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A SCREENING METHOD FOR WIND ENERGY CONVERSION SYSTEMS

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ABSTRACT

We have developed a screening method for evaluating wind energy conversion systems (WECS) logically and consistently. It is a set of procedures supported by a data base for large conventional WECS. The procedures are flexible enough to accommodate concepts lacking cost and engineering detail, as is the case with many innovative wind energy conversion systems (IWECS). The method uses both value indicators and simplified cost estimating procedures. Value indicators are selected ratios of engineering parameters involving energy, mass, area, and power. Cost mass ratios and cost estimating relationships were determined from the conventional WECS data base to estimate or verify installation cost estimates for IWECS. These value indicators and cost estimating procedures are shown for conventional WECS. An application of the method to a tracked-vehicle airfoil concept is presented.

1. INTRODUCTION

SERI is responsible for technical management of the innovative wind system program, a program which is part of the Research and Analysis element allocated to SERI within the U.S. Department of Energy (DOE) Wind Energy Program. The innovative program encourages the development of advanced and innovative system concepts that may provide better performance and lower energy costs than conventional WECS.

The screening method developed by SERI and described in this paper is not meant to inhibit imagination and creativity but rather to bring consistency and objectivity to the evaluation process. However, approximations are necessary to obtain the output estimate of a system's potential for converting wind energy at a reasonable cost. The method does allow for review by technical experts, such as other developers of IWECS, but it does not include optimization studies, parametric studies, or other more detailed cost and engineering analyses. The justification for further studies will depend on the results of simplified techniques such as this screening method.

2. SCREENING METHOD

2.1 Preliminary Analysis

The flow chart for the method is shown in Fig. 1. Preliminary analysis begins with the collection and review of previous studies relevant to the proposed concept. This analysis continues with a gross technical feasibility evaluation to determine if the system is consistent with basic physics and engineering principles. For example, checks are made for conservation of energy and momentum. Structural integrity is crudely tested by rules of thumb (ROT) derived from a conventional WECS data base. One such rule, for example, specifies that if the ratio of the support structure mass to swept area is less than 15 kg m^{-2} (3 lb ft^{-2}), the system may not survive high wind gust loading. Structural design criteria have an important impact on total system costs.

2.2 Energy Estimates

As part of the aerodynamic consistency analysis, a system is often classified as having active elements that use either aerodynamic drag or lift forces. Aerodynamic drag is the force on an object that tends to move it downwind. Lift is a force normal to the relative wind. Either force can extract power from the wind; lift devices, however, have the potential for extracting much more power for the same object area (e.g., blade area). Augmentation devices are used to accelerate the flow and can be composed of either active or passive elements. Consistency and completeness checks refer to ascertaining swept area used in power coefficients as well as characteristic areas or lengths used for lift, drag, or thrust coefficients.

A useful performance parameter in these studies is the estimate of the electrical energy produced in one year by a WECS at a site having specified wind characteristics. The energy outputs of several conventional WECS (listed in Table 1) have been adjusted for the following site characteristics: an annual average wind speed of 6.7 m s^{-1} (15 mph) measured at a height of 9.1 m (30 ft), a wind shear profile with an exponent of approximately 0.14, a Rayleigh distribution of wind speeds, and an air

