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Limits to Wind Power Utilization

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Summary. As wind energy receives increasing attention it is important to understand the noneconomic factors limiting the total power that can be extracted from the wind. These factors are examined here with a macroscopic approach. An upper global limit of 1.3×10^{14} watts is arrived at with a sublimit of 2×10^{12} watts for the continental United States. Some general conclusions are also reached regarding the sites that would have to be utilized to achieve these levels. Even within these limits, wind energy is seen to offer a potential far larger than many other self-renewing energy sources.

The extraction of energy from the wind is receiving increasing attention as a self-renewing energy source (*1*). Assessment of how important wind energy may become requires answers to some key questions. How much can wind energy contribute if it is fully exploited? What are the technology requirements, limitations on siting, and possible side effects of wind utilization? Considering the peculiarities of local wind conditions, can anything that is of both general validity and practical utility be said?

By using a macroscopic approach that focuses first upon the source, one can derive useful answers to all of these questions. Indeed, this top-down approach draws attention to some potentially grave environmental consequences and avoids some difficulties and misunderstandings that can arise out of generalizing from specific details. When source strength estimates are combined with practical and environmental limitations, the potential contribution that wind energy extraction systems could make to our energy needs is less than some enthusiastic advocates have claimed; but is still appealingly large. As a potential source of energy it exceeds in magnitude many other self-renewing sources such as tidal energy capture, geothermal energy, or hydropower.

The Source

The ultimate source of wind energy is the sun, but the conversion of this radiant energy into the kinetic energy of moving air is a very complex process involving many interacting energy transfer paths. The computation of wind patterns directly, even with the use of highly idealized earth models, is made practically intractable by the presence of advection—the displacement of the fields of motion and temperature by the field of motion itself. Because the motion is not uniform, different portions of the advected fields undergo different displacements, and the fields become distorted. The complexity of the nonlinear processes taking place precludes direct calculation of the consequences. Therefore, a mixture of theory and experimental data and some judicious estimating is required (*2*).

The solar flux at the earth's distance from the sun is 1400 watts per square meter resulting in a total intercepted flux of 1.8×10^{17} W or 350 W/m^2 when averaged over the earth's surface. It is the interaction of this radiant flux with the atmosphere, waters, and land surface of the earth which give rise to the winds. Thus, 1.8×10^{17} W constitutes an upper limit on solar energy-based processes, but far exceeds that available from the wind alone (*3*).

Energy must be continually fed into the earth's atmosphere to maintain the wind by offsetting the dissipative effects of turbulence and friction in the atmosphere and at the earth's surface. The ratio of this rate of wind energy dissipation loss to the total solar flux, both taken on a unit area basis, is usually labeled η. This quantity can not be measured directly but must be inferred by using the available data within the framework of a general theory. The several approaches that can be made to estimating η generally concur in indicating 0.02 as a best value (*4*).

Application of this 2 percent figure gives an average for the total rate of solar input to wind energy over an earth element of 7 W/m^2. For the whole earth this amounts to 3.6×10^{15} W.

Wind energy machines interact directly, of course, not with the totality of energy in the atmosphere but rather with that available within the boundary layer at the earth's surface. The focus of most meteorological studies, however, is not how much energy can be extracted but rather how much energy is dissipated as a function of altitude.

A detailed examination of a paper by Ellsaesser (*5*), which makes major use of earlier work by Kung, reveals that 35 percent of the total wind energy dissipation occurs on the average within 1 kilometer of the earth's surface. The kinetic energy dissipation rates given as a function of altitude by Ellsaesser can be used to go one step further (*6*). Extrapolation and integration to ground level from an altitude of 1 km gives an increment in η that is small compared to the surface boundary contribution calculated by Kung (*7*). Indeed, effects at the boundary (resulting only in part from surface roughness) constitute a major portion of the total dissipation; that is, more than 90 percent of the 35 percent figure quoted (*8, 9*).

Application of this near-earth factor of 35 percent to the total dissipation rate of 7 W/m^2 gives 2.5 W/m^2. On a global basis this amounts to 1.3×10^{15} W (*10*).

