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Application of the Darrieus Vertical-Axis Wind Turbine to Synchronous Electrical Power Generation

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APPLICATION OF THE DARRIEUS VERTICAL-AXIS WIND TURBINE TO SYNCHRONOUS ELECTRICAL POWER GENERATION

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ABSTRACT

This report suggests that the Darrieus vertical-axis wind turbine may be particularly well-suited for driving a synchronous generator in parallel with a synchronizing electrical power network. Aerodynamic characteristics of the Darrieus wind turbine can be such that no torque regulation mechanisms are required on the turbine, providing the generator is properly sized. Synchronization to maintain constant turbine rotational speed under any wind conditions is provided by the network. To point out operational differences a discussion is included of synchronous power generation using conventional propeller-type and Darrieus wind turbines. Some directions for future efforts are proposed.

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APPLICATION OF THE DARRIEUS VERTICAL-AXIS WIND TURBINE TO SYNCHRONOUS ELECTRICAL POWER GENERATION

Introduction and Summary

Sandia Laboratories has recently begun a research and development effort[1] in wind energy systems based on the Darrieus vertical-axis wind turbine.[2] This wind turbine consists of several blades with airfoil cross-section which are free to rotate about a vertical supporting shaft. A description of basic operating principles can be found in Reference 3.

A number of potential advantages of Darrieus wind turbines relative to more conventional propeller-type wind turbines have been previously identified:[3]

(a) Vertical symmetry eliminates need for yaw control.

(b) Vertical rotational axis delivers mechanical power at ground level.

(c) Simple support tower construction.

(d) Reduced blade fabrication costs.

The present report suggests that the Darrieus vertical-axis wind turbine may offer an additional advantage over conventional propeller-type wind turbines when applied to a type of electrical power generation. Specifically, the application consists of directly driving synchronous generators by wind turbines in parallel operation with a synchronizing electrical power network.

As will be indicated, the aerodynamic characteristics of the Darrieus wind turbine can be such that, with proper generator sizing, no torque regulation mechanisms, e.g., variable pitch blades, flaps, spoilers need be provided on the turbine. These devices are typically considered for propeller-type turbines to prevent exceeding the pull-out torque rating of the generator.*

*It has been suggested[4,5] that the required aerodynamic characteristics might be designed into propeller-type turbines.

The remainder of this report is in four sections. Basic elements of a wind energy system are described along with some general attractive features of synchronous electrical power generation. Operation of conventional propeller-type wind turbines in this application is reviewed. Use of a Darrieus vertical-axis wind turbine is then discussed. Finally, some directions for future efforts on the problem are proposed.

This report is of a preliminary nature with emphasis on the basic concepts involved in synchronous power generation by wind turbines. A followup report will develop numerical tools which address system design.

Wind Energy System for Synchronous Power Generation

Figure 1 shows in simple block diagram form the basic elements of a wind energy system for synchronous electrical power generation. A turbine rotating at constant speed is connected to a synchronous generator through a transmission. The transmission typically includes a fixed ratio gearbox to better match the turbine to a practical generator. The generator in turn is connected to an electrical power network which determines the synchronous frequency. This last point is important. It is assumed here that the network capacity is large compared to the wind energy system capacity so that it is the network which fixes the frequency, and thereby the generator and turbine rotational speed.