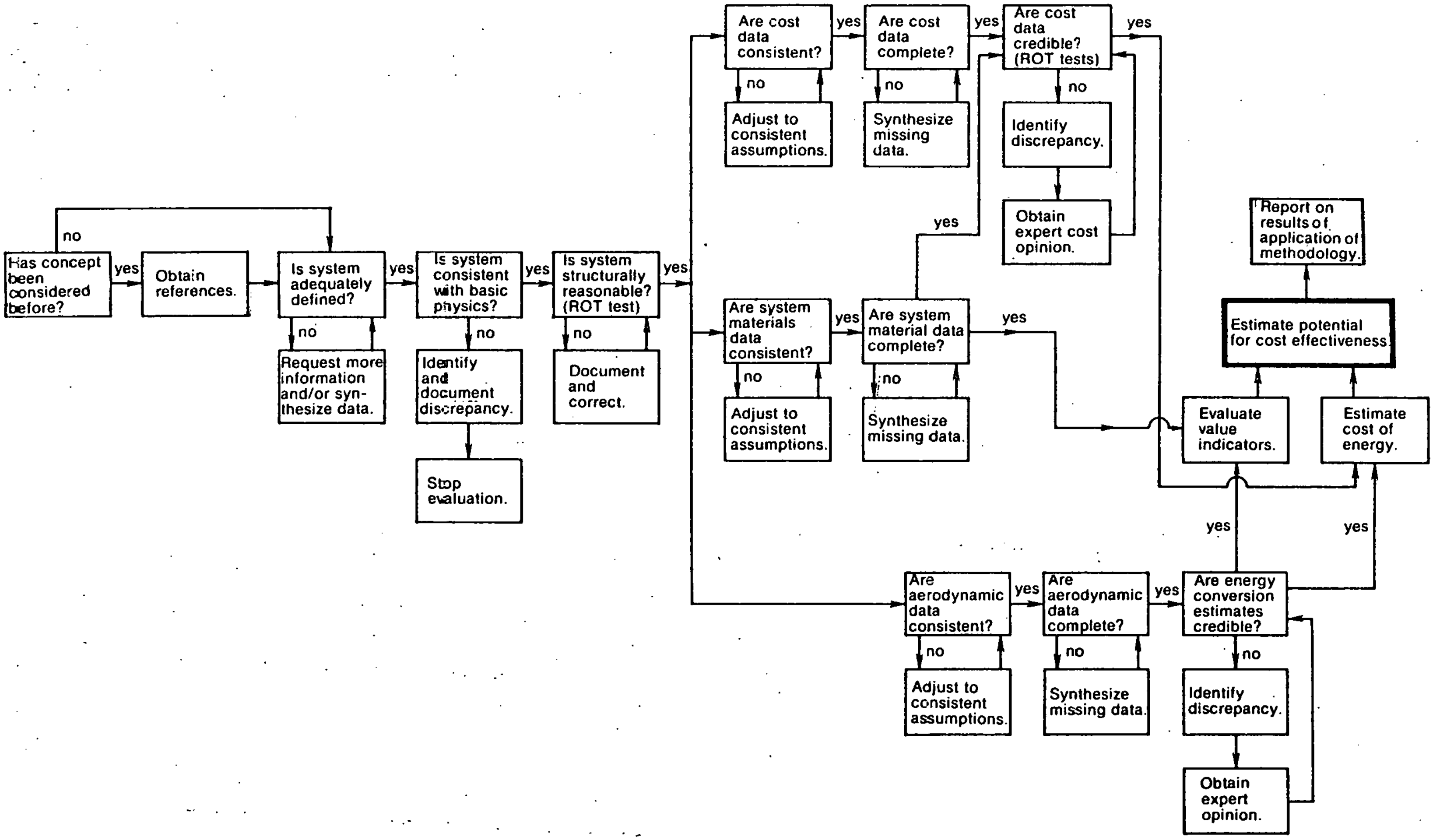

Fig. 1. A Screening Method for Wind Energy Conversion Systems

Table 1. ANNUAL WIND ENERGY ESTIMATES

Wind System	Swept Area (m^2)	Peak Power (kW$_e$)	Rated Wind Speed (center line height) (m s^{-1})	Annual Electrical Energy (MWh)	Reference
Giromill	226	40	8.9	190	1
Magdalen Islands Darrieus	595	224	15.0	387	2
Sandia Darrieus	1394	530	16.1	1070	3
Hütter	915	90	9.0	365	4
Mod 1	2918	2000	14.8	4590	5,6
Mod 2	6567	2500	12.3	10,395	5,7