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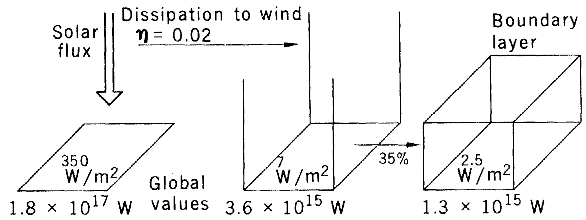

Fig. 1. Solar flux drives the wind.

Figure 1 provides a summary of the key values noted above. Integrated over 1 year, the solar flux value shown equals 5.7×10^{24} joules (5.4 million quads) and even the much smaller boundary layer value equals 4×10^{22} J (39,000 quads) (*11*). The annual world energy consumption, for comparison, is approximately 2×10^{20} J (200 quads) (*12*).

Content Versus Replenishment

A distinction must be made between the amount of kinetic energy in the wind and the rate at which energy can be continually extracted. This is essential not only as an antecedent to the conclusions reached herein, but also because of the confusion surrounding this topic.

Brunt (*13*) provides an estimate of 3×10^{20} J for the total global kinetic energy of the wind which, when combined with the estimated 5.2×10^{21} grams' weight of the earth's atmosphere implies a global average wind velocity of 11 meters per second (38 km/hour) (*12*). Brunt finds approximately this velocity to be justified on the basis of observed pressure differences.

Another and more revealing result follows from dividing this total wind energy content of 3×10^{20} J by the previously calculated global rate of solar input to wind energy of 3.6×10^{15} W. The result, 8.3×10^{4} seconds, indicates that approximately 1 day's worth of input solar energy is typically stored as kinetic energy at any given time. Or, conversely, since at equilibrium the input rate and dissipation rates are equal, in the absence of input the earth's wind energy would be largely dissipated within days, if one assumes that the dissipation rate varies linearly with energy content (*14*).

A More direct comparison with the dissipation rate or driving force can be made by examining the energy content of the winds per unit area of earth's surface. Dividing the total wind energy content of 3×10^{20} J by the globe's surface area of 5×10^{14} m² gives 6×10^{5} J/m². Comparison of this with the 7 W/m² rate of solar input to wind energy gives an idea of the enormous size of the "flywheel" which the circulation of the earth's winds provides. Of course, it is not the size or speed of the flywheel but the rate at which energy is supplied to drive it that determines the rate at which energy can be extracted on a continuous basis.

Environmental Consequences

Knowing the rate at which energy is fed into the earth's wind system still leaves open the question of the rate at which man can safely extract energy from the system. Aside from the practical factors and economic incentives, the only general limitation would appear to be a reluctance to significantly modify the earth's climate. That is, if wind energy extraction were pursued with enormous diligence, the level of energy capture might be so large as to significantly perturb the natural global processes. What fraction or percentage of the near-surface dissipation energy can be extracted safely?

An allowable level cannot be calculated on the basis of current knowledge. It is not even clear that it is correct to talk about a percentage level because there may be great differences in impact depending on where on the earth's surface the energy is extracted. It is, after all, the uneven heating of the earth's atmosphere, more intense near the equator and less in the polar regions, which is the primary driving force that creates the winds. These forces, modified by the earth's declination and orthographic features and coupled with the Coriolis force, give rise to the familiar gross features of the global winds and their seasonal fluctuations. This means, of course, that wind energy is distributed quite differently over the globe than is the input solar energy. Then too, the energy once extracted from the wind would at some time be returned to the earth's near-surface environment (usually as waste heat) as the energy is used. How and where this is done would also determine the impact on global climate.

It is also important to realize, in considering the effects on the world's climate, that what is involved is not a simple system in which the result will necessarily be proportional to the change in input (*15*). Analogous questions have been raised concerning the impact on the world's climate because of other changes caused by humans. Kellogg (*16*) has delineated a broad range of related and interacting variations which might follow from a change in the earth's atmosphere. Some of these, such as a permanent melting of the Arctic Ocean ice, seem likely to involve a stepwise change of great significance once some now unknown threshold level of input change has been exceeded.

