New Rules for AAAS–Newcomb Cleveland Prize

The AAAS–Newcomb Cleveland Prize, which previously honored research papers presented at AAAS annual meetings, will henceforth be awarded annually to the author of an outstanding paper published from September through August in the Reports section of *Science*. The first competition year under the new rules starts with the 3 September 1976 issue of *Science* and ends with that of 26 August 1977. The value of the prize has been raised from $2000 to $5000; the winner also receives a bronze medal.

To be eligible, a paper must be a first-time presentation (other than to a departmental seminar or colloquium) of previously unpublished results of the author's own research. Reference to pertinent earlier work by the author may be included to give perspective.

Throughout the year, readers are invited to nominate papers appearing in the Reports section. Nominations must be typed, and the following information provided: the title of the paper, issue in which it is published, author's name, and a brief statement of justification for nomination. Nominations should be submitted to the AAAS–Newcomb Cleveland Prize, AAAS, 1515 Massachusetts Avenue, NW, Washington, D.C. 20005. Final selection will rest with a panel of scientists appointed by the Board of Directors.

The award will be presented at a session of the annual meeting at which the winner will be invited to present a scientific paper reviewing the field related to the prize-winning research. The review paper will subsequently be published in *Science*. In cases of multiple authorship, the prize will be divided equally between or among the authors; the senior author will be invited to speak at the annual meeting.

Reports

Dependability of Wind Energy Generators with Short-Term Energy Storage

Abstract. *Power fluctuations and power duration curves for wind energy generators, including energy storage facilities of a certain capacity, are compared to those of typical nuclear reactors. A storage system capable of delivering the yearly average power output for about 10 hours already makes the dependability of the wind energy system comparable to that of a typical nuclear plant.*

Wind energy generators may be accommodated within an electricity-producing system without storage facilities, on a fuel-saving basis, but only up to a limit determined by the available surplus generating capacity of the total system connected into a common grid. This leads to a maximum possible coverage by wind energy typically in the range from a few percent to 10 percent.

To obtain a larger fractional coverage by wind, either the surplus (reserve) capacity must be enlarged, or storage facilities must be added to the system. In regions where reservoirs for pumped water storage are available, the wind energy share may easily be enlarged. If such storage possibilities are not available, more expensive types of storage systems may be considered. It thus becomes crucial to determine the minimum storage capacity required, for a particular system. I have shown that under Danish conditions, storage which can replace the average power output for about 10 hours makes a wind energy system as dependable as one large nuclear power plant. With the present grid size, this means that wind energy with such short-term storage could be made to cover 20 to 30 percent of the electricity demand, without lack of reliability. To arrive at a still larger coverage, long-term storage would have to be considered.

It has been suggested that mass-produced wind energy generators (WEG's) of megawatt size may be competitive with other currently available means of generating high-grade energy on a purely economical basis—for example, expressed as cost per kilowatt-hour (*1–3*). However, a number of factors in addition to the average cost of generated electricity should be considered. Mixed social and technical aspects are involved in questions of environmental impact, life and health hazards, scale of technology, independence of fuel supply, and so forth. This report deals with the quantification of such aspects as dependability of the power output and its accordance with expected demand variations. It provides a response to those who wish to reject energy supply systems based on wind energy by referring to fluctuations in output and extended periods of standstill.

To assess the dependability of wind energy systems, one may quote the actual fluctuation relative to either the average power output or the expected load curve, measured over a certain time interval, say a year. The detailed structure of the variations can be expressed in terms of higher moments. Additional insight into the time variation of the output is provided by a power duration curve. This is a curve that gives the percentage of time in which the power output of the system exceeds a certain value E, as a function of E.

In order to calculate the power duration curve one must know the characteristics of the available wind, as well as the response of the particular WEG system in question. I use wind data from the meteorological tower at Risø, Denmark, taken at a height of 56 m. This site is not optimal from the point of view of collecting wind energy, but wind velocity measurements have been made there since 1958, and hourly data are available for a 10-year period in the form of 10-minute averages (*4*). I use only the 1961 data here, since the average power for this year is very close to the 10-year average and the number of missing observations is small.

