.

2.2 SWECS Used in the Assessment

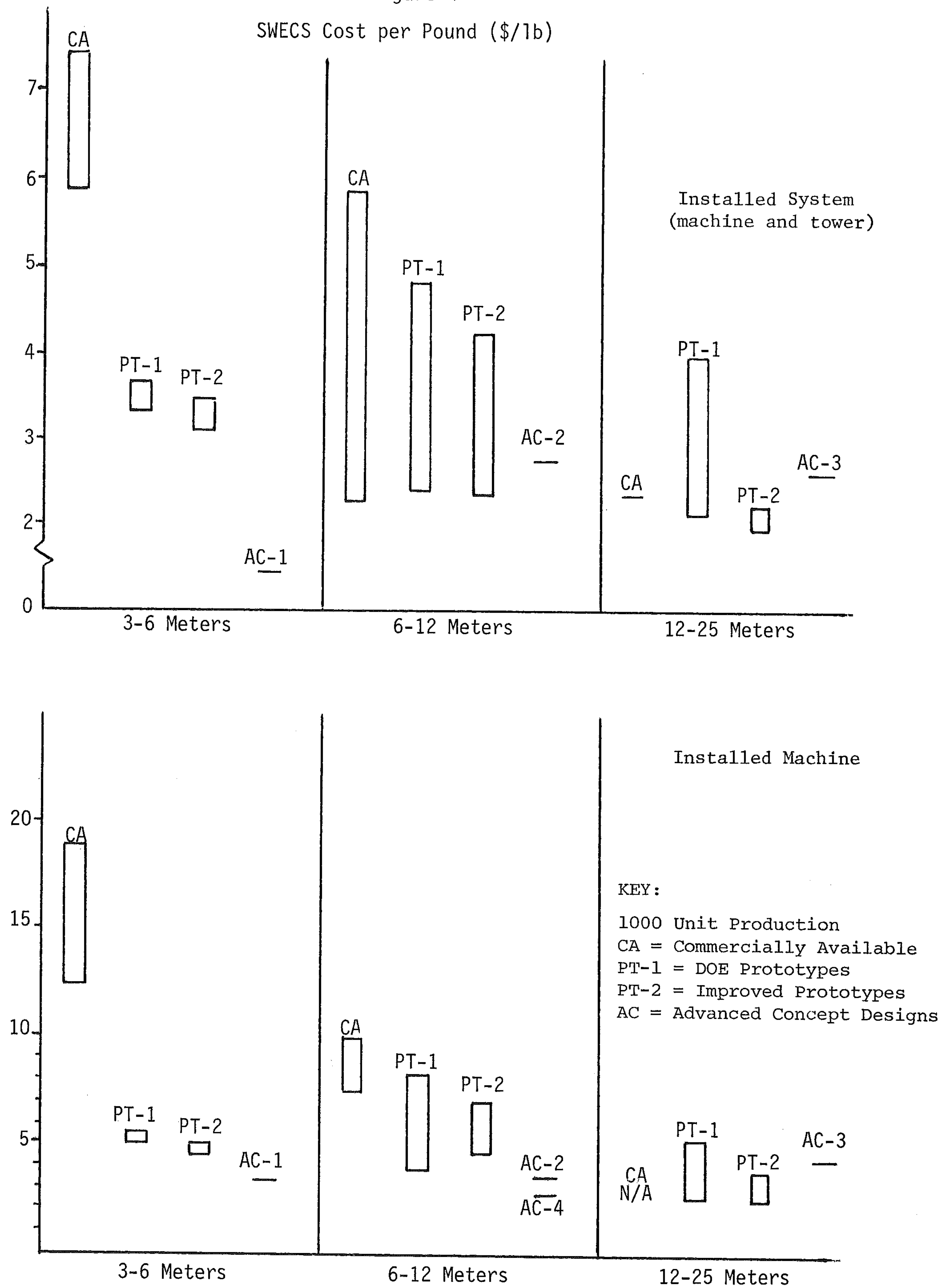
For purposes of assessing the current status of SWECS, six commercially available systems (CA) and seven DOE-funded first generation prototype systems (PT-1) were used. No empirical performance data for these systems are available, since the CA units are recently developed systems (and have not been significantly tested at Rocky Flats) and the DOE prototypes have only recently been fabricated. In the absence of data, manufacturer estimates were used. These estimates were subjected to detailed analysis and conservatively adjusted where the analysis indicated this was prudent.

Near term improvements have been projected by improving DOE prototypes to create second generation units (PT-2). Improvement was projected through the use of modifications proposed by the contractors as well as those indicated by Rocky Flats analysis.

Future improvements which could be realized later in the 1980's are represented in a series of Advanced Concepts (AC) for size ranges and applications with significant market potential. The rotor diameter size ranges considered are 3-6 meters, 6-12 meters, and 12-25 meters. Above

Figure 4

SWECS Cost per Pound ($/lb)



25 meters large system complexity (active controls, yaw drive, etc.) begins to mark the boundary between the economies of scale for small systems and large systems. The applications considered to be of highest near term potential were: 1) remote dc (3-6 meters), 2) utility interconnection (6-25 meters), and 3) direct heat using the mechanical water or heat churn concept (6-25 meters). All advanced concepts defined are horizontal-axis systems. Several innovative cyclogiro concepts were explored, but their figures-of-merit were poor.

It should be noted that Darrieus systems were also omitted from this assessment. This was done because of lack of direct experience with such systems at Rocky Flats. Considerable analysis is being performed by Sandia Laboratories on the conventional aluminum bladed Darrieus system. Continued work on a 4 kW fiberglass Darrieus unit newly subcontracted by Rocky Flats is required before a more definitive assessment of advanced Darrieus concepts can be made.

2.3 Commercially Available (CA) Systems

The cost of energy for six CA's being marketed in 1980 ranges from 3.5 to 30 cents per kilowatt-hour (¢/kWh).* These figures have been derived from manufacturer-supplied data. However, experience at the Rocky Flats Small Wind Systems Test Center (WSTC) indicated that some adjustments to performance estimates were required. This experience, supported by calculations of performance achievable for specific rotor sizes and configurations indicated that some manufacturer-supplied performance data are optimistic. In plotting figures of merit for CA's, it was noted that their kWh/yr/m^2 figures were significantly higher than those for DOE prototypes, whose performance estimates have been subjected to rigorous analysis. Some figures for CA units (such as 888 kWh/yr/m^2 for a 45 kW system) were clearly higher than could be achieved by the rotor configuration. The performance figures for such units (all in the 6-25 meter size range) were reduced 30% - the approximate amount

*Unless otherwise noted, figures of merit in the text represent the value achievable at a site with an annual average wind velocity of 14 mph (using a Rayleigh wind distribution).

performance was overestimated. This adjustment is conservative, however, and some figures are still considered to be inflated in terms of energy output.

It was not possible to accurately adjust cost figures for such characteristics as reliability and system lifetime. These characteristics are not generally known for CA units, making any adjustments somewhat arbitrary. However, experience at Rocky Flats indicates that several of these units are severely deficient in these respects and this makes cost-of-energy figures for these CA units optimistic at best.

2.4 First Generation DOE Prototypes

Energy costs for the current DOE prototype designs (ranging from 2.4 to 18.3¢/kWh) show an improvement over CA units. That the improvement is slight can be attributed to the stringent specifications for the prototypes - particularly for the 2 kW high-reliability units, which were built to survive 165 mph winds and wide temperature ranges. The performance of these DOE prototypes (in kWh/yr/m^2) is considered low and there is room for improvement.

The DOE prototypes are considerably less labor intensive than the CA units, as indicated by the CA's high dollars per pound figures. Since the DOE prototypes were designed to eventually permit high volume production* and most CA units were not, this situation is not easily changeable without CA unit redesign.

The McDonnell Aircraft (MCAIR) 40 kW DOE prototype giromill cost figures required considerable adjustment once the system's original figures-of-merit were determined. The giromill's cost of less than $1.00 per lb (system) based on the contractor's inputs was considered unrealistic and all component costs were assessed. The resulting adjusted giromill cost of $2.65/lb is more realistic.

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*For example, through the use of blade fabrication methods such as pultrusion and extrusion.

Improved DOE prototypes could realize measurable improvements in cost of energy and other figures of merit. An average improvement of 17% in COE is projected for all systems (with variations from 7% to 30%) due to weight reduction, material modifications, and slight configuration changes suggested by the contractors or proposed by Rocky Flats. Use of lighter, cheaper materials for blades on several systems (and reducing overall blade chord on the Grumman) increased kWh/yr/lb considerably, as shown in Figure 2.

Throughout the analysis, it became apparent that rotor and system efficiency can be more important cost drivers than component cost. While component costs are overshadowed by installation costs, distribution costs, and the like, performance improvements often have a greater impact in the cost-of-energy equation. Thus, system performance played a significant role in the definition of possible second generation systems. For example, in several instances it was found that performance improvements realized through the use of higher cost, heavier components would result in lower energy costs.

2.5 Second Generation SWECS (Advanced Concepts)

Alternative or unconventional component concepts were assessed for lower cost through improved performance, reduced weight, or increased reliability compared with CA and prototype units. From several concept matrices component configurations were selected for four second generation advanced concept (AC) units. The configurations of these concepts are discussed in detail in Section 5 and are summarized in Table II (page47).

It should be recognized that a primary purpose for defining such systems is to illustrate and provide a frame of reference for potential and achievable improvements in SWECS. While the Advanced Concept systems may serve to focus future efforts, they are by no means fixed prototype designs. Likewise, the sizes and applications chosen reflect current data regarding the near term SWECS market.

The projected cost of energy for the AC-1 dc battery charger shows a dramatic 36% improvement over the improved DOE prototypes. This is derived from the use of a light integral transmission/generator subsystem, passive rotor controls, and a wood pole tower.

The two AC-2 and AC-3 systems (designed for utility interconnection) would incorporate integral transmission/hub/field modulated induction generation subsystems. The rotors for these systems would consist of two flapping blades attached to the hub with large-angle "delta-three" hinges. FOM improvements over improved DOE prototypes would be more notable in the smaller (6-12 m) size range, due primarily to an increase in performance (25% higher kWh/yr/m^2) afforded by the use of the variable speed generator and the improved rotor system. As rotor size increases (in the 20 m AC-3 class), these increases would not be as notable.

The most startling improvements could be realized in the AC-4 unit, which incorporates a mechanical heat churn. Such power conversion devices can be built far less expensively than electrical generators, do not require high rpm gearboxes, and offer the dual advantages of very high efficiency and optimum rotor-load matching. The 2.3¢/kWh (equivalent) cost of heating water with such systems would be immediately competitive with electric heating and could be competitive in the near term with oil and gas heat. Optimization of the SWECS used to power a heat churn would include the use of a flapping rotor; tailor-made drive-train components; and tubular, easily insulated, fluid-bearing towers. This advanced concept could assume a huge market which would stimulate private industry investment and high volume production by the mid 1980's.

2.6 Summary of Conclusions Derived from Figures of Merit

It was deduced from the figures of merit that improvements are possible in commercially available and DOE prototype systems in all size ranges. Given the projected improvements in cost-of-energy for the second generation advanced concept SWECS, it was also concluded that the use of current off-the-shelf components in the commercially available and prototype SWECS has inhibited achievement of their full cost potential. The use of innovative component concepts in the second generation SWECS is the primary reason for projected reduced energy costs. While many of these innovative concepts involved hardware weight/cost reductions, improved performance was a far more important factor in reducing cost-of-energy.

The figures of merit indicate that several of the original DOE prototype designs are roughly comparable to some CA units and that some improved versions may be much less cost-effective than second generation SWECS. Assessment of these systems to determine the value of continued development is required.

Significant cost-of-energy improvements are possible in the 3-6 meter and 6-12 meter size ranges for electrical units and for mechanical heat churn systems. These projections indicate that additional technology development for such systems should be pursued. However, the projected improvements for the 12-25 meter electrical system size range are not as great.

3.0 COMMERCIALLY AVAILABLE SWECS

The commercially available machines used in this analysis were generally selected from among the SWECS purchased by Rocky Flats for the Field Evaluation Program. Ranging from less than 3 m to 14 m in diameter, most of these machines were introduced since 1978 and have been designed to incorporate new ideas, modern materials, and innovative fabrication methods. However, because of the many unknowns still associated with these machines, extensive long term field testing and user experience is required to assess their true merits. Ultimately, these data will help identify the more reliable and cost-effective concepts. However, while the reliability and durability of some of the SWECS assessed are questionable, no attempt has been made to compensate for such factors in this assessment.

3.1 Cost Drivers for Commercially Available SWECS

Minimum cost of energy for a wind machine is primarily dependent on three factors: 1) installed machine cost, 2) machine performance, and 3) annual operation and maintenance. Installed machine cost is comprised of hardware cost, marketing/distribution cost (including overhead), shipping cost, and installation cost as shown in Figure 5. Of these costs, hardware cost (62%) offers the most potential for reduction. Installation cost, which represents 20% of the total, offers another area for potential improvement. The other two components, distribution and shipping cost, are relatively inelastic at the size ranges under consideration.

Because of the dominance of hardware cost in the overall installed cost it is desirable to determine a means of reducing component costs, particularly the costs of those components that represent a large percentage of the hardware cost. Of even greater importance is machine performance. Improvements in efficiency have a proportional impact on energy cost, whereas reductions in hardware cost are somewhat diluted when mixed with other components of the installed cost.

The efficiency of most commercially available SWECS is quite low, with system power coefficients of .20 to .25 being the norm. To complicate the matter, manufacturer-supplied performance data are in many cases optimistic and not representative of actual operational test data.[1] (Calculated values of annual energy output for horizontal-axis DOE prototype machines are considered more realistic and in most cases have been supported by extensive Rocky Flats analysis.)