In view of these uncertainties, a judgment must be made in estimating what fraction of the near-earth dissipation rate can be safely extracted. The issues noted above suggest considerable caution may be necessary. But one can also argue that in some areas humans will simply be substituting their own turbulence-generating structures for those already present in the form of mountains, trees, and other natural features. Also, the system may have some elasticity in that artificially induced losses (that is, removal of energy by humans) may be partially replenished by shifts in the natural processes or in the level of the boundary layer interface.

As a compromise between caution and imprudence in the face of inadequate knowledge, 10 percent of the near-surface dissipation will be taken here as a limiting value. Certainly many will see this figure as being too generous by far. In this sense it would clearly seem to be an upper limit that could not safely be exceeded. It would, indeed, be desirable for this and many other purposes if meteorological studies could elucidate the relations between climate and man-made changes, but such an elucidation seems to be well beyond current knowledge.

This 10 percent limitation is, of course, not applicable to small areas considered individually. For example, since there are some areas, such as mid-ocean areas, that may never be exploited, on-land use could be increased proportionally.

Applying this 10 percent to the numbers previously calculated gives 0.25 W/m². On a global basis this amounts to 1.3×10^{4} W.

Recommended Values

It is clear that the wind energy in the atmosphere varies widely depending on global zone (*2*, *8*). Furthermore, at every scale down to those of the microclimatologists there are variations in the local wind energy. The rate of dissipation also appears to vary from area to area, although there is much less knowledge about these variations. Kung (*17*) concluded that despite land and ocean differences in surface roughness, the dissipation rates in the boundary layer are about the same over land masses and over the oceans. Ellsaesser (*5*) has provided global maps of the dissipation for various altitudes. These maps suggest that the area covered by the United States (*18*) closely approaches the global average. That it is identical to the global average is assumed in what follows.

The 3 million square miles or 8×10^{12} m^2 of the United States therefore involve a near-surface dissipation rate of 2×10^{13} W (*19*). Application of the 10 percent limitation suggested in the preceding section would set a limit of 2×10^{12} W on the capturable energy, a value not dissimilar from that estimated by others (*15, 20, 21*). Most of these estimates, however, do not incorporate any explicit concern for impacts on climate (*22*).

Table 1 lists the values estimated above. In alternate units the annual extraction rate limits derived here are 4×10^{21} J (3900 quads) globally and 6.3×10^{19} J (60 quads) for the United States (*11*). As noted previously, any application of the extraction rate limit per unit area must be made with due consideration for the particular geographic area involved. For example, it might reasonably be argued that since so much of the earth's surface is open ocean where wind energy extraction may not occur, then the limiting areal value for the United States could be increased at least threefold. Others, who think that the 10 percent figure suggested is too high, may find some comfort in the fact that no such increase has been included here.

Table 1. Summary of recommended values.

Quantity	Area of interest (values in watts)		
	Per m^2	Global	United States*
Solar input rate	350.0	1.8×10^{17}	2.8×10^{15}
Dissipation rate (at 2 percent of solar input)	7.0	3.6×10^{15}	5.6×10^{13}
Near-surface dissipation (at 35 percent of total)	2.5	1.3×10^{15}	2.0×10^{13}
Extraction rate limit (at 10 percent of near-surface dissipation)	0.25	1.3×10^{14}	2.0×10^{12}

*For the 48 contiguous states.

Table 2. Unit efficiency as a function of array size and spacing (*26*).

Spacing parameter λ	Array size, *N* by *N*			
	Infinite	50×50	10×10	5×5
0.001	0.89	0.95	0.98	0.99
0.003	0.73	0.87	0.96	0.98
0.010	0.38	0.62	0.86	0.94
0.030	0.10	0.29	0.70	0.85

Limitations on Extraction Machines

Given a particular site, numerous factors limit the extent to which it is either feasible or economic to extract energy from the wind. Speed and constancy of the wind are the site characteristics of primary importance. But before such site-specific attributes are discussed, some more general nonsite-specific factors such as conversion efficiencies, design velocity limits, the Betz coefficient, and degradation arising from close packing deserve consideration.