I use a WEG efficiency curve taken from (*1*), based on the design values for the Danish experimental mill at Gedser (its actual output was lower, probably because of high losses in an inadequate gearbox). This WEG of fixed frequency starts at a wind speed of 5 m/sec (11.25 miles per hour), and reaches its rated out-

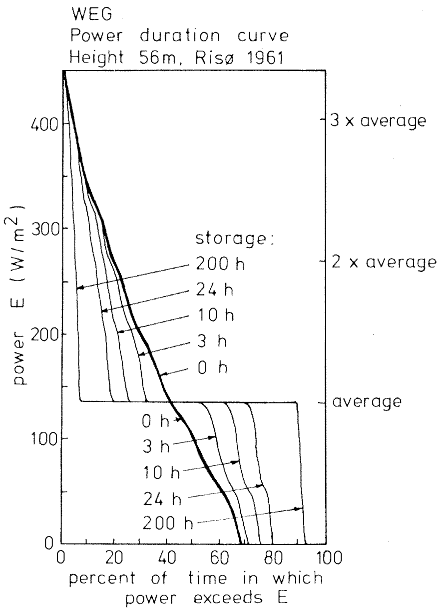

Fig. 1. Power duration curve (heavy line) for the wind energy generator system considered, in the absence of energy storage facilities. Thin lines show power duration curves for WEG's with storage capacities of 3 to 200 hours (see text).

put of 450 watt/m² (watts per square meter swept by the rotor) at a wind speed of 17 m/sec. By changing the rotor blade profile or the tip velocity, the power duration curve may be altered in the direction of delivering a higher output over a shorter time, or a lower output over a longer time. However, the total yearly energy output for the site considered is about maximum for the efficiency curve chosen (5).

The resulting power duration curve is shown in Fig. 1. The WEG is at a standstill 31 percent of the year, and its power output exceeds the yearly average 42 percent of the time. The yearly average output is 136 watt/m².

I now add an energy storage facility, assuming that energy is transferred to storage if the power output exceeds the yearly average and the storage system is not full, and is drawn from storage if the power output is smaller than average and the storage system is not empty. The capacity of the storage system is expressed as the number of hours in which it can sustain the average power. Examples of possible storage systems are batteries, flywheels, pumped water, compressed air, and hydrogen. These systems differ with respect to energy losses during the storing and electricity regeneration processes, the smallest losses (5 to 10 percent) probably being associated with a flywheel system.

In Fig. 1, power duration curves are shown for storage capacities ranging from 3 to 200 hours, assuming negligible losses. For a storage capacity of 10 hours, the WEG is productive 74 percent of the time, and the power output exceeds the average 64 percent of the time. If losses occurred during the storage and retrieval cycle, these figures would be diminished. If the efficiency of the storage system went down from 1 to 0.9, the productive and above-average periods would become 73 and 62 percent, respectively; at an efficiency of 0.7 the figures would be 70 and 58 percent; and at an efficiency of 0.5 they would be 69 and 53 percent.

To determine how much energy storage capacity would be needed for the WEG system to be considered a reliable power plant for base load (continuous) operation, one may compare the power duration curve of Fig. 1 with that of a typical nuclear power plant (6), shown in Fig. 2. The percentage of time in which the power output from the nuclear plant exceeds the yearly average is 68 for the plant considered, but there is a considerable spread in this figure from reactor to reactor and from year to year. The WEG system provides an output above average 64 percent of the time with a 10-hour storage facility and 72 percent of the time with a 24-hour storage facility. Figure 2 also shows that the addition of a storage facility, within the range considered, to a nuclear plant does not improve its power duration curve nearly as much as that of the WEG system.

It should be added that part of the outage time for nuclear reactors can be planned (about one-third in the example of Fig. 2), and so an improved power duration curve may be obtained for a system comprising several nuclear reactors. Still, unplanned simultaneous outage of several nuclear units can occur. A WEG plant comparable in size to current fuel-based plants will consist of hundreds of independent units, so simultaneous outage due to repair and maintenance is not expected.