density of 1.23 kg m^{-3} (0.076 lb ft^{-3}). The references in Table 1 describe equipment characteristics and give further details necessary to make the estimates. The energy estimates assume 90% availability of the machines when the wind is above the cut-in speed and engineering estimates have been made for drive-train and generator losses. The energy estimate for the Hütter machine, a WECS built in the late 1950s, is based on its measured power curve and E. W. Golding's (annual energy)/(peak power) curves (8). The Golding curves provide useful estimates of capacity factor as a function of annual wind speed; three curves were calculated for three sets of cut-in, rated, and cut-out wind speeds. The Giromill, Sandia Darrieus, and Mod 2 data came from design studies, whereas the remaining WECS have been built. It has not yet been possible to validate these energy estimates by means of field measurements.

2.3 System Materials

It is important to note that different materials, typically steel and aluminum, make up the total WECS mass. Aluminum accounts for about 6% of the Giromill mass and from 20% to more than 30% of the Darrieus system masses. About 13% of the Hütter machine mass was contained in fiberglass reinforced plastic blades. The majority of the mass is steel for the Mod 1 and Mod 2 systems. Total system masses are shown in Table 2. Completeness can be verified by ensuring that all component masses, excluding utility components such as transformers, are included in the total. Foundation masses, typically concrete, also are not included.

Value indicators are shown in Table 2. The mass ratios, (annual energy)/mass and mass/(swept area), are expected to be important because correlations exist between system masses and system costs. The (annual energy)/mass indicator is particularly relevant because it can be combined with cost approximations ($/kg) to estimate total system cost and, consequently, the cost of energy produced by a WECS (1,9). This parameter has been estimated for WECS as small as a few kW and as large as a few MW (9). A DOE goal for this value indicator is 55 to 88 Wh g^{-1} (9). The (annual energy)/(peak power) indicator, when divided by 8760 hours, is the capacity factor for the system. The value indicator of (annual energy)/(total blade area) is considered because it seems to be particularly relevant to evaluation of the tracked-vehicle airfoil concept.

It should be noted that the design criteria of fatigue life, safety factors, special wind gust conditions, and temperature and environmental extremes are not uniform for the systems listed in Table 2. Ideally, all of the systems should have the same design criteria before value indicators are compared.

Table 2. MASS AND WIND ENERGY VALUE INDICATORS

Wind System	Mass (Mg)	Weight (klb)	Annual Energy/ Mass (Wh g^{-1})	Mass/ Swept Area (kg m^{-2})	Annual Energy/ Peak Power (kWh kW^{-1})	Annual Energy/ Total Blade Area (MWh m^{-2})
Giromill	9.07	20	21	40	4750	7.2
Magdalen Islands Darrieus	22.0	48	18	37	1728	7.0
Sandia Darrieus	33.6	74	32	24	2020	8.6
Hütter	13.2	29	28	14	4056	13
Mod 1	297	655	15	102	2295	34
Mod 2	263	580	40	40	4158	43
Tracked-vehicle airfoil	13,700	30,200	10	—	—	0.6

2.4 Cost Considerations

The screening method uses simplified cost estimating procedures. In the development of tools for costing, subsystem cost estimates were tabulated from previous WECS design and cost studies. Tower structures, for example, were estimated to cost between \$1 to \$4/kg (steel). Steel airfoil cost mass ratios, however, were higher and ranged from \$5 to \$37/kg. Installation costs were related to manufactured equipment costs, to estimate or verify the installation costs. As in the case of value indicator estimation, simplified cost estimating techniques must be used carefully and judiciously. Table 3 gives some rules of thumb based on a review of DOE-funded studies. Additional details are given in Reference 1. The important equation is (10):

$$\text{Cost of Energy} = [(0.18)(\text{Total Capital}) + \text{Levelized O\&M}]\,(\text{Annual Energy Production})^{-1}\ .$$

In the case of the Giromill, the cost of energy was estimated to be 8.2¢/kWh (1).