The most obvious limitation on extracting energy from the wind is the inefficiency associated both with the frictional processes in rotating machinery and in the conversion, when required, of mechanical energy to some other form such as electricity. Although improved designs can reduce these losses, such improvements are unlikely to prove economical beyond some level. Today, an overall efficiency of 80 percent for conversion to electrical energy would be considered a rather demanding goal (*20, 21, 23*).

Since it is never economical to construct a wind machine so that it is able to extract the full energy from the maximum wind velocity likely to be encountered at a given site, less than the full potential of a site will be realized in practice. Furthermore, because the energy contained in the wind varies as the cube of the velocity, this loss could be significant. For a given site, speed-duration data can be used to calculate the fraction of the available energy that would be captured as a function of the maximum usable speed, and the most attractive limit then selected. More generally, many workers have observed that the speed-duration curves for most sites have a rough similarity when the wind speed is scaled to the mean speed for the site. Lapin's (*24*) calculations, as well as other data (*25*), indicate that, if the maximum usable speed is set at twice the mean wind speed then for many sites the loss thus incurred is unlikely to be greater than 15 percent. This represents an economically attractive situation (*26*).

Another limitation on wind energy extraction by means of a rotor system arises from optimizing the relation between pressure drop and flow rate. The goal is to maximize the product of these two closely related quantities—that is, where increasing the pressure drop invariably reduces the flow rate. The relationships involved were first elucidated by Betz (*27*). He demonstrated that, at most, 16/27 or 0.593 of the energy in a windstream can be extracted by a turbine or rotor-type device.

If the problem faced is that of fully developing the energy production potential of a fixed geographic site, then another factor comes into play; namely, a limitation imposed by using sufficiently sparse spacing that the performance of individual units is not significantly degraded by the presence of other units. That is, sufficient space must be allowed between units to permit smearing out of upstream wakes by turbulent processes and vertical or horizontal replenishment of the kinetic energy (*28*).

A typical rule of thumb for avoiding interaction among wind energy extraction machines is to allow 5 to 15 times the rotor diameter for intermachine spacing (*20, 21, 25*). This limitation has been explored to some extent in scaled wind-tunnel experiments and in several theoretical studies (*29–31*). These studies indicate that the critical parameter is the ratio of the rotor-swept area to the land surface area, usually denoted as λ. That is, the power that can be extracted is very nearly directly proportional to the swept area and is a much weaker function of rotor height (*32*).

For very extensive arrays, where only vertical energy replenishment can be effective, losses can be substantial if λ values exceed 0.001. The magnitude of this effect is suggested by the first column of Table 2 which shows the decreased (< 1) unit efficiency for each element of an infinite array of wind energy extraction machines as a function of λ (*33*). In exploiting a given land area, closer spacing results in reduced unit output but, up to

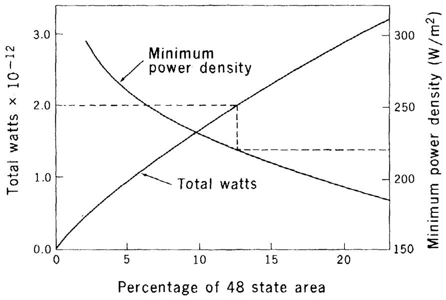

Fig. 2. Energy available for capture and minimum power density as a function of U.S. land area (for $\lambda = 0.02$ and 40 percent capture fraction).

some level of crowding, a higher total output. However, the decreased output per unit of capital investment which results with more than minimal crowding weighs strongly against achieving maximum energy capture at the expense of unit performance.

The rule of thumb of 5 to 15 rotor diameters corresponds to λ's of 0.003 to 0.03. Such values are quite reasonable for limited arrays in which horizontal as well as vertical replenishment can be significant. This is well illustrated by the unit efficiency values shown in Table 2; that is, for arrays involving tens of units, the per unit performance is still high for λ values as high as 0.03. In actual practice, such small arrays are most likely to be used to take advantage of local high-quality sites and valuable topographic channeling. Further experimentation and calculation would be required to elucidate the full situation, particularly in complex topographies.

Siting Opportunities

Considerations of wind energy extraction will naturally tend to focus first on the exploitation of areas of high-speed and persistent winds (*34*). Two general questions of importance are: how large a geographic area must be exploited and how poor a quality site must be used to achieve the allowable limit previously established? Consideration of these questions can also serve to correct some misunderstandings about isodyn maps: those showing the contours of equal power density perpendicular to the wind.