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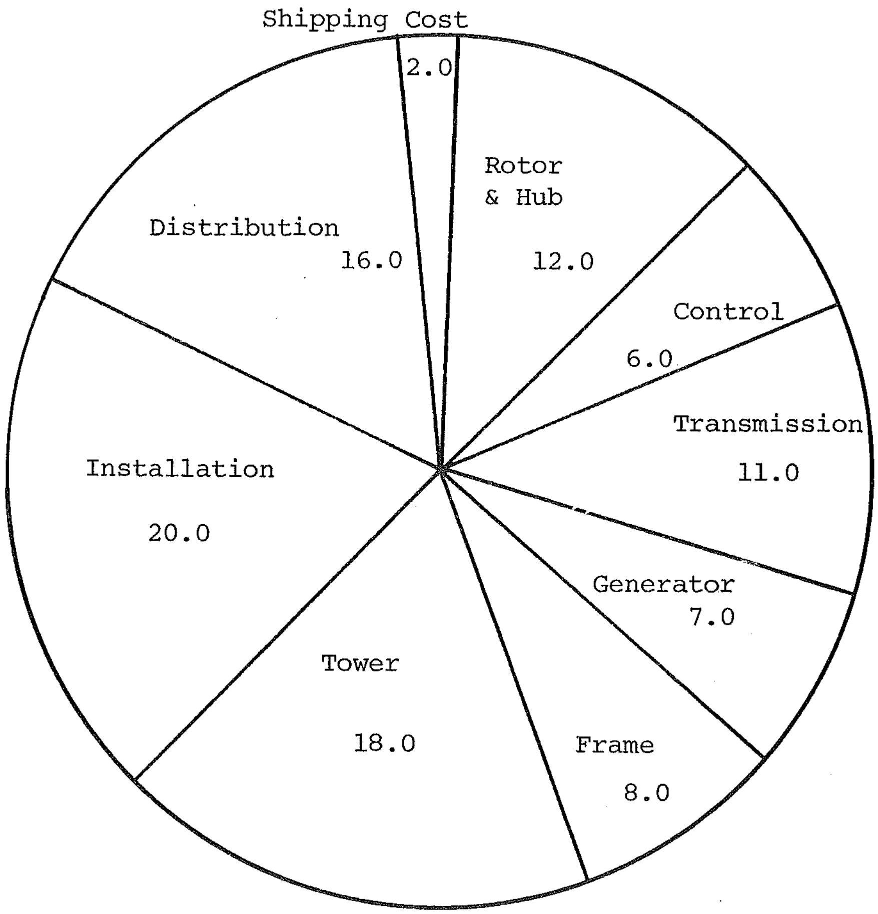
[1] References: Rocky Flats data reports.

Figure 5

Installed Cost Distribution
-Commercially Available SWECS-



PER CENT OF INSTALLED COST

SYSTEM		HARDWARE	
Hardware Cost (FOB)	62%	Rotor	20% (62) = 12%
Installation Cost	20%	Controls	9% (62) = 6%
Distribution Cost	16%	Transmission	18% (62) = 11%
Shipping Cost	2%	Generator	10% (62) = 6%
		Frame	12% (62) = 7%
		Tower	31% (62) = 19%
TOTAL	100%		62%

Overall system efficiency is the product of rotor, transmission, and generator efficiency. The efficiency of most commercial machines is limited most by that of the rotor. It is presently most expedient to use constant chord, nontwisted blades with time-proven airfoils such as the NACA 0012, 4415, and 23012. Increases of 10-15% in rotor performance would be possible by optimizing these parameters for a given machine size and design. This improvement translates to a 10-15% increase in annual energy output. The constant rpm operation of many commercial utility intertie machines also results in a rotor efficiency loss. Additional performance improvements of up to 20% are possible by allowing the rpm to vary so that the tip speed ratio remains constant and the rotor can operate at or near its maximum power coefficient.

Limited production volume contributes to the high machine cost of commercially available SWECS. Small lot fabrication forces manufacturers to use off-the-shelf components not specifically designed for their application. This generally leads to an inefficient and less reliable design due to overly complex system integration. (For example, slip rings required to transmit power past the yaw axis and off-the-shelf transmissions have been found by Rocky Flats prototype subcontractors to be the most unreliable components - other than the rotor - in the DOE-funded systems.) Strongbacks required to mount generators and transmissions on many systems add unnecessary expense and add weight which could be used to advantage in other areas to increase durability.

The assembly of machines with many components adds hundreds of dollars to unit production costs and makes mass production difficult. The fact that many CA units are labor intensive is illustrated in the high cost-per-pound figures for these systems, particularly those in the 3-6 m size range (see Figure 4).

Most commercially available units are now produced in quantities of tens rather than hundreds. Just as the auto industry had to await high volume assembly line production for a major breakthrough in unit cost, so too will the SWECS industry's unit costs be determined by its ability to achieve high production volume. However, experience at the Rocky Flats Test Center with commercially available systems indicates that most such units are (understandably with today's small market) not designed for such production. In many cases, mass production of SWECS which require constant surveillance and maintenance for minor but persistent problems would be unthinkable without major system redesign.

Installation costs typically represent 20% of the installed cost. However, for some machines this cost runs much higher. To a large degree installation cost is driven up by requirements for heavy equipment such as cranes and for excessive hours of skilled labor. Innovative installation techniques are being used by some manufacturers to reduce these requirements, but more innovation is needed.

3.2 Commercially Available SWECS Reliability

Maintenance costs are highly dependent on thorough consideration of reliability during the design process and a concerted effort toward quality control during the manufacturing process.

The reliability of commercial machines is difficult to establish. However, experience to date indicates that reliability is not high for most commercially available machines. Poor reliability stems from a variety of problems, the most important of which are attributed to poor blade construction, unreliable yaw control, active blade pitch control, electric power control, and slip rings. Most of these problems apparently stem from inadequate designs or poor quality control of hardware parts. All of these factors can lead to high maintenance cost, poor operational characteristics, and (in some cases) catastrophic failures early in system life. The industry's consensus is that annual maintenance costs are one to two percent of the total system cost. While such costs would be acceptable, evidence to date indicates a much higher percentage for most machines.

3.3 Areas Where Improvements Are Needed

Reductions in the cost of energy of CA units can be achieved through: 1) improved rotor efficiency, 2) more reliable* and material-efficient transmissions and generators, and 3) reduced installation and maintenance costs.

Improved rotor power coefficient and annual energy output can be achieved in several ways. The individual or combined effects of twist and taper can increase the annual energy output up to 8 percent. By using specific purpose airfoils, in the various size machines, additional improvements in annual energy output of up to 7 percent might be realized.

Substantial reduction in component weight and cost could be achieved through the use of custom-designed transmissions and generator configurations. However, few (if any) small SWECS manufacturers have the capital (or the valuable time) required to risk such design efforts. Without the real promise of high market demand, no larger manufacturers have taken the required risks either. Most manufacturers seeking to reduce power train costs turn to direct drive, low speed generators which are notoriously heavy and inefficient. The variable speed, field modulated induction generator concept has been known for several years to offer rotor control and power quality advantages while optimizing the performance of rotors through the maintenance of constant tip speed ratio. To date, no commercially available unit has been designed to incorporate

*The ability of transmissions and generators to operate reliably through the 20-30 year life of a wind system has been questioned by Rocky Flats prototype subcontractors; however, due to the short (2-3 year) maximum test periods on current wind systems the reliability of these components (as used in wind machines) has not been established.

such a generator. The SWECS industry, while apparently willing to innovate, is not able to do so. Cost reductions have sometimes been made at the expense of reliability. Rather than reducing the weight and (eventually) the cost of power train components, critical load points at the hub and in the rotor are sometimes apparently designed for cheapness rather than strength. In this manner, the drive to produce SWECS with low energy costs may have damaged rather than strengthened the technology.

Installation costs must also be reduced if the costs for CA units are to be significantly improved. Most manufacturers use off-the-shelf or slightly modified towers which were designed for applications which are not as cost or dynamically sensitive as small scale energy production. Materials and construction techniques exist which could be used to produce towers which would reduce tower installation and machine installation costs. Some of the more innovative manufacturers have utilized ready-built hardware (such as steel water pipe) which serves to reduce fabrication and hardware costs. However, no true innovations have emerged other than the use of the labor intensive octahedron tower.

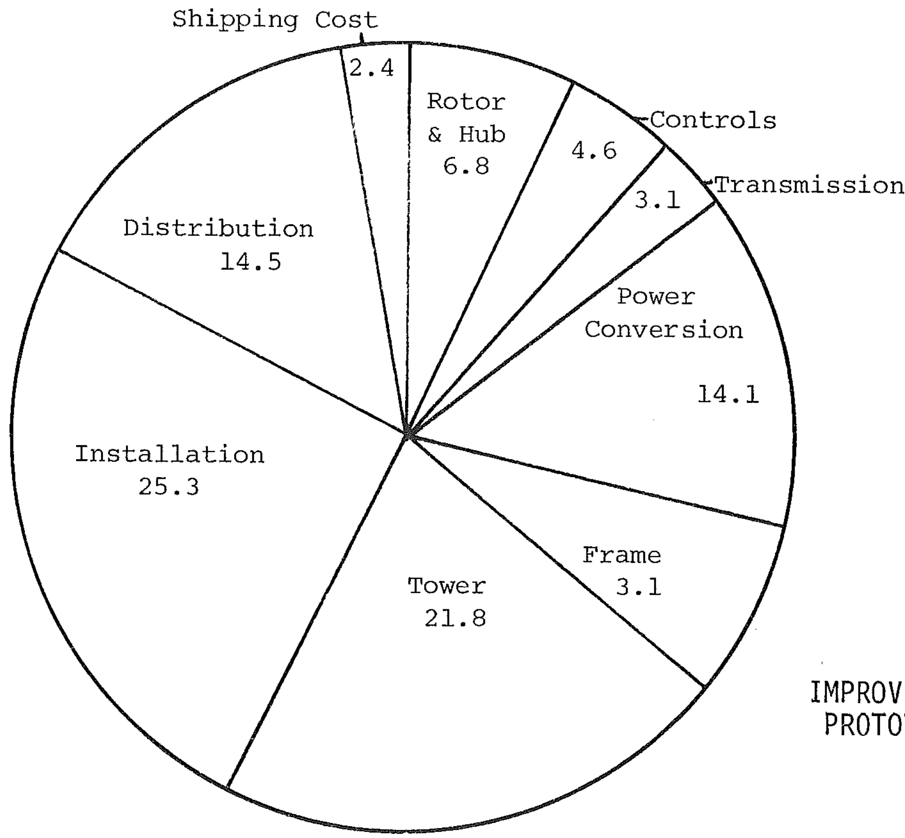
As noted in the next section, the manufacturers of several DOE prototype systems have begun to reverse the tendency to minimize near term costs at the expense of future reliability and potential long term energy cost reductions. Some innovation is also occurring in private industry independent of federal support. However, there is more than enough room (and considerable need) for further effort in this direction.

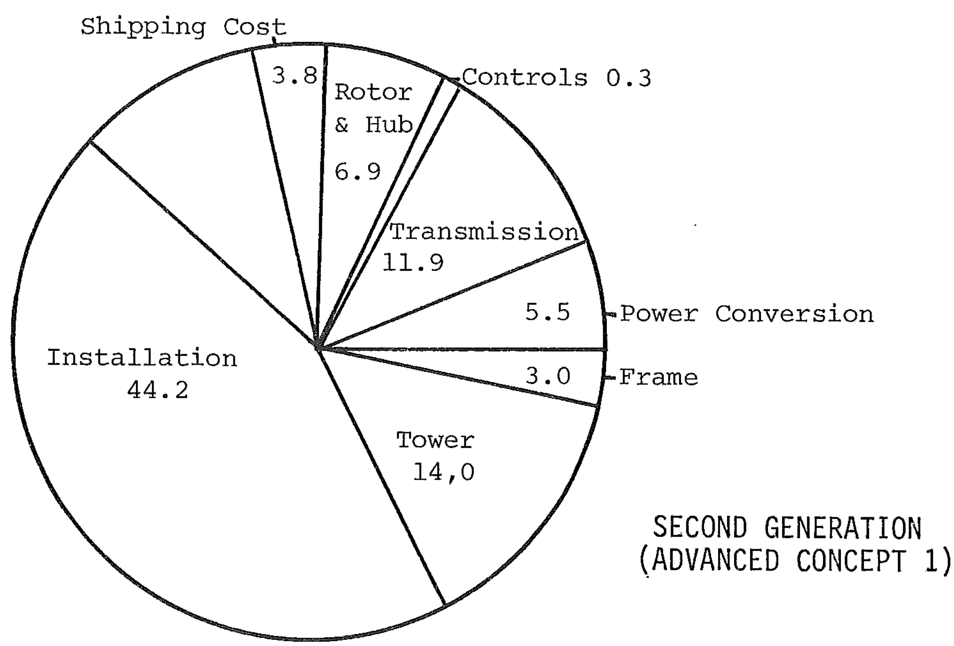
4.0 DOE PROTOTYPE SYSTEMS (FIRST GENERATION)

In all size ranges, figures of merit for the first generation DOE prototype systems show a general improvement over commercially available machines. The characteristics of these systems are shown in Table III (pg. 48) Average installed cost distributions are shown in Figures 6-8.