The power duration curves of groups of WEG's placed at different locations may also be improved. If improvements of more than a few percent are to be attained, the different sites should probably be so far separated that they often experience different types of mesoscale atmospheric motion. Molly (7) finds that interconnecting WEG's at several wind measurement sites within the Federal Republic of Germany could reduce fluctuations by as much as a 24-hour storage.

For a particular site, the year-to-year variation in the total power output from a WEG will typically be much smaller than the variation in output from an individual nuclear reactor. At Risø, the yearly output from a WEG with the characteristics described above would have varied between 0.72 and 1.22 times the 10-year average. During 6 or 7 of the 10 years the yearly output would have varied less than 10 percent from the 10-year average.

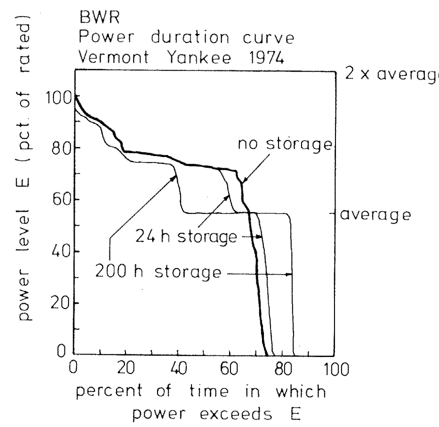

Fig. 2. Typical power duration curves for a light water nuclear reactor; *BWR*, boiling water reactor.

It appears from the discussion above that a WEG system, including an energy storage facility with a capacity in the range 10 to 24 hours, would be equivalent to one nuclear generating facility (but not several) as far as dependability is concerned, and provided the comparison is made for base load application.

For WEG systems to be used above the base load level, a different analysis of the influence of storage facilities has to be made. The storage should now be charged if the power exceeds the load, and discharged if the load exceeds the power output. Thus, instead of the conventional power duration curve, one may plot the percentage of time in which the power output minus the load at a particular time exceeds a certain value E, as function of E.

A simpler way to express the correlation between WEG output and load is through the yearly average power fluctuation. If the load was constant this fluctuation would be the mean fluctuation of the power duration curve in Fig. 1 about the average value. This amounts to 136 watt/m² if no storage facility is attached, and decreases as the storage capacity is augmented: 130 watt/m² (3 hours), 120 (10 hours), 107 (24 hours), 93 (60 hours), 79 (120 hours), and 69 (200 hours). The power fluctuations diminish rapidly as soon as even a small storage facility is added, and less rapidly when the storage capacity exceeds 24 hours. This can be understood in terms of the frequency distribution of the wind spectrum (4), which has periods corresponding to the typical climate cycles (the diurnal cycle due to day-to-night temperature variation, a 3- to 7-day cycle due to the passage of mesoscale front systems, and finally the seasonal cycle).

The actual load distribution depends on social and climatic factors, such as the length of day, the amounts of electricity used for space heating and cooling, and the working hours in industry and commerce. I will give the WEG power fluctuations relative to an approximate load function representing Danish conditions (*8*). Here the hourly variation ranges from 0.57 (2 to 4 a.m.) to 1.23 (10 a.m.) times the average, with a second peak occurring at 6 p.m. The monthly variation ranges from 0.8 (July) to 1.2 (January) times the average. This is somewhat different from the U.S. situation, where a second maximum occurs during summer in most states.

At the Risø site the WEG output exhibits a monthly maximum in March, a minimum in July, an hourly maximum just after noon, and a broad minimum at night (10 p.m. to 6 a.m.). The fluctuations relative to the approximate load function are 137 watt/m^2 (without storage), 131 (3 hours' storage), 121 (10 hours), 109 (24 hours), 95 (60 hours), 83 (120 hours), and 73 (200 hours). In other words, the expected output from a WEG plant with or without storage is practically as well correlated with the actual load (in Denmark) as it is with a constant load.