Some of the data most pertinent to wind energy extraction have been assembled by Reed and his co-workers (*35*, *36*). Of special interest here are Reed's contour maps which show the average annual power density in watts per square meter over the United States (*18*). Although Reed notes that these data are for airport and city locations rather than having been selected with wind power collection in mind, and that severe smoothing was required to generate these maps, they appear to provide an adequate basis for the considerations which follow (*37*).

One can compute the minimum quality site that would have to be used to achieve a given level of total wind energy extraction in the United States by using a $\lambda = 0.02$ limit on close packing and Reed's isodyn maps and, to allow for the Betz coefficient limitation and other collection inefficiencies, by assuming that only 40 percent of the energy intercepted by the rotor area is actually extracted. The results of such a computation are shown in Fig. 2. These values have been calculated without reference to any environmental limitations, but the previously established extraction limit of 2×10^{12} W is indicated by a dashed line (left axis). The pertinent curve shows that under the assumptions made here, 12.4 percent of the land area must be exploited to reach this limit. Actual land usage will, of course, be very much smaller. For example, if one assumes (on the high side) that each extraction device requires a land area equal to five times the rotor area, the used area will be slightly more than 1 percent of the land surface (*38*). This percentage is small (albeit large in absolute terms) because of two factors: There is an abundance of good sites and most of the exploited area need not, indeed cannot effectively, be dedicated to wind energy machines.

Figure 2 also permits one to deduce the minimum quality site in terms of average annual power density which will have to be exploited to achieve the 2×10^{12} W limit. The dashed line indicates (right axis) that the minimum site will have a power density of 220 W/m². This corresponds to an average wind speed of 7 m per second (25 km per hour), a speed that is quite adequate to achieve good operating efficiencies. Thus, presuming that there is full freedom to develop the highest power density sites, the answers to the earlier questions are that there are an adequate number of very good sites and that full exploitation would require the use of only a small percentage of the land area of the United States.

The estimates given here for both the area required and the minimum quality sites are at best first approximations. These calculations are based on wind speeds close to the ground, most often an elevation of approximately 10 m; no attempt was made to identify particularly good sites for wind energy extraction.

Table 3. Usable energy potentials on a global basis.

Resource	Energy potential	
	Watts $\times 10^{-12}$	Quad/ year
Wind extraction limit	130	3900
Potential useful hydropower	2.9	86
Usable geothermal heat	0.13	4
Usable tidal energy	0.06	1.9

Since wind speed generally increases with altitide the use of large rotors or tower mounts will result in more energy being captured per unit rotor area, decreased land area requirements, and enhanced site quality (*37*). Careful selection of sites on the basis of their merit for wind energy extraction would have similar effects. Movement in these directions may, at least in part, be balanced by the undesirability for other reasons of using some of the best sites. On balance, the estimates given here are likely to be conservative; that is, land requirements are likely to be lower and minimum site quality higher than indicated.

Isodyn maps are valuable for recognizing those areas in which prevalent brisk winds offer the greatest opportunity for practical capture and for estimating the maximum levels of extraction achievable with isolated wind machines. However, as Reed points out, "wind power patterns do not show how much power can be extracted from the wind" (*36*). It would not be correct to integrate over the whole area depicted to arrive at a total for the wind energy that might be extracted (*15*). Indeed, were one to do this using Reed's map, the indicated average for the United States is 140 W/m², which exceeds by 20-fold the 7 W/m² rate at which energy is supplied to maintain the winds. Simply put, the energy extracted in 1 m² will not appear in another square meter to be extracted again. Rather, these power density numbers should be visualized as the rate at which energy is passing, as kinetic energy of mass motion, over a specified ground element (*39*).

In some ways the volume occupied by the earth's atmosphere can be looked on as an enormously large and complex duct. Examined at specific points an estimate can be made of the energy which could be extracted locally by a suitable wind energy machine. But all of the sites thus identified cannot be simultaneously occupied without regard for the solar input which is the "engine" that causes the air to flow through this "duct."