Figure 6

Installed Cost Distribution 3-6 Meter SWECS*

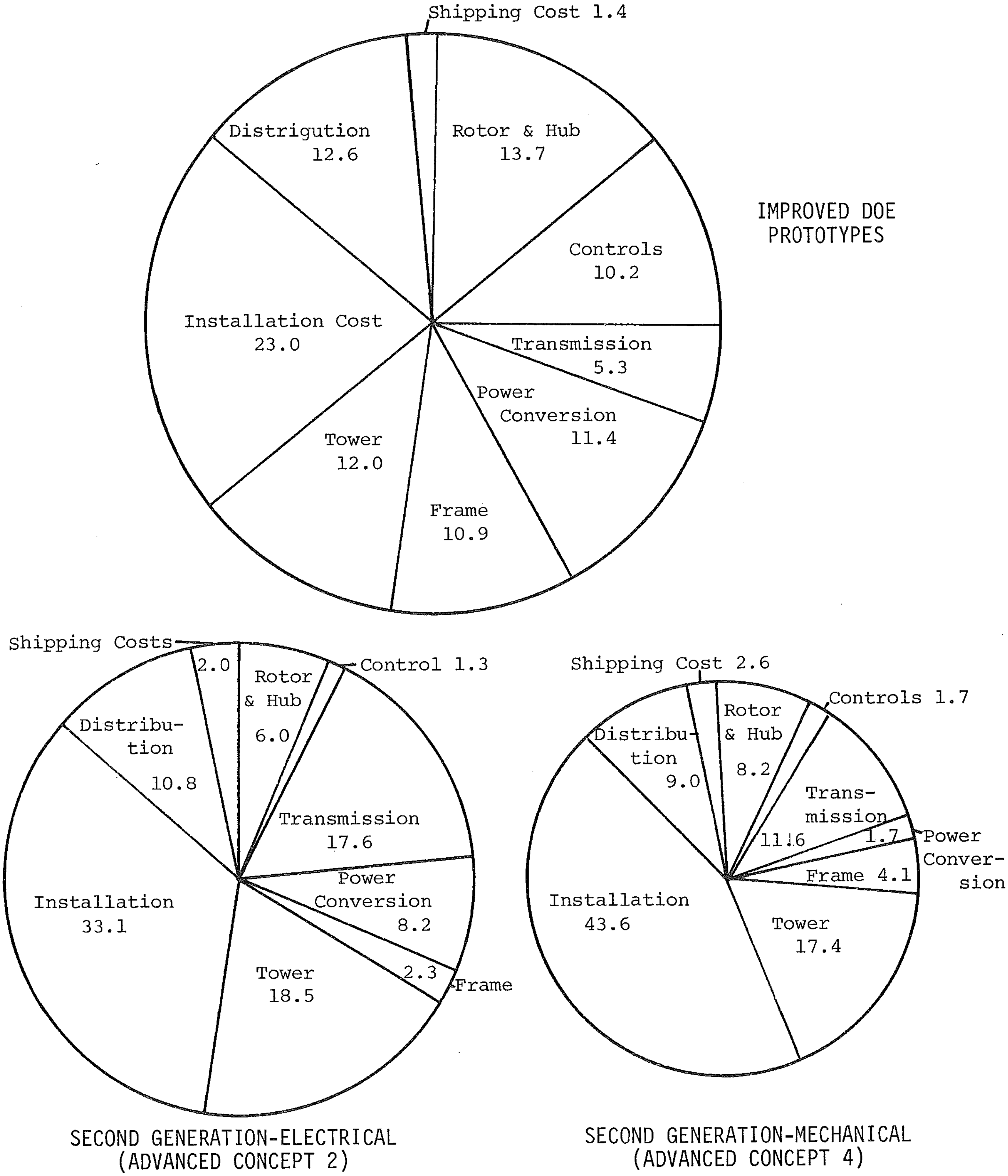




*Circle size shows relative cost

Figure 7

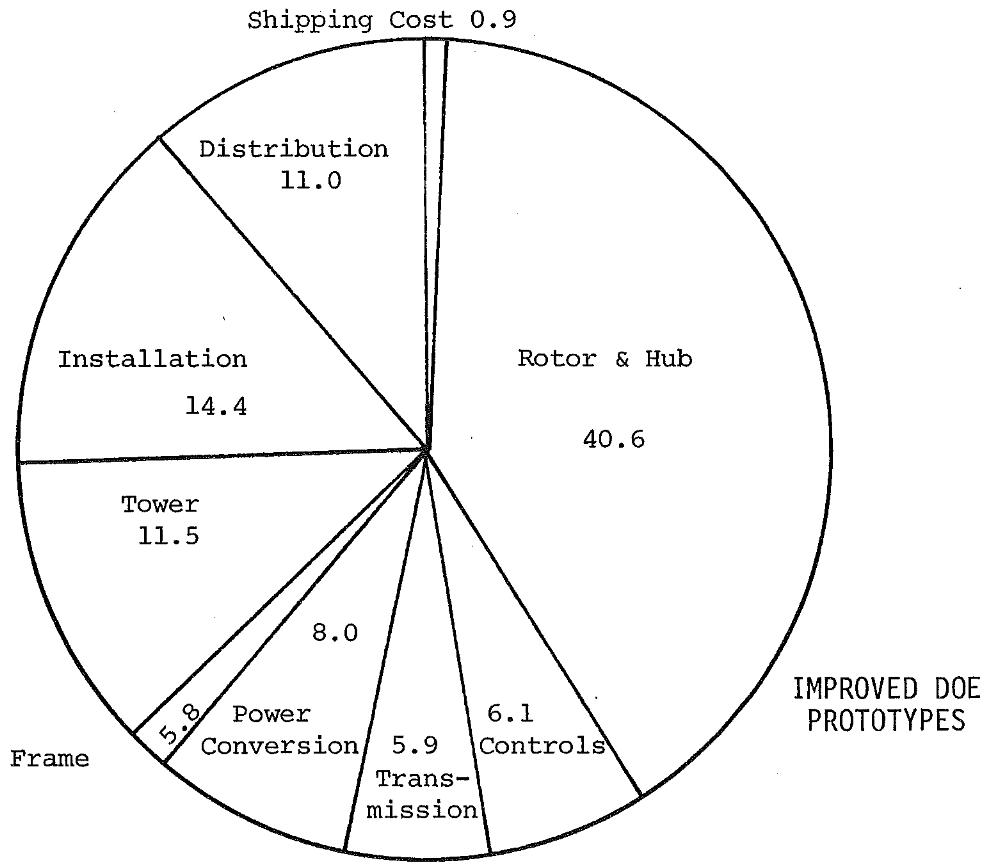
Installed Cost Distribution 6-12 Meter SWECS*

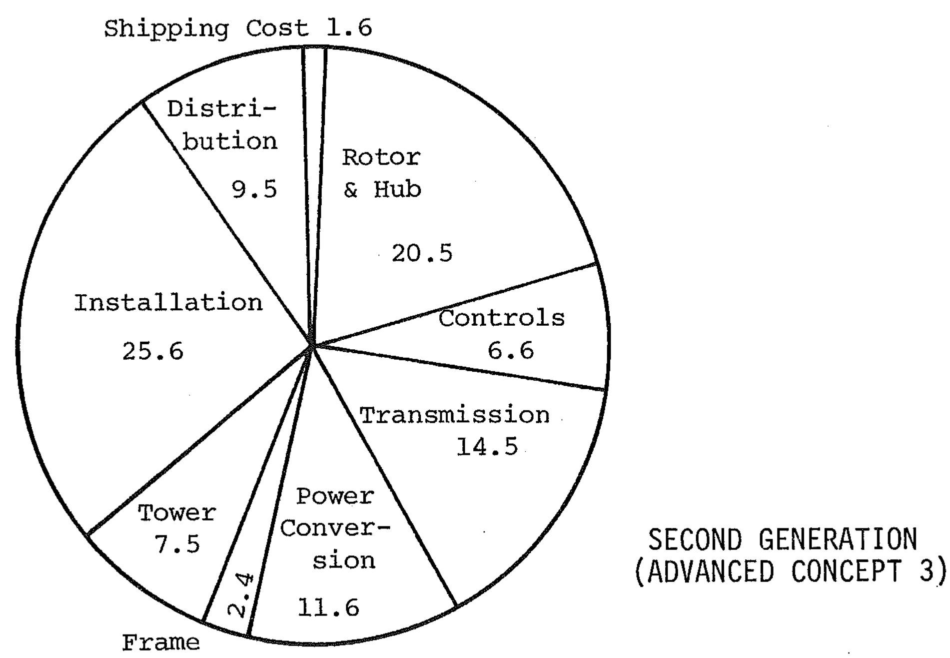


*Circle size shows relative cost

Figure 8

INSTALLED COST DISTRIBUTION 12-25 Meter SWECS*





*Circle size shows relative cost

While improvement was realized over CA units, the characteristics of these systems indicated that additional improvement is possible. Prototypes were investigated for possible improvements in weight, performance, and cost of production, materials, and installation.

In this section the DOE prototypes are assessed for cost drivers and for unique characteristics reflected in the FOM's. The modification of each system in improved prototype designs is also discussed. Modifications noted in this section were prepared by prototype subcontractors or were developed by the authors after consultation with Rocky Flats program monitors. None had been used on prototype units when this document was written. Detailed matrices itemizing the impact of all modifications on the basic designs are included in Attachment 2.

4.1 North Wind - 2 kW

Prototype

The North Wind 2 kW prototype total system costs are dominated by the tower costs (41% of the system). This is due primarily to a 165 mph survival wind speed and 80 mm icing criteria in the contract specifications to achieve high reliability and enable unattended electrical generation in very severe environments. This machine has one unique component - a vertical axis rotor control (VARC) spring which is used to allow the rotor to rotate upward to a vertical axis in high winds. The cost of energy is 18.3 and 13.6¢/kWh for wind regimes of 12 and 14 mph, respectively.

Improved Prototype

Improvements are projected for both reducing the costs by fabricating the blades out of pultruded fiberglass and improving the energy output by optimally load-matching the North Wind VARC spring to the rotor and using better airfoil sections. The design changes can also increase the kWh/yr/lb and could result in lower $/lb (machine) and $/lb (system) costs. Tower costs could be reduced by 50% if wind speed requirements were relaxed for less severe environments. Cost of energy would be 15.4 and 11.4¢/kWh for 12 and 14 mph wind regimes.

4.2 Enertech - 2 kW

Prototype

As with the North Wind, the tower costs dominate the system cost (40%). The Enertech COE is lower due primarily to better system kWh/yr/lb and kWh/yr/m^2 and lower $/lb (system) costs.

Improved Prototype

The system costs can be reduced slightly by replacing the wood blades with cheaper pultruded fiberglass blades and selecting an available lower cost gearbox. Improved energy production could be obtained through optimum rotor-load match or redesign of the control system (centrifugally pitching hub). These modifications could reduce COE by about 7% to 9.7¢/kWh. This improvement would be due in part to slight improvement in kWh/yr/lb and kWh/yr/m^2 and reduction in $/lb costs.

4.3 UTRC - 8 kW

Prototype

The system costs for the 8 kW UTRC design are dominated by the tower (25%) and electrical controls (24.3%) followed by the rotor/hub costs (18.0%). Since the UTRC rotor uses aerodynamic stall for control, the kWh/yr are lower than for a feathering rotor of the same size. Tower costs appeared high but there was no valid reason to lower them. Rotor costs (at $7.86/lb) cannot be lowered in the present design without advances in flexbeam materials and fabrication. Each of these factors explain in part the relatively high COE (7.5¢/kWh) for this machine.

Improved Prototype

Improvements in COE are projected due to both system cost and weight reductions and energy improvements. Fiberglass materials could be used in the flexbeam in lieu of the more expensive present graphite fiber design. The strongback could be cast or forged instead of welded. Weight and costs can be reduced substantially by using a pultruded fiberglass tower with steel rods instead of wire cables. With advances in pultrusion technology the blades could be twisted, thus improving system output. Production improvements for blade attachments, bearing interface and control electronics could reduce costs further. As a result, the COE could be reduced by about 20% (to 6.0¢/kWh) and the other FOM's could also be improved slightly.

4.4. Windworks - 8.5 kW

Prototype

The Windworks system costs are dominated by the power conversion subsystem (30%) which includes the alternator ($6.13/lb), electrical controls, and Gemini inverter ($27/lb). These high subsystem costs contribute to the relatively high machine ($8.42/lb) costs but are offset by lower tower ($1.16/lb) costs. This unit achieves high energy output due to in part the efficient blade and feathering rotor design. COE is 7.8¢/kWh.

Improved Prototype

In the improved Windworks design, COE improvement could come from reduction in costs and not performance improvements. One of the three blades could be eliminated and the overly redundant hydraulic controls could be simplified. The blade weight and cost could be reduced slightly by using a pultruded fiberglass design. Production improvements are envisioned for an additional 10% in cost savings, but a weight savings is not believed possible. The resultant COE could be approximately 10% lower than for the prototype design. The other system FOM's could also be improved slightly.

4.5 Grumman - 11 kW

Prototype

The Grumman prototype system costs are dominated by the rotor/hub (78%), frame (18.3%), and power conversion (18.2%) subsystems costs. The basic rotor/hub and frame are heavy. The electrical controls are expensive, so that even with an induction generator the power conversion subsystem costs are $5.54/lb. The energy output is good, due in part to the feathering rotor design, so that the overall COE is relatively low (5.8¢/kWh) compared to the UTRC (7.5¢/kWh). The contractor cost estimates for the overall tower (55¢/lb) and G/A (10%) may be low, but these estimates were not adjusted. Even if the tower and G/A costs were doubled the resultant COE would still be lower than for the Windworks and UTRC systems.

Improved Prototype

In the improved Grumman design, COE reductions could come from across-the-board reductions in weight and cost as well as performance improvement due to modifications in the system's present conservative design. The overall machine weight could be reduced by about 26% by shortening the strongback and low speed shaft, reducing rotor solidity, and changing from aluminum extruded blades to pultruded fiberglass. The savings in manufacturing costs would be approximately 17%. By changing airfoil sections and twisting the lower solidity rotor, the energy output could be enhanced by at least 9%. The costs would be reduced by an additional 5% through general production improvements. The resultant COE (4.7¢/kWh) would be about 19% lower than the COE for the prototype design. The design changes would result in a 21% improvement in kWh/yr/lb.

4.6 Enertech - 15 kW

The Enertech 15 kW prototype is in the early stages of design. The machine will be configured like the present Enertech 1500 in that it will be a horizontal-axis, three-bladed, fixed-pitch downwind machine with an induction generator. The early contractor cost projections indicate that the generator costs (32.4%) will dominate the machine costs. Note that this design may be considered an improved CA design since it does represent an improved "1500" design. The design is in its early phases and further improvements are not considered here.