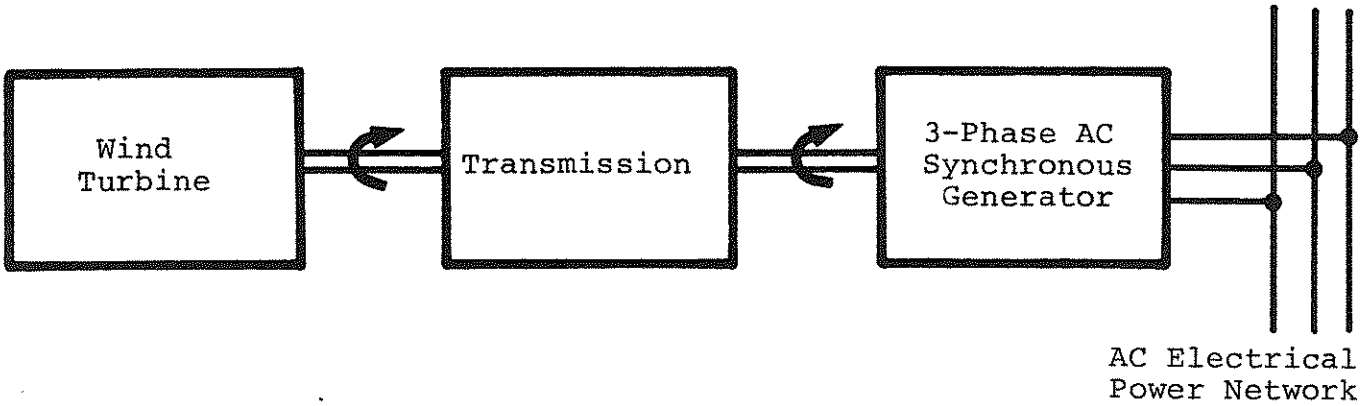

Figure 1. System Diagram

Some general features can be noted which make synchronous power generation appear attractive:

(a) Synchronous operation of the turbine is maintained automatically by the frequency regulation control systems of the other network generators.

(b) Synchronous generators are preferred by utilities since they can be used to deliver reactive power to the network to improve power factor.

(c) Synchronous generators represent standardized hardware which is readily available.

(d) Such systems have been built and operated successfully - the most famous being perhaps the Smith-Putnam wind turbine.[6]

The fundamental mathematical description of wind turbine performance is given by

$$P = \frac{1}{2} \rho A V^3 C_p \left[\frac{R\omega}{V}\right] \tag{1}$$

where P is shaft power derived from the wind, ρ is air density, A is swept area, V is wind speed, R is turbine radius, ω is turbine rotational speed, and C_p represents the aerodynamic efficiency which is a function of the so-called tip speed ratio, i.e., $R\omega/V$. In synchronous operation the rotational speed is fixed and for a given design the radius, swept area, and aerodynamic characteristics are fixed. Power in this case becomes a function only of the wind speed. This relationship will be used in the following sections to discuss operation of wind turbines for synchronous electrical power generation.

Operation of Conventional Propeller-Type Wind Turbines

Figure 2 shows the relation between power and wind speed at a fixed rotational speed for a conventional propeller-type wind turbine. The

feature of importance is that power tends to increase with increasing wind speed. Some wind speed termed the rated wind speed corresponds to the power rating of the generator. As long as the wind speed is less than rated, no torque regulator need be provided on the turbine. Synchronization is provided by the network. For example, the Smith-Putnam wind turbine[6] at Grandpa's Knob, Vermont had a rated power of 1250 kw at a rated wind speed of 34 mph with a turbine rotational speed of 30 rpm. Figure 3 shows generated power as a function of time for wind conditions below 34 mph. Blade pitch is fixed, that is, the torque regulation mechanism on the Smith-Putnam wind turbine is inoperative.