Comparisons

The extraction rate limit of 2×10^{12} W set for the United States is roughly 75 percent of the current national total energy consumption rate, whereas the global limit of 1.3×10^{14} W is about 20 times the worldwide energy consumption rate. These figures suggest the enormous potential contribution that wind energy extraction could make to global energy resources. In the United States alone, 2 million 1-megawatt installations would be required to attain the suggested rate—far beyond anything likely to be done in the foreseeable future.

Tidal, hydro-, and geothermal power are also self-renewing resources. They also have another similarity to wind power in that nature provides for some concentration in sites where capture is more readily effected. The global total hydrologic runoff energy amounts to 9×10^{12} W, while that which can be usefully collected has been estimated at just over 30 percent of this amount. A similar situation exists for tidal power, with the total being 3×10^{12} W, but here the portion usefully collectible appears to be about 2 percent of this value. Finally, for geothermal power the spread is even wider, running from a total geothermal flux of 2.7×10^{13} W down to a usefully collectable level of 1.3×10^{11} W or 0.5 percent (*12*, *40*).

The usable energy potentials on a global basis for these renewable resources are summarized in Table 3. Should the large-scale capture of wind energy prove economically rewarding and otherwise acceptable, this tabulation makes it clear that wind energy has a magnificent potential.

References and Notes

1. N. L. Brown and J. W. Howe, *Science* **199**, 651 (1978).
2. See E. N. Lorenz, *The Nature and Theory of the General Circulation of the Atmosphere* (World Meteorological Organization, Geneva, 1976), for a discussion of these matters.
3. Some popular accounts have suggested even larger values for the potential contribution of wind energy.
4. With time there has been a tendency for estimates of η to increase. Lorenz (*2*, chap. 5, particularly pp. 101 and 107) suggests a current best estimate of 0.02 and provides some general grounds for believing that this may represent very nearly a maximum value. Ellsaesser (*5*) appears to concur with this judgment. Brunt (*8*) reached this same conclusion at an earlier date but on the basis of a calculation of turbulent dissipation which did not fully include surface interaction.
5. H. W. Ellsaesser, *Mon. Weather Rev.* **97**, 415 (1969), table 2 in particular.
6. Note particularly the values given in table 2 of Ellsaesser (*5*) for North America.
7. E. C. King, thesis, University of Wisconsin, Madison (1963).
8. D. Brunt, *Physical and Dynamical Meteorology* (Cambridge Univ. Press, Cambridge, 1939), pp. 285–287. Brunt calculates a value of 5 W/m^2 for the turbulent dissipation in a column of air 1 m in cross section. If this is compared with the 7 W/m^2 resulting from applying $\eta = 0.02$, then the deficit of 2 W/m^2 might be attributed to surface effects. This would imply a value within a few percentage points of that suggested here.
9. The boundary layer, with the resulting dissipation by turbulent processes of wind energy, is a direct consequence of the motion of the atmosphere relative to the earth's surface. Local "roughness" in the form of waves, mountains, trees, or wind energy extraction machines can augment the near-surface dissipation rate.
10. T. Wentink, Jr. "Study of Alaskan wind power and its possible applications" (Univ. of Alaska, Fairbanks, mimeographed, 1976) has tabulated a number of estimates of this same quantity which range, with one exception, between 0.25 and 2.5×10^{15} W.
11. One quad = 10^{15} British thermal units = 1.0548×10^{18} J; one quad/year = 3.4×10^{10} W.
12. M. R. Gustavson, *Dimensions of World Energy* (Rep. 75-4, Mitre Corporation, Washington, D.C., 1975).
13. See Brunt (*8*, p. 285).
14. Brunt (*8*, pp. 285–287) reached similar conclusions. L. Machta, as cited by Wentink (*10*, p. 11) estimated that without continuous energy addition the atmosphere would become stationary in about 10 days.
15. W. S. von Arx, *Trans. Am. Geophys. Union* **55**, 828 (1974).
16. W. W. Kellogg, *Climate Change and the Influence of Man's Activities on the Global Environment* (Rep. 72-166, Mitre Corporation, Washington, D.C., 1972).