4.7 UTRC - 15 kW

The UTRC 15 kW is essentially a scaled-up and improved version of the UTRC 8 kW design. In comparing the two UTRC designs, significant improvement can be seen in the system kWh/yr/lb (38%).

4.8 Kaman - 40 kW

Prototype

The Kaman 40 kW prototype machine costs are dominated by the rotor/hub (35.4%). The contractor costs for tower and transmission subsystems were adjusted upward due to unrealistic cost per pound values. The contractor's data indicated a 5,000 lb tower at 28.2¢/lb. and a transmission at 34.1¢/lb. These were adjusted to more realistic values of $1/lb for the steel tower and $3.40/lb for the transmission. The resultant COE's were still promising at 3.8¢/kWh (12 mph) and 3.0¢/kWh (14 mph).

Improved Prototype

The improved Kaman prototype could have reduced COE due to lower system weights and costs, but not increased performance. The electrical controls could be simplified. A teetering hub could be incorporated into the rotor design. The blades could be fabricated of wood composite. The resultant system weight and cost savings could be 7.6% and 25.1%, respectively. The new COE's would be 2.7¢kWh (12 mph) and 2.1¢/kWh (14 mph), or about a 30% improvement at 14 mph. The system $/lb of $2.25 would be very low, but may be achievable.

4.9 McDonnell Aircraft - 40 kW Giromill

Prototype

The McDonnell Aircraft (MCAIR) 40 kW prototype system costs are dominated by the rotor/hub (69.1%). The rotating structure of this machine is very heavy and the kWh/yr/lb (system) are the lowest of all the prototypes. The COE was estimated at 6.0¢/kWh (12 mph) and 4.6¢/kWh (14 mph). In estimating the system FOB costs, the contractor's estimates were adjusted for major subsystems due to a reported $/lb (system) figure below $1.00, which is not realistic for this type of structure. These adjustments are itemized in Table I.

TABLE I

ADJUSTMENTS TO 40 kW GIROMILL COMPONENT COSTS

Components	Contractor ($/lb)	Adjusted ($/lb)
Blades	3.37	5.00
Hub/Shaft	.276	2.00
Struts	.649	3.00
Gearbox	2.82	3.40
Tower	.44	.90

The resultant machine FOB costs increased by $14,718 from the original contractor estimate, to $46,684 ($2.65/lb). The adjusted machine FOB costs reflect a more realistic view of what it would actually cost to build a Giromill. The FOB system $/lb cost increased from $.72/lb to $2.10/lb.

Improved Prototype

Reductions in the COE for the improved MCAIR 40 kW prototype could be achieved through lower system weights and costs but not higher performance. The electrical controls could be simplified. Weight savings (total of 16.8%) could be made through the use of wood struts and a guyed tower. Additional cost savings could be accomplished by the use of wood blades (composite) produced with the layup process. The total cost savings are approximately 5%. The new COE's are 5.2¢/kWh (12 mph) and 3.9¢/kWh (14 mph) or about a 15% improvement at 14 mph.

5.0 ADVANCED CONCEPTS

Commercially available and prototype SWECS have usually been designed to employ off-the-shelf components and state-of-the-art technology. This has been done to minimize development costs and risks. In addition, the federal procurement process has limited component development in proposed designs because of the desire of proposers to minimize project costs and increase the likelihood of winning a contract. If they are to achieve their full low-cost potential, mass produced SWECS of the future must use components optimized for specific applications and designed for the unique requirements of wind systems.

Four hypothetical Advanced Concept SWECS have been conceived which assume moderate improvements through supporting research and technology and development programs. The following philosophy and ground rules have been applied to the conceptual designs:

1. Use of active system controllers, actuators, and sensors should be minimized wherever possible. Both the relatively high cost and intrinsically lower reliability of active controls make them undesirable, particularly in small SWECS.

2. Dynamically "soft" systems result in lower weights and costs and provide relative insensitivity to turbulence in the ambient wind. Therefore, tower, rotors, and drive trains should be as soft as practicable.

3. The systems will be produced in sufficient volume to preclude any advantage from using currently available off-the-shelf components. Thus, custom-designed gearboxes, generators, and housings and easily installed, custom-built towers may be employed.

4. Subsystems will be selected to minimize the cost of energy deliverable from the SWECS. In many cases the use of a more expensive or heavier subsystem resulted in lower net cost of energy.

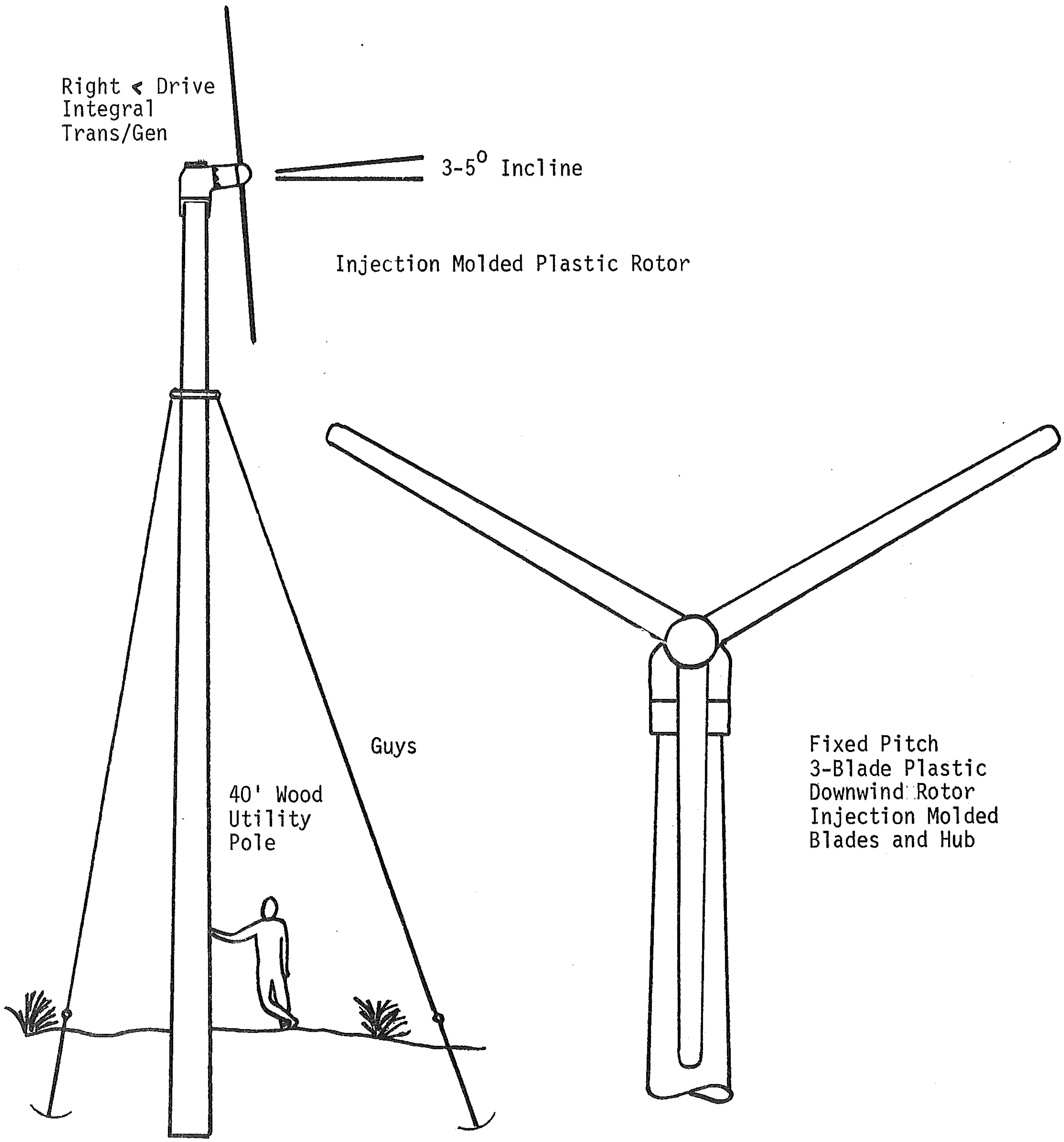
5. Ease of maintenance and reduction of maintenance requirements will be important considerations in the selection of designs and subsystems.

The following paragraphs describe four conceptual designs for Advanced Concept SWECS. Two of the systems are for utility interface operation, one for direct water or space heating, and one for dc or battery charging applications. These systems were selected at this time because they offer potential for low energy cost and high market volume. Systems which can generate 60 Hz ac power independent of a utility grid and hybrid wind/solar systems could find a major market in the future as they become available.

5.1 Advanced Concept 1

This system (shown in Figure 9) produces 12,500 kilowatt-hours of dc power in one year at a site with an average wind speed of 14 mph. The injection-molded plastic rotor uses rotor flexing induced by centrifugal action on fly weights impregnated in the blades for speed and load control. The integral right-angle drive, free yaw assembly, and alternator minimizes installation and maintenance costs as well as system weight and complexity. The right-angle drive incorporates a 5:1 speed increaser. The alternator is a moderate speed 900 rpm unit that achieves the efficiency of high speed operation without the lower reliability of a two-stage gearbox. The rotor axis is tilted from the horizontal to create a small amount of yaw bias and compensate for the yaw torque of the generator shaft. Use of the right-angle drive also eliminates the need for power slip rings on the yaw axis. The wood pole tower, though quite heavy, is inexpensive. (Typically, a single 40 ft telephone pole can be purchased and installed for less than $500, or $.50/lb.)

Figure 9
Advance Concept 1 (5 meter SWECS)



5.2 Advanced Concept 2

This 10 m diameter system uses a field modulated, variable speed, constant frequency, induction generator to produce 60 Hz ac power when tied to a utility grid. The system, shown in Figure 10, uses two twisted, constant chord fiberglass pultrusion blades. The blades are attached to the hub through flapping hinges with large-angle "delta-three" pitch/flap couplings. The blade mass distribution and hinge geometry as well as generator loading are used to provide rotor speed control and to minimize wind loads in strong winds.

The integral gearbox, right-angle drive, and free yaw assembly is similar to the concept used in the AC-1 system except that a gearbox is needed to increase the shaft speed for the nominal 1800 rpm generator. The integral system eliminates need for a nacelle and strongback and makes simple, modular installation possible.

The tower uses fiberglass pultrusion with telescoping reinforcements to minimize land use requirements and cost. This system could be more aesthetically pleasing than many CA and prototype units due to the elimination of guy wires.

It should be noted that the COE for this system (3.5¢/kWh at 14 mph) is inflated due to the use of installation costs identical with those of similarly sized CA units and DOE prototypes. It is estimated that some reductions in these costs can be realized with the use of sectional fiberglass pultruded towers.

5.3 Advanced Concept 3

This system (Figure 11) is the largest of the four conceptual designs, producing 166,000 kWh/yr of 60 Hz ac power at a site with an annual average wind speed of 14 mph. Though this particular system uses a 19.5 m diameter rotor, the concept could easily be applied to larger systems.

Figure 10

Advance Concept 2 (10 meter SWECS)