3. TRACKED-VEHICLE AIRFOIL

Figure 2 shows a sketch of a tracked-vehicle airfoil concept studied by Montana State University several years ago (11,12). The airfoils are mounted on vehicles travelling on an oval track. A site having a strong prevailing wind direction is assumed. From a parametric study the (annual energy output)/(system mass) was estimated for 10 configurations (12). The basic configuration (system number 5 in Ref. 12) consists of 6570 airfoils mounted on 2190 carriages. (Note that a preliminary aerodynamic analysis of this concept indicates the lift on an individual airfoil is likely to be significantly reduced by the small spacing between airfoils.) The length of each airfoil is 12.2 m and the chord is 3.0 m wide. The length of the straight track section is 7.6 km and the radius of the oval section is 762 m. The system was estimated to produce 78,000 MWh yr^{-1} at a 5.4-m s^{-1} (12-mph) site, or about 140,000 MWh yr^{-1} at a 6.7-m s^{-1} (15-mph) site. The energy output is equivalent to that of about 15 Mod 2 systems. The energy estimates include energy losses due to rolling friction as well as aerodynamic drag losses. The total mass estimated for the system is about 13,700 Mg so that the (annual energy)/mass is about 10 Wh g^{-1}, a value lower than any shown in Table 2. The (annual energy)/(total blade area) is dramatically lower than the ratios for the conventional WECS. The other two value indicators could not

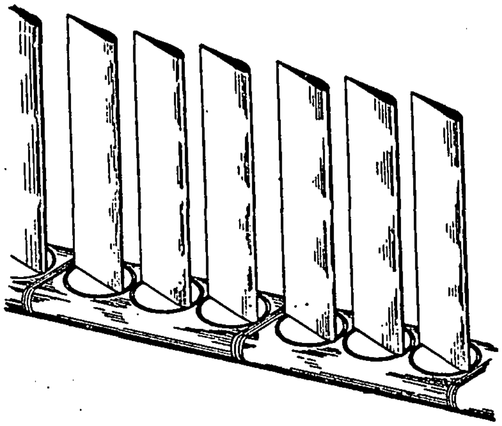

Fig. 2. Artist's concept of tracked-vehicle airfoil design (12)

Table 3. COST ESTIMATES

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 × 2.5 or manufactured equipment × 1.2
Indirect field	16% of total direct field
Interest	2% of total direct and indirect field
Spares	3% of wind generator
Contingency	10% of total direct field
Fee	10% of total direct field and spares
Total capital	Total of direct, field, indirect, interest, spares, contingency, and fee
Annual O&M	2% of total direct field
Levelized O&M	2 × annual O&M
Carrying charges	0.18 × total capital
Total annual	O&M plus carrying charges

be estimated. The peak power was not given in the reference (12), and the swept area of the tracked-vehicle airfoil is ill defined: How should the oval sections be treated and what wind reduction should be given for the downwind straight portion of the track? From the simplified costing techniques outlined in Table 3 (estimating 50,000 m^3 of concrete for track foundations), the system is estimated to produce electrical energy at a cost of about 21¢/kWh.

Since these values for the tracked-vehicle airfoil are the result of a parametric design study (they may be optimistic when compared with results of a complete detailed engineering design), relatively more effort and funding will be devoted to developing the conventional WECS of Table 2. The guidance for determining such a priority has to wait for the complete results of the application of the screening method. The remaining value indicators would be estimated and compared; cost data would be collected, evaluated, and compared; and the results of the individual aerodynamic, structural, and costing analyses would be presented. We have found, however, that the value indicators alone provide valuable guidance. Incidentally, no additional development of the tracked-vehicle airfoil concept has been funded by the federal government.

4. CONCLUSION

Because of the many approximations necessary in the use of the screening method, the results are not as reliable as detailed engineering and cost analyses or actual field tests. The justification for additional development of a wind system will, however, depend in part on the results of such a method.

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