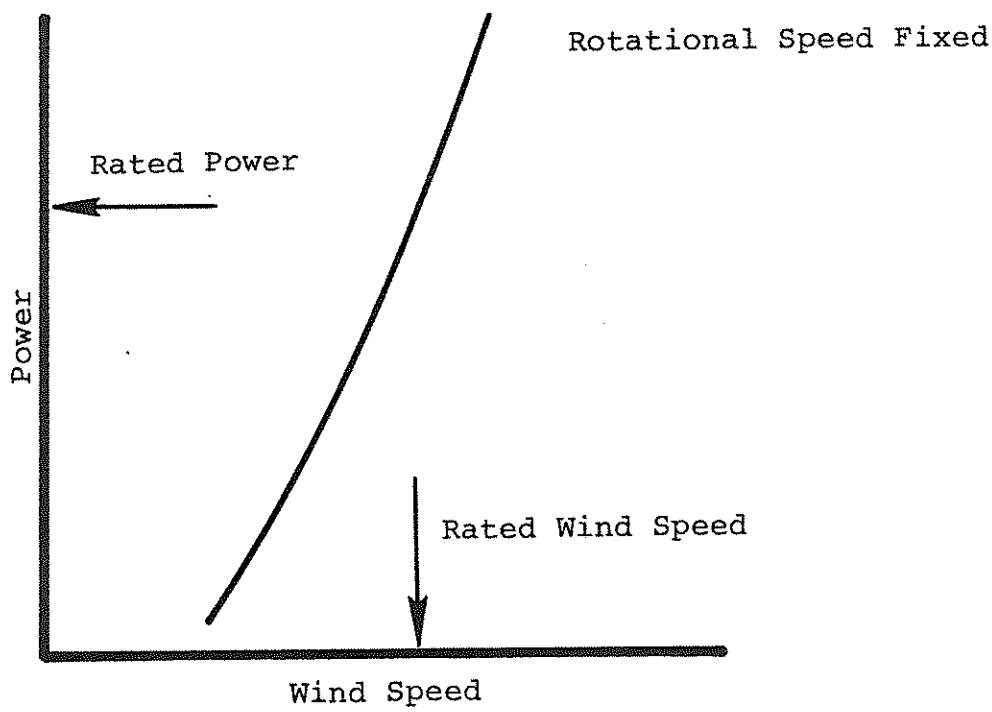

Figure 2. Conventional Propeller-Type Wind Turbine Characteristic

When wind speed exceeds rated wind speed, some means of torque regulation is needed on the turbine. This is due to the fact that synchronous operation will be lost if the generator pull-out torque rating is exceeded. The artificial effect of regulation, depicted in Figure 4, is to spoil the natural power characteristic above rated wind speed.

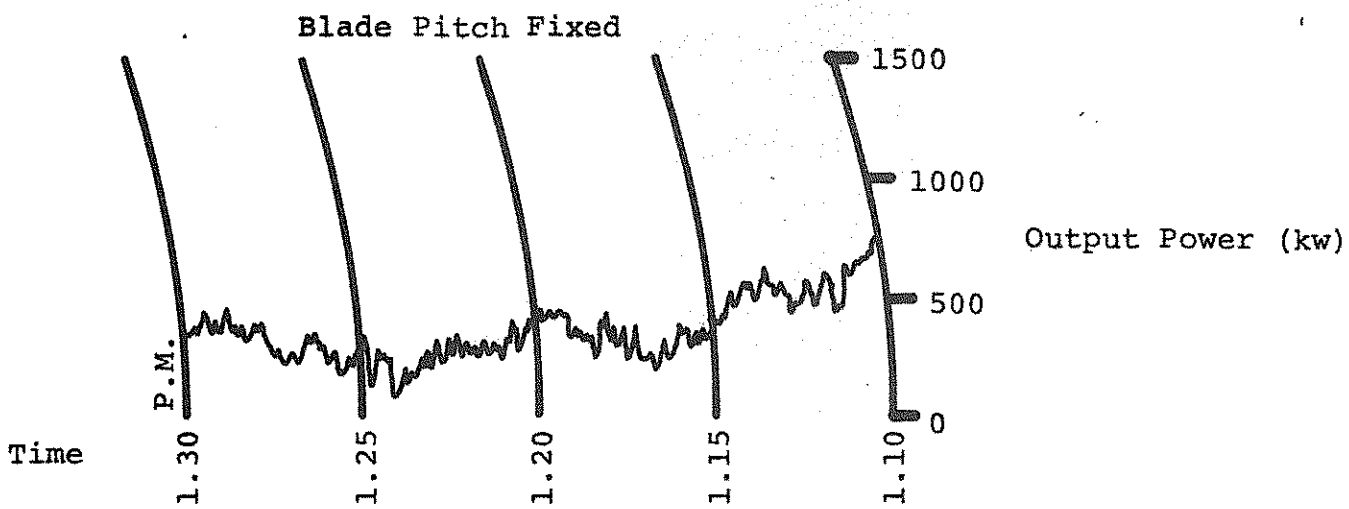

Figure 3. Smith-Putnam Turbine Operating below Rated Wind Speed (From Ref. 6)