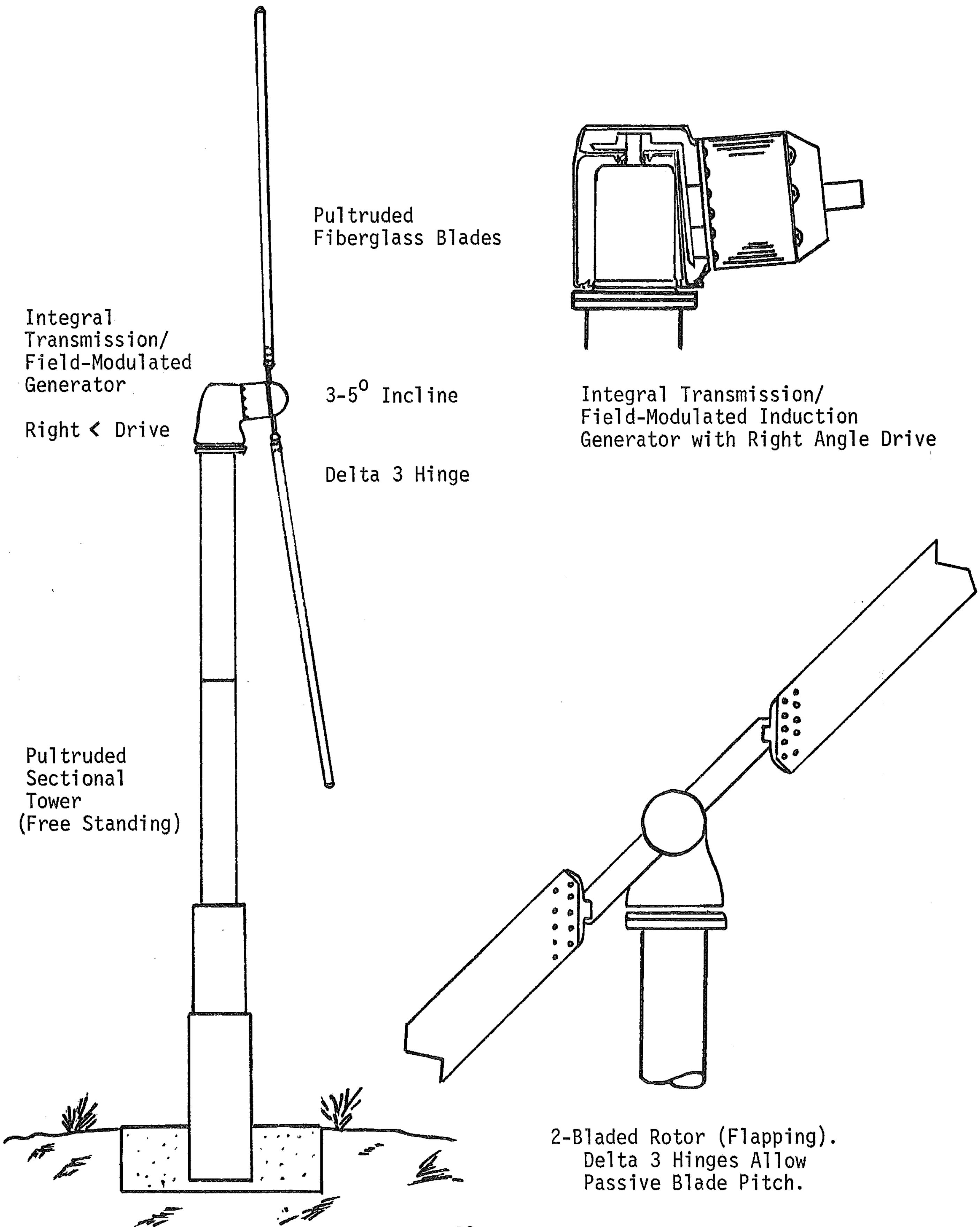
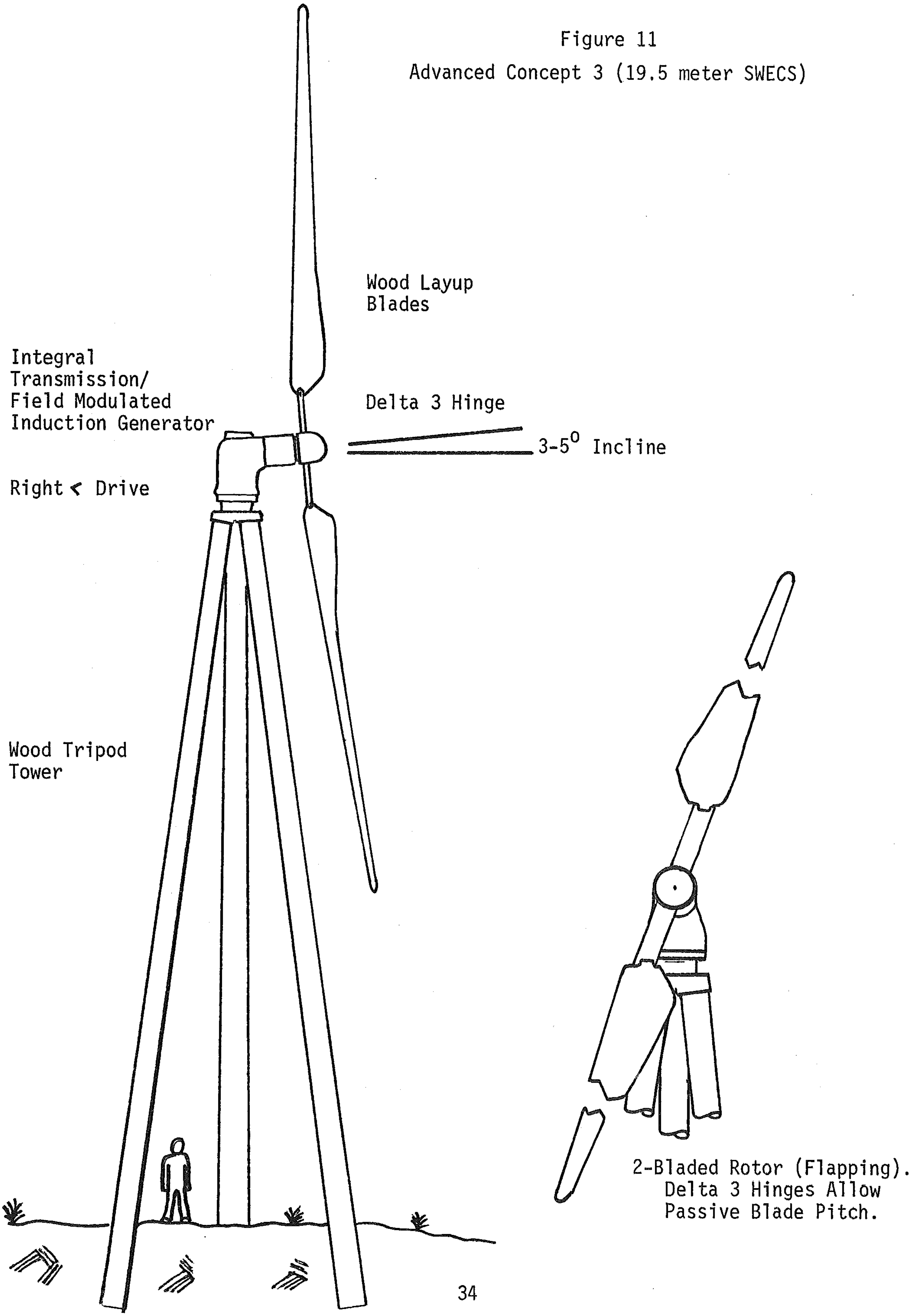


Figure 11

Advanced Concept 3 (19.5 meter SWECS)



The system uses low-cost wooden blades fabricated using a veneer layup process. These blades have been found by NASA to be highly cost-effective on large machines and are being considered by Enertech Corporation for the 15 kW DOE prototype. The blades have twist and taper to maximize energy yield. The hub and control system on this SWECS are identical to that used on AC-2. The hinged blades mitigate undesirable effects due to free yaw, tower shadow, and wind shear. The totally passive blade pitch offers maximum control reliability at minimum cost.

The integral gearbox-generator operates at variable speed while generating constant frequency output. The resulting operation at a constant tip speed ratio increases system output up to 20% over a stalling rotor.

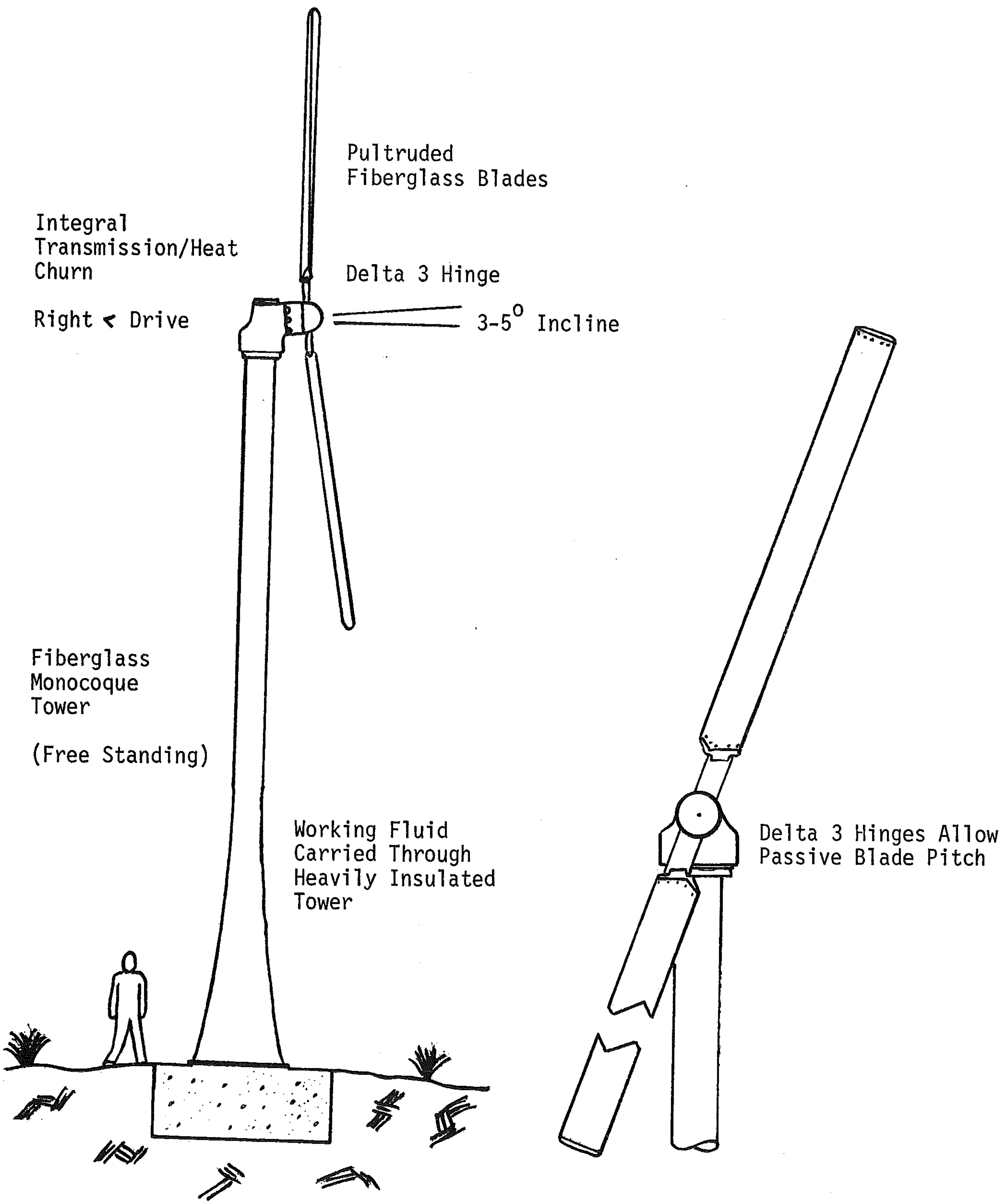
The tower is a wooden tripod 60 feet high with a cast or forged tower-top adaptor. Though quite heavy, the solid wooden poles offer the same cost advantage noted with AC-1. In addition, this tower offers the possibility of installation costs lower than the 8 kW DOE prototype installation costs. Additional reductions in the system COE calculations may be easily realized.

5.4 Advanced Concept 4

This system (Figure 12) is basically the AC-2 system modified to operate a mechanical heat churn for water and space heating applications. When the heat churn is used, no complex gearbox is needed for high speed increases. The churn itself costs less than a generator and system efficiency is improved 10-20% because the heat churn is very efficient at all speeds. Thus the cost of energy (2.3¢/kWh) is reduced both by decreasing system capital cost and increasing energy yield. In applications which require year-round process heat and in domestic applications with high winter average winds, this system promises to provide an immediately competitive energy source.

Figure 12

Advance Concept 4 (10 meter SWECS)



The heat churn is connected to the SWECS rotor through a right-angle drive to eliminate the need for a swivel hydraulic coupling at the yaw axis. For this conceptual design the heat churn is at the top of the tower and the working fluid is carried inside the tower through heavily insulated pipe. Tradeoff studies may determine that it is more cost effective to run a drive shaft down the tower to a ground level water churn. This would eliminate the need for auxiliary pumping at the expense of added shaft length and bearings.

6.0 SUPPORTING RESEARCH AND TECHNOLOGY REQUIREMENTS

Present SWECS designs have depended largely upon the use of readily available and off-the-shelf components, subassemblies, and standard manufacturing processes. This dependence has had significant impact on the attempt to optimize SWECS designs. The results of this study indicate that achieving near and far term COE goals strongly depends on the development of components which are tailored toward SWECS applications. In addition, significant cost savings can be made by introducing changes in various fabrication techniques.

Our analysis shows that improvements to the present SWECS designs can reduce costs through improved performance and reliability. However, unless average energy costs exceed 8-10 cents per kWh (1980 dollars) these improvements are not expected to bring the designs to a point where widely competitive COE ranges can be realized within 6 to 8 years, allowing the wind industry to be self-sustaining. In order for SWECS to achieve their fullest potential in the shortest possible time, research and technology on a series of advanced component and subsystem concepts must be supported. These concepts were identified by Rocky Flats assessment of the current state-of-the-art and were selected for their significance in achieving a maximum impact on cost of energy. Many of these concepts are incorporated in the hypothetical second generation advanced concept designs detailed elsewhere in this report. However, other concepts, such as the teetering rotor; advanced blade spoilers; the mechanical feather-run-feather mode of blade operation; advanced circulate, epicyclic, and traction-drive transmissions; dual output transmissions to allow variable and constant speed loads; wood layup towers; and low profile guy wires deserve further consideration due to their high potential for improving SWECS performance and reliability and/or reducing cost of energy.

Five general areas have been defined in which SRT efforts could be made to allow the improvements projected by this study. The following paragraphs itemize specific projects within the areas of Systems Integration, Rotors and Controls, Transmissions and Gearboxes, Power Conversion and Interfacing Subsystems and Towers and Installation Methods.

Rapid initiation of the itemized projects would provide tangible benefits in reducing SWECS cost-of-energy, given the importance of development time in the time required to eventually bring second generation SWECS to volume production. It is beyond the scope of this document to prioritize all of these projects; however, high priority projects are identified in the text.

6.1 Systems Integration

Throughout this study it has been noted that the scope and depth of the tradeoff analyses performed on the present DOE prototypes have been limited. This was done intentionally to focus tradeoffs on a proposed baseline design, with emphasis placed on minimizing schedule and cost risks to the prototype development effort. Though the resultant prototype designs are feasible and employ sound engineering principles, the limited perspective has not produced optimized systems. A thorough and detailed tradeoff optimization study of advanced concepts is necessary if future SWECS are to achieve their full potential. This study must be made independent of the development of a particular design to insure objectivity and broad applicability. The results of Rocky Flats prototype evaluation tests will soon provide the necessary data for a variety of design concepts, and would support a tradeoff study in FY 1981.

6.2 Rotors and Controls

It is estimated that performance improvements of 10 to 15% can be realized through improvements in the rotor subassembly alone. Prime areas for future research and technical development include:

- Analysis and development of the "delta-three" hinge for both teetering and flapping rotors.
- Development of injection molding techniques for the rotor hub and blades.
- Developing pultruded blades which are larger in length and chord, twisted, and stiffer.
- Detailed tradeoff analysis and development of aerodynamically controlled rotors (stall, feather, pitch, and yaw) identified in the systems integration analysis.
- Improving rotor loads/stress and performance analyses techniques.
- Developing an improved data base on high performance airfoil characteristics for use in the Reynolds number regime where SWECS typically operate.