The power-minus-load duration curves are quite similar to the corresponding ones in Fig. 1, except that the flat part of the curves including storage is now at $E = 0$ (power output equal to actual load). This part extends to a few percent more of the time than do the flat parts of the curves in Fig. 1, reflecting the gross similarity between the power output and Danish load variations. Since the fluctuations are the same as when compared to constant load, or even a bit higher, this can be interpreted by saying that the power output exceeds the actual load more often than it exceeds the yearly average, but the surplus or deficit in some periods of time may reach larger values when actual load is considered.

The prospects of developing economically viable short-term storage systems for use in conjunction with WEG's have been considered elsewhere (*9*), as have the requirements for long-term storage, which will allow an arbitrarily large coverage with wind energy (*10*).

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References and Notes

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5. In calculating the power duration curves, the efficiency was approximated by a step function, referred to integral values (in meters per second) of the wind speed.
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10. ———, in preparation.
11. I thank N. E. Busch and E. L. Petersen for making the Risø meteorological data available to me.

1 June 1976; revised 21 September 1976

Calcium Carbonate Production, Coral Reef Growth, and Sea Level Change

Abstract. *Shallow, seaward portions of modern coral reefs produce about 4 kilograms of calcium carbonate per square meter per year, and protected areas produce about 0.8 kilogram per square meter per year. The difference is probably largely a function of water motion. The more rapid rate, equivalent to a maximum vertical accretion of 3 to 5 millimeters per year, places an upper limit on the potential of modern coral reef communities to create a significant vertical structure on a rising sea.*

The rate at which a coral reef community produces sedimentary materials has long been a subject of speculation and estimation. Indeed, it has been recognized that coral reefs are unique in their ability to precipitate materials from seawater at a sufficient rate to keep pace with a rising sea, and to consolidate those materials into a regionally extensive three-dimensional structure. We consider here primarily the rate of production of $CaCO_3$ sediment by coral reefs in relation to the potential of coral reef growth to keep pace with a rising sea.

Most estimates of the $CaCO_3$ production rates of reefs have been based upon either biological or stratigraphic evidence. The standing crop of reef organisms multiplied by the growth rate of these organisms provides a biological measure of the $CaCO_3$ production rate. Alternatively, the vertical accumulation of materials (for example, in a drill core) together with isotopic (for example, ^{14}C) ages yields a stratigraphic record of the net accumulation rate. Chave *et al.* (*1*) summarized much of the pre-1971 literature on coral reef $CaCO_3$ production as estimated by one or other of these approaches.

A third method is based on the mass balance of $CaCO_3$ precipitated from seawater. The reduction in the total alkalinity of the water (normalized with salinity to account for conservative changes in alkalinity associated with evaporation, rainfall, groundwater input, and other factors) multiplied by an estimate of the flushing rate of water through the reef system can be converted to an estimate of $CaCO_3$ precipitation rate (*2–7*). Observed alkalinity changes range from near analytical detection limits (that is, < 0.005 meq/liter) to 100 or more times these limits. Production rates reported here involve approximately 100 to over 1000 individual analyses from each site.

This method avoids the tedium and inaccuracies inherent in any cumulation of the contributions by individual biological components. Moreover, the alkalinity estimate of $CaCO_3$ production is not sensitive to the potential stratigraphic biases of physical dispersion or concentration of detrital sedimentary materials. Finally, where applicable, the alkalinity method provides real-time data on the $CaCO_3$ production rate at the site of production.

Inspection of recent published and unpublished data on the alkalinity reduction of seawater has revealed some striking consistencies which have important implications with respect to potential coral reef growth as a function of sea level change, major calcifying biota, physiography (and consequently physical environment), and latitude. We present these data and our interpretations, not as new concepts, but rather as the restatement of old concepts in the light of these modern data.

The $CaCO_3$ production rates obtained from numerous measurements in each of six shallow, well-flushed seaward reef flat environments are consistently near 4