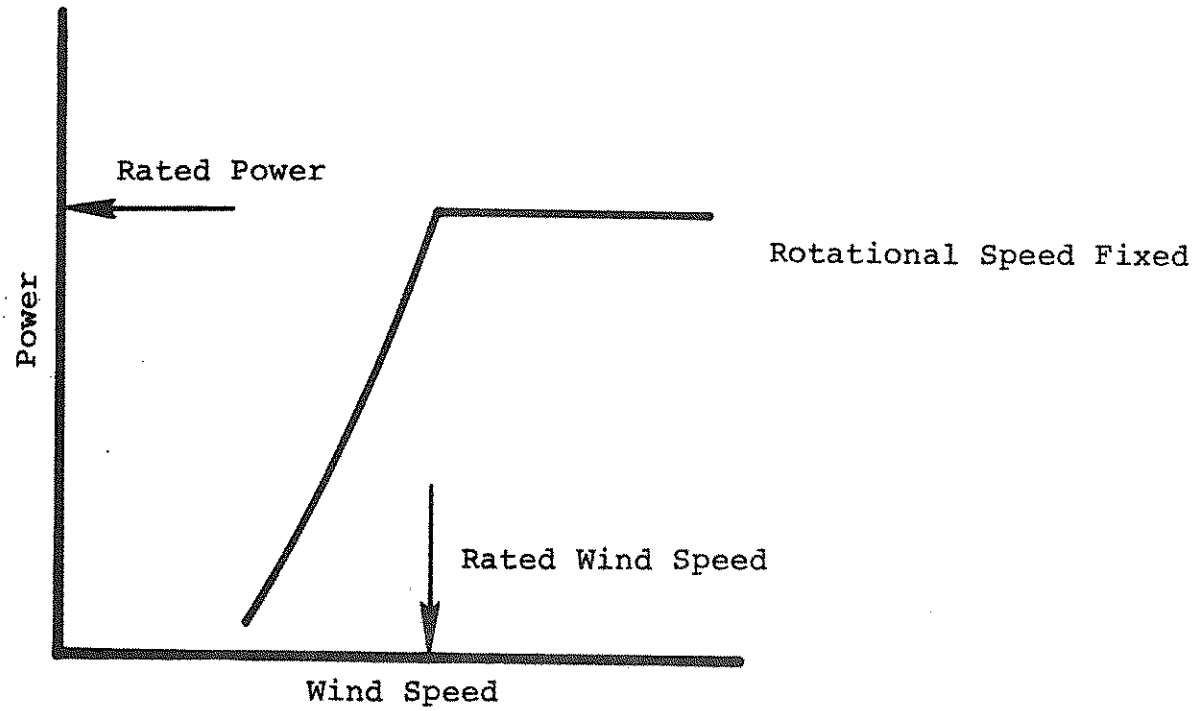

Figure 4. Power Regulation to Spoil Performance of Conventional Propeller-Type Wind Turbine

The Smith-Putnam turbine utilized a centrifugal flyball speed governor of great sensitivity and a hydraulic clutch which could slip to allow a slight change of turbine speed at rated power. This speed increase

actuated the governor which in turn hydraulically altered the blade pitch. Figure 5 shows operation of the Smith-Putnam turbine in wind conditions exceeding the rated wind speed. The system was taken off-line for persistent winds above 60 mph because of regulation difficulties induced by high energy gusts.

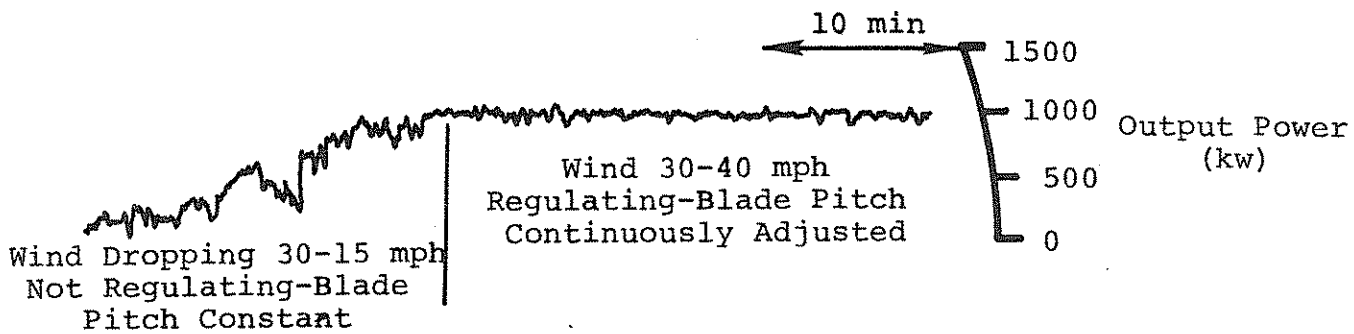

Figure 5. Smith-Putnam Turbine Operating above Rated Wind Speed (From Ref. 6)

Operation of Darrieus Vertical-Axis Wind Turbines

Figure 6 shows the relation between power and wind speed at a fixed rotational speed for a Darrieus vertical-axis wind turbine. The particular shape is derived from aerodynamic data taken on an experimental wind tunnel model by National Research Council of Canada.[7] It is noteworthy that power is always less than some maximum power for all wind speeds.* If the generator rating is made to correspond to this maximum power, then no torque regulation mechanism is necessary on the turbine for synchronous operation.