Another factor which has impacted all aspects of the present SWECS designs is the lack of comprehensive methodology for treating wind turbulence characteristics. This single factor has resulted in an overall conservative treatment in designing SWECS. Higher than necessary safety factors have been used in these designs making them heavy, rigid, and expensive. Significant advances in reducing the cost of future SWECS will be made through the incorporation of improved wind characteristics model utilization methods.

6.3 Transmissions and Gearboxes

Present SWECS use off-the-shelf transmissions and generators which have not been tailored to SWECS applications. This requires costly adaptors such as slip rings, additional bearings, extended drive shafts, and bedplates. Cost savings can be achieved through the following research and technology development efforts:

- Development of an integral right-angle drive gearbox and generator subassembly.
- Conducting a detailed tradeoff study of innovative (i.e., circulute, planetary, or traction-drive) transmissions identified in the systems integration analysis. Initiation of testing and development of the most promising design(s).
- Obtaining accurate dynamometer efficiency measurements on several existing gearbox designs identified in the systems integration tradeoff study.
- Development of a dual output gearbox for multiple applications.

6.4 Power Conversion and Interfacing Subsystems

Power conversion and interfacing subsystems have also been restricted to off-the-shelf hardware which is not optimum for SWECS operations. The available technology and hardware favors constant speed generator schemes, high rpm operating ranges, and three-phase power output, all of which are not most favorable for all SWECS applications. Interfacing wind-driven electrical generators with utility lines has resulted in various technological uncertainties regarding safety, power quality, and electrical stability. Little attention has been given to optimizing SWECS for direct heating applications. Nor have efforts been made to develop ways of providing load control to minimize energy losses. Substantial gains can be made in energy production and utilization through the following efforts:

- Development and testing of single- and three-phase field modulated induction generators which produce constant frequency output at variable speeds and allow the rotor to operate at high efficiency due to the maintenance of constant tip-speed ratio.

- Design and development of optimum mechanical direct heating components for use with SWECS.

- Optimization of induction generator controls for startup and instability situations such as overspeed, over voltage, and self-excitation.

- Tradeoff analysis and development of low cost load control and switching techniques which can improve energy utilization.

6.5 Towers and Installation

Towers presently used are rigid structures difficult to tune dynamically and often expensive to install. They are generally not very aesthetically pleasing and require high land use due to the need for guy wire assemblies. Shipping and installation of towers is usually difficult and expensive. The dynamic interactions among tower, guy wires, and wind machine are not adequately understood or accounted for in present SWECS designs. The potential for significant cost reductions is high in making lighter, less rigid, freestanding towers and in improved installation. Areas of major impact and importance are:

- Development of aesthetic, lightweight, freestanding, "soft" towers.

    - Interlocking sectional fiberglass pultrusion.
    - Pre-impregnated woven fiberglass monocoque (possibly installed by inflation during cure of resin material).
    - Wood layup.

- Compiling a catalog of tower dynamic characteristics and development of improved analytical techniques for evaluating these dynamics of tower design.

- Conducting a survey and tradeoff study of low-cost installation techniques.

7.0 CONCLUSIONS

The energy costs achievable from commercially available, DOE prototype, and advanced concept SWECS by 1990 are plotted in Figures 13, 14, and 15. These costs assume 1980 dollars and high volume production with a doubling of production (from an original run of 1,000 over) every three years for 3-6 m and 6-12 m systems and every five years for 12-25 m systems. A 95 percent learning curve has been used. The production volume achieved by 1990 is conservative (i.e., 7,000 units for an 8 kW prototype system), but if a consistent increase was maintained to the year 2000, total SWECS installed capacity in that year (from only three manufacturers) would be more than 5,000 megawatts.

This analysis shows that major advances in energy cost reduction can be made with advanced concepts in the 3-6 m and 6-12 m size ranges. In each figure, it can be seen that improved DOE prototypes and/or advanced concepts achieve significant energy cost improvements over commercially available systems.

The major conclusions of this analysis are:

- Significant cost-of-energy improvements can be made in SWECS of all size ranges, as indicated by the figures of merit.

- Reliability and system life are key factors in SWECS utilization, but the reliability and life of commercially available and DOE prototype systems are not known.

Figure 13

Projected SWECS Cost of Energy (3-6 meter)

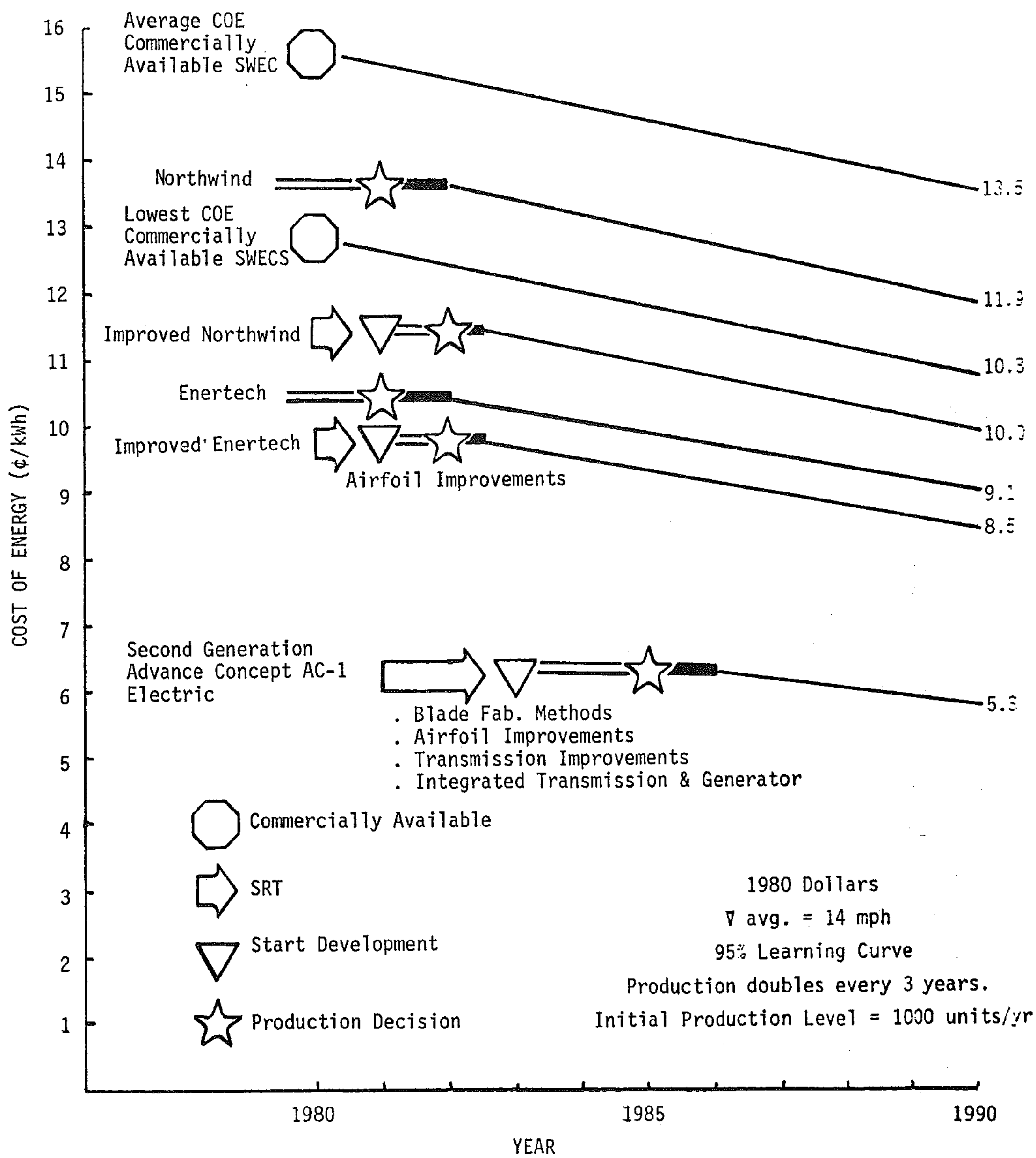


Figure 14
Projected SWECS Cost of Energy (6-12 meter)

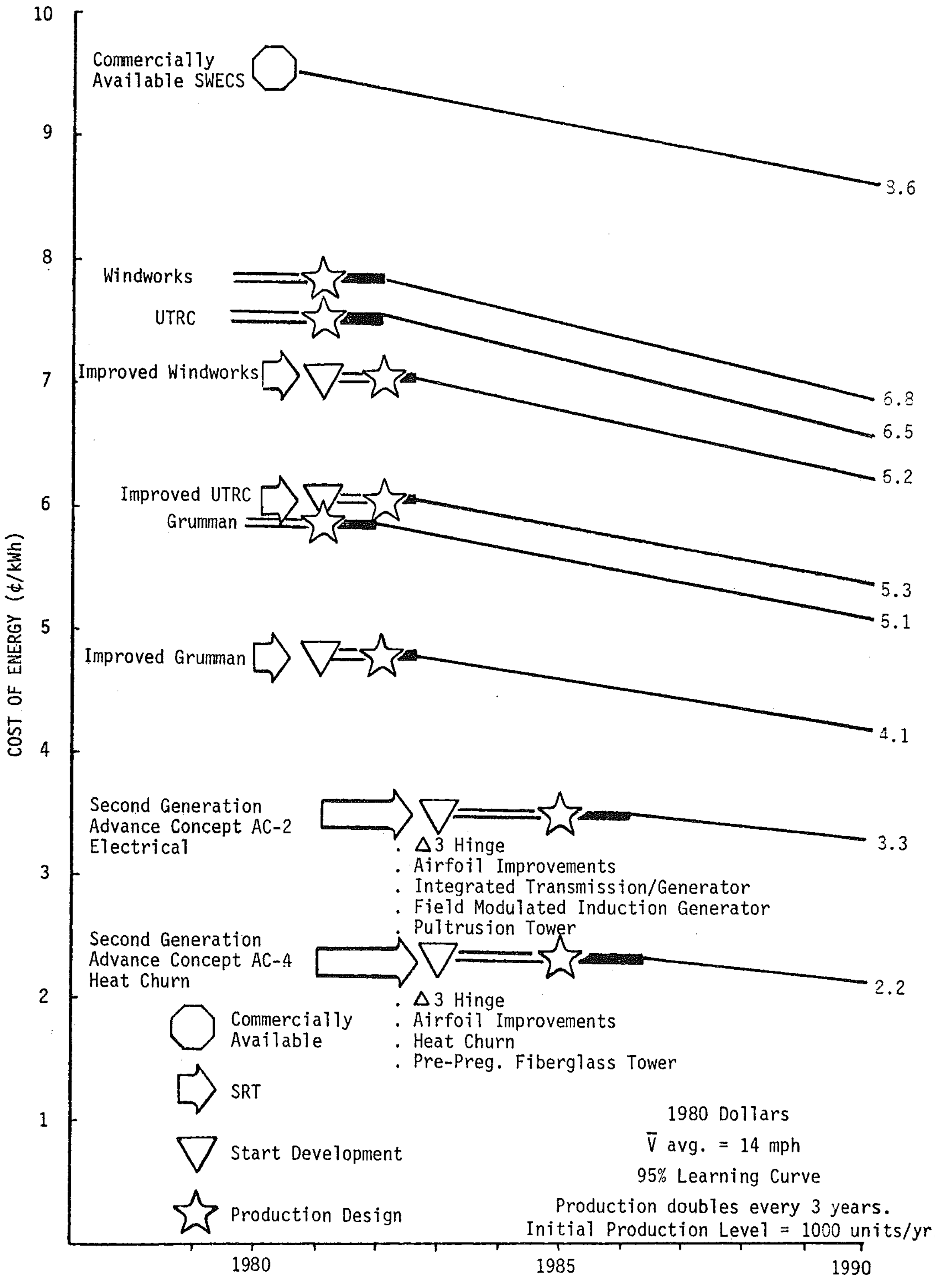
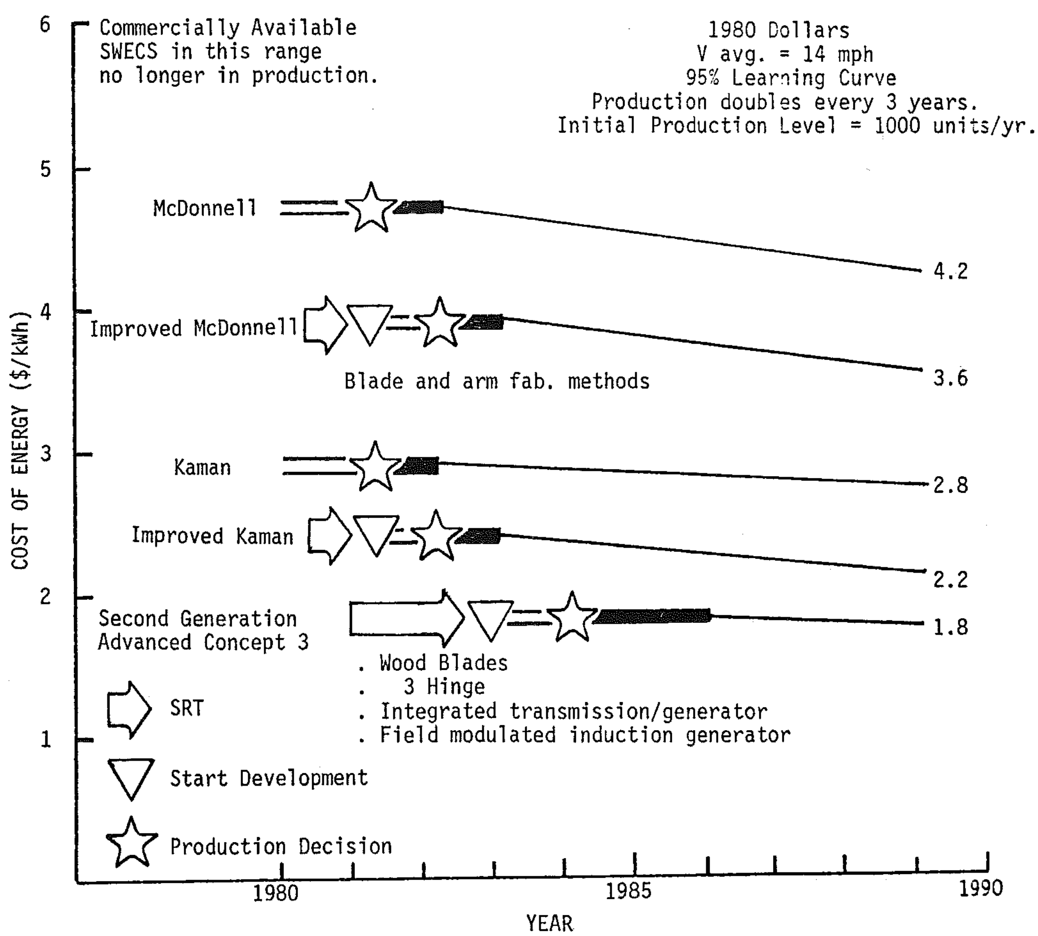


Figure 15

Projected SWECS Cost of Energy (12-25 meter)



- Use of off-the-shelf components in commercially available SWECS has inhibited innovative systems approaches to design and achievement of the full low-cost potential of SWECS.