It is desirable to maximize energy derived from the wind and yet require no torque regulation. The power-wind speed characteristic then should not only achieve some maximum power but also remain near the maximum power over some wide range of wind speeds. Figure 7 shows such a characteristic which is derived from a theoretical analysis[7] of the Darrieus vertical-axis wind turbine. The benefit is, of course, dependent on the wind distribution at a particular site.

*Experimental evidence[8] of this effect has recently come to the attention of the authors.

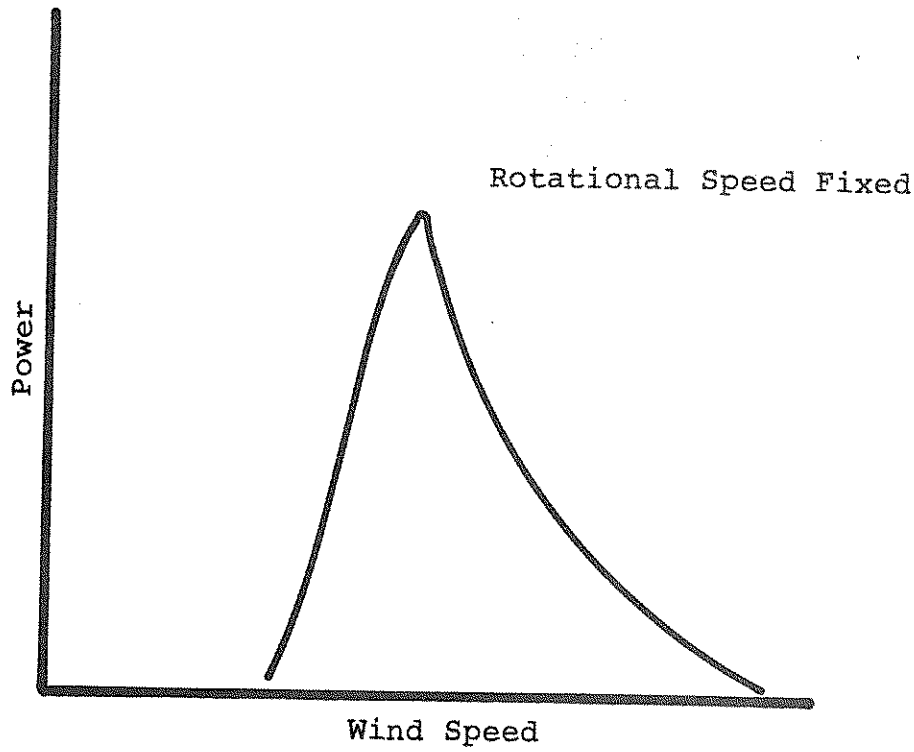

Figure 6. Experimental Darrieus Wind Turbine Characteristic

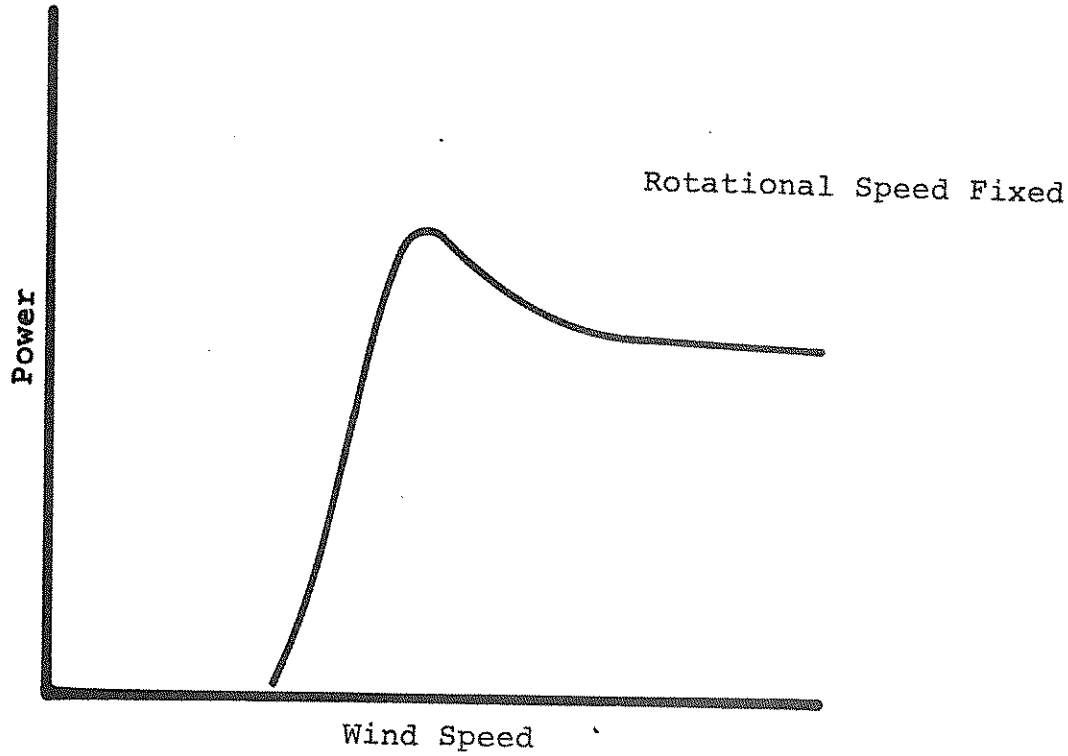

Figure 7. Theoretical Darrieus Wind Turbine Characteristic

If the distribution has an appreciable spread, then there would be an advantage to having turbine power be relatively constant over that wide distribution of wind speeds. Indeed, Equation (1) indicates that constant power output is obtained if the aerodynamic efficiency, C_p varies as the cube of the tip speed ratio. It remains for future aerodynamic studies to determine if such a power characteristic can be realized in a Darrieus vertical-axis wind turbine.

Directions for Further Efforts

This report has indicated that for synchronous electrical power generation aerodynamic characteristics of Darrieus vertical-axis wind turbines can be such that no torque regulation mechanisms need be provided on the turbine. With proper choice of a generator the Darrieus wind turbine will not produce more power than the generator rating under any wind condition. Synchronization to maintain constant turbine rotational speed is provided by the network.

Several further efforts need to be undertaken before the actual design of a system can be accomplished:

(a) The power-wind speed characteristic is directly related to the aerodynamic characteristics of the wind turbine. It is important to know to what extent these characteristics can be altered, and the effect of such alterations on system performance.

(b) The system must be sized to minimize cost and maximize energy conversion while accounting for aerodynamic efficiency, transmission efficiency, and generator efficiency for various site dependent wind speed distributions. Although torque regulation mechanisms are not required on the turbine with proper aerodynamic characteristics and generator sizing, tradeoffs based on cost and energy recovery for systems with regulators and undersized generators should be understood.

(c) It was assumed in this work that the network is capable of maintaining the synchronous frequency. An investigation is required to determine the limits of wind energy capacity before this assumption breaks down.

(d) It is known that synchronous power generation is less efficient than asynchronous power generation, wherein the turbine rotational speed changes to maintain a favorable tip speed to wind speed ratio. However, asynchronous systems will require sophisticated controls and therefore will incur a greater system cost. The relative cost-efficiency tradeoff should be understood.

(e) Because a controlled propeller-type wind turbine produces constant power at wind speeds above rated, it is likely that efficiency will be greater than that for a Darrieus vertical-axis system. But indications are that the Darrieus system will cost less. The relative cost-efficiency tradeoff should be understood.

(f) The absolute cost of electrical power generation by wind energy systems must be compared to fossil fuel, hydroelectric, nuclear, etc., methods of energy production.

An effort is now in progress to develop a mathematical systems analysis for synchronous systems which considers factors such as wind speed distributions, wind turbine power coefficients, rotational speed, transmission and generator efficiencies, component costs, etc. This analysis, to be described in an upcoming report,[9] is geared toward optimization of sizing and siting of wind power systems, and to aid in examining some of the cost tradeoffs mentioned above.

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