- Contractor prototype tradeoff analyses to achieve higher reliability have been limited by the requirements of lowest contract cost and accelerated schedules and by lack of test data. This has required the use of off-the-shelf components on DOE prototypes and has prevented them from achieving widely competitive cost, although reliability and service life should be significantly improved over commercially available units.

- A need for component and subsystem development is indicated by the inability of improved first generation SWECS to achieve their lowest cost potential. This study indicates that such development will be beneficial.

- Cost-of-energy is more sensitive to SWECS performance (through increased system efficiency, reliability, and lifetime) than to hardware cost. Future development efforts must consider cost-of-energy reduction through performance improvement.

- Components specifically designed for SWECS may offer improvements in reliability as well as lower hardware cost.

- Through component improvements, SWECS can produce energy at costs competitive with nonrenewable energy sources. This is based on the following energy costs estimated as achievable in 1990 for second generation SWECS (1980 dollars):

  5.8¢/kWh (3-6 meter)
  2.2¢/kWh (6-12 meter)
  1.8¢/kWh (12-25 meter)

TABLE II

Advanced Concept SWECS

AC	ROTOR DIA. rated output	ROTOR/HUB	ROTOR CONTROLS	TRANSMISSION ASSEMBLY	POWER CONVERSION	TOWER	APPLICATION	kWh/Yr 12-14 mph
1	5 m (2 kW)	Plastic injection molded (soft downwind 3 blade rotor	Centrifugal (weights in blade)	Integrated Hub/Trans/ Generator (RT drive)	Alternator (single output)	Wood utility pole (guyed)	Battery Charger (DC output)	8,820 12,500
II	10 m 8-10 kW	2 blade downwind rotor; figerglass pultruded blades (twisted, flapping)	Delta-3 passive hinge	Integrated Hub/Trans/ Generator (RT drive)	Field Modulated induction generator	Free standing sectional pultruded	Utility Interconneciton	38,400 55,200
III	19.5 m	2 blade downwind wood lay up modes (twisted, flapping)	Delta-3 passive hinge	Integrated Hub/Trans/ Generator (RT drive)	Field Modulated Induction generator	Tripod (3 wood utility poles)	Utility Interconnection	130,000 166,000
IV	10 m 8-10 kW	2 blade downwind fiberglass pultruded blades (twisted, flapping)	Delta-3 passive hinge	RT drive	Heat Churn tower mounted	Free Standing flared fiberglass (pre-impregnated)	Direct heating	44,600 64,000

TABLE III

Prototype System Characteristics

MACHINE	ROTOR SIZE	RATED OUTPUT (9.0 m/s)	ROTOR CONFIGURATION	APPLICATIONS
North Wind	5 m	2 kW	2 blade, downwind horizontal axis	Remote battery charger
Enertech	5 m	2 kW	3 blade, upwind horizontal axis	Remote battery charger
UTRC	9.5 m	8 kW	2 blade, downwind horizontal axis	Utility inter-connection
Windworks	10 m	8.5 kW	3 blade, downwind horizontal axis	Utility inter-connection
Grumman	10 m	11 kW	3 blade, downwind horizontal axis	Utility inter-connection
Kaman	19.5 m	40 kW	2 blade, downwind horizontal axis	Utility/ mechanical
McDonnell	18.5 m	40 kW	3 blade, vertical axis giromill	Utility/ mechanical

Attachment 1

ASSUMPTIONS USED IN CALCULATING COSTS
WITH THE JBF FORMULA

ASSUMPTIONS USED IN CALCULATING COSTS WITH THE JBF FORMULA

1) To calculate Installed Cost (IC):

IC = system FOB +
DIST +
Shipping +
Installation cost

2) To calculate cost-of-energy (COE):

$$COE = \frac{\text{(INSTALLED COST X FCR) + annual maintenance}}{\text{annual kWh}}$$

3) System FOB was calculated in 1980 dollars based on contractor weight/ dollar estimates and manafacturer quotes for tower and machine. -Note: Kaman and McDonnell figures were "adjusted".

4) Distribution cost was calculated as a precentage of System FOB cost as follows: small,(3-6 meters)-25%
medium, (6-12 meters)-20%
large, (12-25 meters)-15%

5) Shipping costs for a "short haul" were used:

3 - 6 meters - $250
6 - 12 meters - $300
12 - 25 meters - $500

6) Installation cost was taken from curve using rotor diameter as the determining factor.

7) Fixed Charge Rate (FCR) =.087 for remote, agricultural, and light commercial applications (1-2 kW, 15 kW, 40 kW)

= .115 for residentials (8-10 kW)

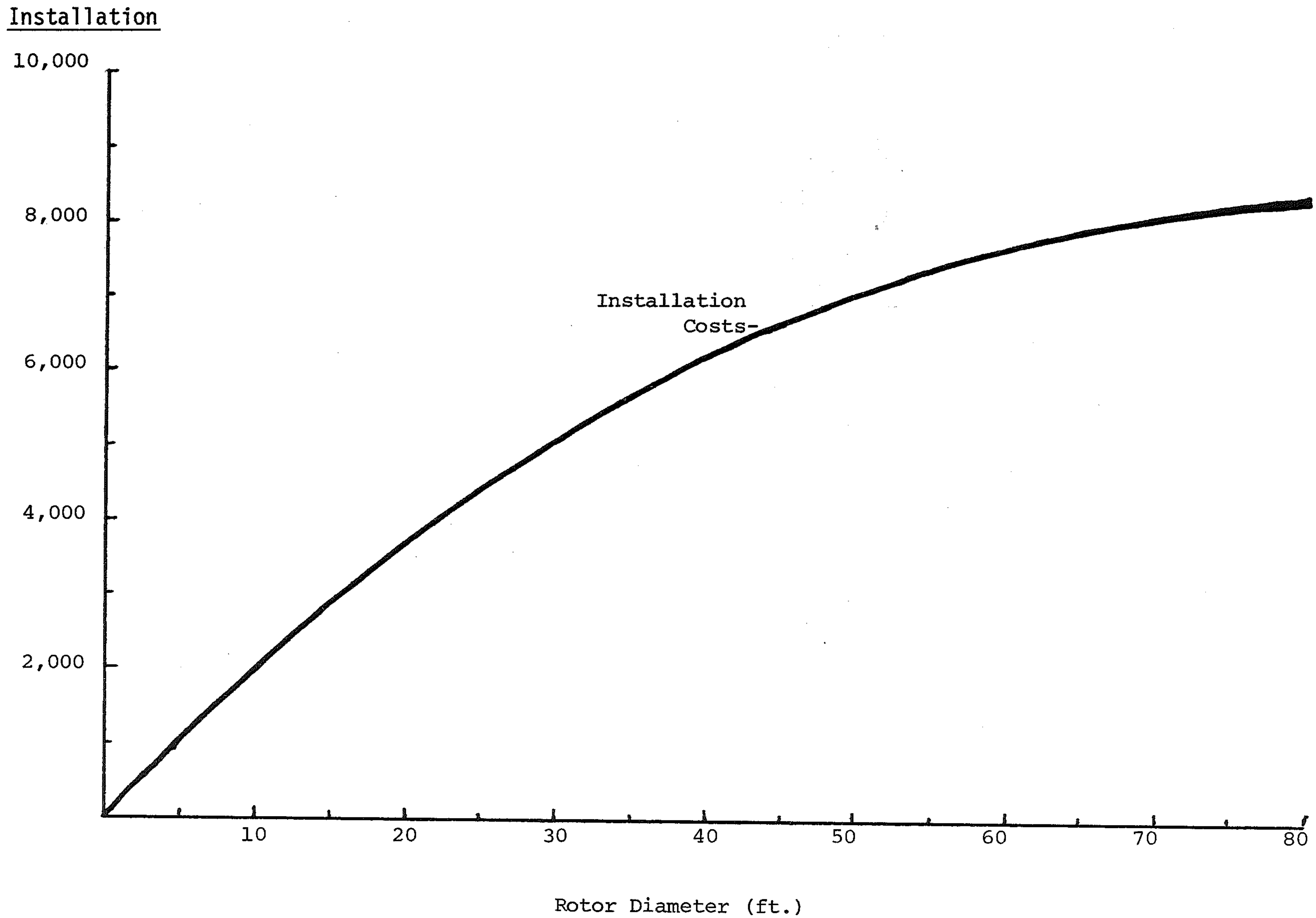
8) Annual maintenance costs used were:

a) actual contractor estimates in 1980 dollars for DOE Prototypes

b) 2.5% of the system FOB costs for other SWECS

9) kWh/yr. figures taken from manufacturer estimates for 12-14 mph cases. In advanced concepts, estimates were based on achieveable performance improvements.

INSTALLATION COST VERSUS ROTOR DIAMETER



Attachment 2

IMPROVED DOE PROTOTYPES

The charts in this attachment illustrate the modifications suggested for seven DOE prototype SWECS, and resultant weight, cost and performance, (kWh/yr.) improvements. The impact of these improvements on the cost of energy is itemized and the overall energy cost reduction provided.

IMPROVEMENT OF DOE PROTOTYPES

ENERTECH HR 2kW

IMPROVEMENTS	Δ* WT (lbs)	Δ COST ($)	Δ EN @ 12	Δ EN @ 14
PULTRUDED BLADES	+26	-34	—	—
HUB CONTROLS	—	—	+420	+543
OTHER PRODUCTION IMPROVEMENTS		-141		
OVERALL IMPROVEMENTS	+26	-175	+420	+543

OLD COE	Δ COST	Δ ENERGY	TOTAL Δ	NEW COE
¢/kWh (V=12 mph)= 14.7	-0.3¢	-0.7¢	-1.0¢	13.7¢
¢/kWh (V=14 mph)= 10.4	-0.2¢	-0.5¢	-0.7¢	9.7¢

RATIONALE

- Optimize pitch control springs and airfoil to improve energy output.
- Reduce blade cost through the use of pultruded blades.

* Delta (Δ) = Change from first unit of prototype

IMPROVEMENT OF DOE PROTORYPES

NORTH WIND HR 2kW

IMPROVEMENTS	Δ* WT (lbs)	Δ COST ($)	Δ EN @ 12	Δ EN @ 14
BLADES	+17	-114	+344	+465
VARC SPRING	—	—	+687	+930
OTHER PRODUCTION IMPROVEMENTS		-168		
OVERALL IMPROVEMENT	+17	-282	+1031	+1395

OLD COE	Δ COST	Δ ENERGY	TOTAL Δ	NEW COE
¢/kWh (V=12 mph)= 18.3	-0.6¢	-2.3¢	-2.9¢	15.4¢
¢/kWh (V=14 mph)= 13.6	-0.4¢	-1.8¢	-2.2¢	11.4¢

RATIONALE

- Optimize VARC spring to allow machine to produce more energy at high wind speeds.
- Reduce blade cost by using pultruded blades.
- Utilize twist and improved airfoil for greater energy output.

* Delta (Δ) = Change from first unit of prototype

IMPROVEMENT OF DOE PROTOTYPES

UTRC 8kW

IMPROVEMENTS	Δ* WT (lbs)	Δ COST ($)	Δ EN @ 12	Δ EN @ 14
BLADE TWIST	—	+30	+1000	+1500
PULTRUDED FIBERGLASS FLEXBEAM	NEG.	-300	—	—
CAST STRONGBACK	+30	-300	—	—
PULTRUDED FIBERGLASS TOWER (Free Standing)	-600	-1400	—	—
OTHER PRODUCTION IMPROVEMENTS		-500		
OVERALL IMPROVEMENT	-750	-2470	+1000	+1500

OLD COE	Δ COST	Δ ENERGY	TOTAL Δ	NEW COE
¢/kWh (V=12 mph)=11.2	-1.8¢	-0.4¢	-2.2¢	9.0¢
¢/kWh (V=12 mph)= 7.5	-1.2¢	-0.2¢	-1.4¢	6.0¢

RATIONALE

- Tower - eliminate guys ($1900)
- Improve energy output by using blade twist.
- Reduce cost by using fiberglass flexbeam.
- Utilize cast strongback for lower cost.

* Delta (Δ) = Change from first unit of prototype

IMPROVEMENT OF DOE PROTOTYPES

WINDWORKS 8kW

IMPROVEMENTS	Δ* WT (lbs)	Δ COST ($)	Δ EN @ 12	Δ EN @ 14
ELIMINATE ONE BLADE	——	-250		
PULTRUDED FIBERGLASS BLADES	-66	-100		
SIMPLIFY HYDRAULIC CONTROLS	——	-300		
OTHER PRODUCTION IMPROVEMENTS	——	-1000		
OVERALL IMPROVEMENT	-66	-1650		

OLD COE	Δ COST	Δ ENERGY	TOTAL Δ	NEW COE
¢/kWh (V=12 mph)= 9.8¢	-1.0¢	-0.0¢	-1.0¢	8.8¢
¢/kWh (V=14 mph)= 7.8¢	-0.8¢	-0.0¢	-0.8¢	7.0¢

RATIONALE

- Elimination of one blade will not reduce weight due to increase in chord needed to maintain rotor solidity and performance.
- Permanent magnetic alternator - reduce number of poles; make smaller diameter.
- Reduce blade cost and weight with pultruded blades.
- Reduce hydraulic control costs by reducing adjustability and redundancy.

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* Delta (Δ) = Change from first unit of prototype

IMPROVEMENT OF DOE PROTOTYPES

GRUMMAN 8kW

IMPROVEMENTS	Δ* WT (lbs)	Δ COST ($)	ΔEN @ 12	ΔEN @ 14
REDUCE BLADE CHORD AND TWIST	-300	-450	+640 ,	+920
PULTRUDED BLADES	-30	-45	——	——
HIGH PERFORMANCE AIRFOIL	-85	-200	——	——
REDUCE STRONGBACK LENGTH	-300	-400	——	——
REDUCE LOW SPEED SHAFT LENGTH	——	——	+2240	+3220
OTHER PRODUCTION IMPROVEMENTS	——	-428	——	——
OVERALL IMPROVEMENT	-715	-1723	+2880	+4140

OLD COE	Δ COST	Δ ENERGY	TOTAL Δ	NEW COE
¢/kWh ($\bar{V}$=12 mph)=8.3¢	-0.9¢	-0.6¢	-1.5¢	6.8¢
¢/kWh ($\bar{V}$=14 mph)=5.8¢	-o.6¢	-0.5¢	-1.1¢	4.7¢

RATIONALE

- Reduce machine weight by shortening the strongback and low speed shaft, and reducing the blade chord.
- Improve energy output by using blade twist and a better airfoil profile.
- Simplifiy controls by using a single actuator and a preprogrammed microprocessor chip.

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* Delta (Δ) = Change from first unit of prototype

IMPROVEMENT OF DOE PROTOTYPES

MCDONNELL GIROMILL 40kW

IMPROVEMENTS	Δ* WT (lbs)	ΔCOST ($)	ΔEn @ 12	Δ En @14
WOOD BLADES (Lay up)	—	-1500	—	—
WOOD SUPPORT ARMS (Lay up)	-700	—	—	—
SIMPLIFY MICRO-PROCESSOR CONTROLS	—	-400	—	—
GUYED TOWER	-3700	-1600	—	—
OTHER PRODUCTION IMPROVEMENTS	—	-2300	—	—
OVERALL IMPROVEMENT	-4400	-5800	—	—

OLD COE	Δ COST	Δ ENERGY	TOTAL Δ	NEW COE
¢/kWh (V=12 mph)= 6.0¢	-0.8¢	---	-0.8¢	5.2¢
¢/kWh (V=14 mph)= 4.6¢	-0.7¢	---	-0.7¢	3.9¢

RATIONALE

- Improvements are based on Rockwell cost estimates for weights provided by McDonnell.
- Weight savings provided by using wood blade struts and guyed tower.
- Reduced blade cost by using wood blades.
- Preprogrammed microprocessor chip.

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* Delta (Δ) = Change from first unit of prototype

IMPROVEMENT OF DOE PROTOTYPES

KAMAN 40kW

IMPROVEMENTS	Δ* WT (lbs)	Δ COST ($)	Δ EN @ 12	Δ EN @ 14
SIMPLIFY ELECTRONIC CONTROLS	——	-2000		
WOOD BLADES (Lay up)	-450	-1800		
TEETERING HUB	-400	-300		
OTHER PRODUCTION IMPROVEMENTS	——	-1300		
OVERALL IMPROVEMENT	-850	-5400		

OLD COE	Δ COST	Δ ENERGY	TOTAL Δ	NEW COE
¢/kWh (V=12 mph)= 3.8¢	-0.8¢		-0.8¢	3.0¢
¢/kWh (V=14 mph)= 3.0¢	-0.6¢		-0.6¢	2.4¢

RATIONALE

- Wood Blades - Reduce weight and fabrication costs-
- Teetering Hub - Reduce hub weight; adds complexity.
- Optimize pitch schedule and feather rate.
- Relocate controller to tower base.

* Delta (Δ) = Change from first unit of prototype

ATTACHMENT 3

ADVANCED CONCEPT CHARACTERISTICS

ADVANCED CONCEPT - 1

Diameter: 5 meter (2kW)

kWh/Yr: 8820 (12 mph)
12,500 (14 mph)

Application: Battery Charger - DC output

Subassembly	Description	Efficiency	Wt (lbs)	$/lb*	Total $*
Rotor/Hub	Injection molded (soft) downwind 3 blades(plastic)	.42	86	4.0	344
Controls	Centrifugal (weights in blades)	-	15	1.0	15
Trans. Assembly	Integrated Hub/Trans/Gen (RT < drive)	.95	250	1.20	600
Power Conv.	Alternator (single output)	.85	50	5.25	275
Tower	Wood utility pole (guyed)	-	1400	0.50	700
System Integration	Flanges, Lead-in wiring etc.	0.9	150	1.0	150
TOTALS					
	System	0.31	1951	1.07	2084
	Machine	0.31	551	2.51	1384

	12 mph	14 mph
Cost of Energy:+	8.8 ¢/kWh	6.2 ¢/kWh
kWh/yr/lb:	4.5	6.4

* Material and fabrication cost only

\+ Includes installation,) & M and all other costs

ADVANCED CONCEPT - 2

Diameter: 10 meter (8-10kW)

kWh/Yr: 38,400 (12 mph)
55,200 (14 mph)

Application: Utility Interconnection

Subassembly	Description	Efficiency	Wt (lbs)	$/lb*	Total $*
Rotor	Fiberglass Pultrusion 2-blade, Dw, twisted, flapping	.42	260	2.65	690
Controls	Delta-3 Passive hinge	-	20	7.0	140
Trans. Assembly	Integral Transmission/ Gen. Rt angle Dr.	.95	700	2.78	1950
Power Conv.	Variable speed - const. freq. Field-Mod. Induc.	.85	310	2.90	900
Tower/Guys	Free Standing pultrusion sectional	-	1470	1.39	2040
System Integration	Flanges, lead-in wiring, etc.	.9	250	1.0	250
TOTALS					
	System	.31	3010	1.98	5970
	Machine	.31	1540	2.55	3930

	12 mph	14 mph
Cost of Energy:+	5.10¢	3.5
kWh/yr/lb:	12.76	18.34

* Material and fabrication cost only

+ Includes installation, O & M and all other costs

ADVANCED CONCEPT - 3

Diameter: 19.5 meter

kWh/Yr: 130,000 (12 mph)
166,000 (14 mph)

Application: Utility Interconnection

Subassembly	Description	Efficiency	Wt (lbs)	$/lb*	Total $*
Rotor/ Hub	Wood lay-up, two blade, downwind, twisted, flapping	.42	750 Blades 500 Hub	3.50 3.50	2625 1750
Controls	Delta-3 passive hinge	--	200	7.00	1400
Integral Trans. Assy	Integral hub/ trans/gen (Rt angle drive)	.95	900	3.50	3150
Power Conversion	Variable speed const. freq. field mod. induc.	.90	800	3.10	248 *
Tower (60')	Wood utility pole tripod	--	4000	.40	160 *
System Integration	Flanges, lead-in wiring, etc.	0.9	500	1.0	500
TOTALS					
	System	.32	7650	1.76	13500
	Machine	.32	3650	3.26	11900

	12 mph	14 mph
Cost of Energy:+	2.4	1.9
kWh/yr/lb:	16.9	21.7

* Material and fabrication cost only

\+ Includes installation, O & M and all other costs

ADVANCED CONCEPT - 4

Diameter: 10 meter (8-10kW)

kWh/Yr: 44,600 (12 mph)
64,000 (14 mph)

Application: Direct Heating

Subassembly	Description	Efficiency	Wt (lbs)	$/lb *	Total $ *
Rotor	Fiberglass Pultrusion, two blade, downwind, twisted, flapping	.42	260	2.65	690
Controls	Delta-3 passive hinge	-	20	7.0	140
Trans. Assembly	Rt angle Drive	.96	500	1.95	975
Power Conv.	Heat churn tower mounted	.99	75	2.0	150
Tower/guys	Free standing flared F.G. pre-preg	-	650	2.25	1460
System Integration	Flanges, pipe, etc.	.9	295	1.19	350
TOTALS					
	System	.36	1800	2.09	3765
	Machine	.36	1150	2.00	2305

	12 mph	14 mph
Cost of Energy:+	3.3	2.3
kWh/yr/lb:	24.8	35.6

* Material and fabrication costs only

\+ Includes installation, O & M and all other costs

Attachment 4

FIGURES OF MERIT BY MACHINE

The tables in this appendix itemize figures of merit for six commercially available SWECS (CA), nine DOE prototypes (PT-1), seven improved DOE prototypes (PT-2), and four advanced concept (AC) SWECS. For purposes of comparison, SWECS are categorized into three size ranges according to rotor diameter: 3-6 meters, 6-12 meters and 12-25 meters.

The figures of merit (FOM's) used are:

1. Cost of Energy in cents per kilowatt hour - COE (¢/kWh)
2. Kilowatt-hours per year per square meter of rotor area - kWh/Yr/Lb (Sys)
3. Kilowatt-hours per year per square meter of rotor area - kWh/Yr/m^2
4. Dollars per pound ($/Lb.) for system and machine, using FOB costs.

Where noted, cost-of-energy and other FOB's were calculated using manufacturer-supplied FOB cost and performance data. Assumptions used in these calculations are listed in Attachment 1. In the 6-12 and 12-25 meter size ranges, it was necessary to adjust performance estimates approximately 30 percent for commercially available units the reported performance for which was higher than could be predicted given rotor size and blade configurations. The impacts of these adjustments are noted on the charts.

FIGURES OF MERIT

3-6 Meter Diameter Systems

(12 and 14 mph wind regimes)

SWECS	COE (¢/kWh)		Kwh/Yr/Lb(sys)		Kwh/Yr/m^2		INSTALLED $/lb.	
	12	14	12	14	12	14	SYSTEM	MACHINE
CA 4.9m (3kW)	30.4 *	19.4 *	4.3	4.7	228	356	7.43	18.90
4m (1.5kW)	17.4 *	12.8 *	4.4	5.4	348	474	5.86	18.30
4.3m (4kW)	24.7 *	14.8 *	6.0	10.0	438	731	7.22	12.44
PT(1) North Wind HR(2 kW)	18.3 *	13.6 *	3.6	4.9	350	474	3.63	5.59
Enertech HR(2 kW)	14.7 *	10.4 *	4.2	6.0	428	604	3.27	5.12
PT(2) Northwind HR(2 kW)	15.4	11.4	4.1	5.6	403	545	3.40	5.01
Enertech HR(2 kW)	13.7	9.7	4.4	6.2	449	632	3.10	4.61
(3) AD. CON. #1	8.8	6.2	4.5	6.4	449	632	1.41	3.32

* From MFR Data

FIGURES OF MERIT

6-12 Meter Diameter Systems

(12 and 14 mph wind regimes)

SWECS		COE (¢/kWh)		30% Energy Reduction		kWh/Yr/Lb(sys)		$kWh/Yr/m^2$		Installed $/lb.	
		12	14	12	14	12	14	12	14	SYSTEM	MACHINE
CA	7.6m (10kW)	9.7*	6.8*	13.9	9.7	3.9	5.7	254	370	3.10	7.45
	10m (18kW)	10.0*	6.8*	14.3	9.7	6.7	9.9	247	363	5.83	10.00
PT(1)	Grumman (8kW)	8.3*	5.8*	0.0	0.0	6.0	8.6	396	570	2.35	4.0
	UTRC (8kW)	11.2*	7.5*	0.0	0.0	5.6	8.4	356	533	2.98	4.95
	Windworks (8kW)	9.8*	7.8*	0.0	0.0	9.4	11.8	420	526	4.79	8.42
PT(2)	Grumman	6.8	4.7	0.0	0.0	7.6	10.9	432	621	2.27	4.33
	UTRC	9.0	6.0	0.0	0.0	6.8	10.1	371	554	2.61	4.19
	Windworks	8.8	7.0	0.0	0.0	9.6	12.0	420	526	4.22	7.33
(3)	AC #2	5.1	3.5	0.0	0.0	12.8	18.3	489	703	2.74	3.52
	AC #4 (Heat Churn)	3.3	2.3	0.0	0.0	24.8	35.6	568	815	2.89	2.77

* From Mfg. Data

FIGURES OF MERIT

12-25 Meter Diameter Systems

(12 and 14 mph wind regimes)

SWECS	COE (¢/kWh)		30% Energy Reduction		kWh/Yr/lb(sys)		kWh/Yr/m^2		Installed $/lb.	
	12	14	12	14	12	14	12	14	SYSTEM	MACHINE
CA 14.4m (45kW)	4.0*	3.2*	5.7	4.6	10.0	12.5	710	888**	2.3	0.0
PT(1) Kaman (40kW)	3.8*	3.0*	0.0	0.0	10.9	13.7	406	510	2.78	4.36
McDonnell (40kW)	6.0*	4.6*	0.0	0.0	4.8	6.4	559	737	2.10	2.65
UTRC (15kW)	5.5*	4.4*	0.0	0.0	10.8	13.5	327	410	3.92	5.49
Enertech (15kW)	6.5*	5.3*	0.0	0.0	8.7	10.6	367	448	2.78	3.63
PT(2) Kaman	3.0	2.4	0.0	0.0	11.8	14.8	406	510	2.25	3.90
McDonnell	5.2	3.9	0.0	0.0	5.8	7.7	559	737	2.15	2.51
(3) AC #2 (19.5m)	2.4	1.9	0.0	0.0	16.9	21.7	432	555	2.54	4.69
* From Mfg. Data										

** Machine appears to be over-rated (even with 30% reduction annual energy output)

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