17. E. C. Kung, *Mon. Weather Rev.* **94**, 57 (1966); *ibid.*, p. 627.
18. As used here, the area covered by the United States refers only to the 48 contiguous states.
19. It is interesting that this same value attributed to Willett is quoted without further details in P. C. Putnam, *Power from the Wind* (Van Nostrand, New York, 1948), p. 209.
20. General Electric Company, *Wind Energy Mission Analysis* (report under ERDA contract No. EY-76-C-02-2578, Washington, D.C., 1977).
21. Lockheed-California Company, *Wind Energy Mission Analysis* (report under ERDA contract No. AT (04-3)-1075, Washington, D.C., 1976).
22. *Solar Energy Research and Development: Program Balance*, annex, vol. 2 (prepared for U.S. Department of Energy Solar Working Group under contract No. EA-77-C-01-2693, Washington, D.C., 1978). This report discusses potential wind energy exploitation levels of up to 30 quads per year (1×10^{12} W) for the United States without explicitly recognizing in its discussion of environmental considerations any potential impact on climate—despite the fact that 1×10^{12} W represents 50 percent of the environmentally limited value recommended here (Table 1) for the United States. The Council on Environmental Quality [*Solar Energy: Progress and Promise* (Washington, D.C., 1978)] gives an estimate of 1 to 2 trillion kilowatt-hours per year (1.1 to 2.3×10^{11} W) as the wind potential of the nation, excluding offshore regions. This amounts to a much more modest 5 to 10 percent of the value recommended here. However, it is not clear that climatic factors were considered limiting in arriving at this estimate.
23. J. O'M. Bockris, *Environ. Conserv.* **2** (No. 4), 283 (1975).
24. E. E. Lapin, in preparation.
25. F. R. Eldridge, *Wind Machines* (Rep. MTR-6971, Mitre Corporation, Washington, D.C., 1975).
26. There are enough specific locations cited in the literature where these "typical" figures do not apply that each site requires specific investigation and, except for small mass-produced units, appropriate design optimization.
27. A. Betz, *Naturwissenschaften* **15** (No. 68) (1927).
28. J. W. Railly [*Wind Eng. 1* (No. 1), 23 (1977)] provides an extensive theoretical analysis of the process of vertical energy replenishment. He also points out the importance of taking into account how the forces which drive the surface winds can be altered by major interference with the free flow of air over the earth's surface.
29. R. J. Templin, *An Estimate of the Interaction of Windmills in Widespread Arrays* (Rep. N.A.E. LTR-LA-171, National Research Council of Canada, Ottawa, 1974).
30. B. G. Newman, *Energy Convers.* **16**, 169 (1977).
31. C. Crafoord, "An estimate of the interaction of a limited array of windmills" (International Meteorological Institute, Stockholm, 1975).
32. Wind speed varies with altitude and this fact is of importance both in site selection and in calculating correctly the force differentials on large turbine blades.
33. The data are based on evaluations presented by Crafoord (*31*) for wind extraction machines of approximately 1-megawatt size in rectangular arrays of size *N* units by *N* units. That is, the 50 by 50 column refers to an assemblage of 2500 machines.
34. This follows from the higher rate of return per unit of capital investment for such areas. The issue of central station as opposed to distributed use of wind energy extraction machines involves other factors such as distribution costs. In what follows the only assumption made as to the size of individual groupings is that they will be small enough that λ's up to 0.03 can be used without significantly impacting unit efficiency.
35. J. W. Reed, *Wind Power Climatology of the United States* (SAND 74-0348, Sandia Corporation, Albuquerque, N.M., 1975).
36. ——, *Wind Power Climatology* (SAND 74-0435, Sandia Corporation, Albuquerque, N.M., 1974); *Weatherwise* **27**, 6 (1974).
37. D. L. Elliott [*Synthesis of National Wind Energy Assessment* (Battelle Pacific Northwest Laboratories, Richland, Wash., 1977) provides an excellent summary of the factors that complicate the construction of wind power density maps.
38. That is, five times 2 percent of 12.4 percent.
39. A case in which the type of integration or addition discussed here may have occurred can be found in *Solar Energy as a National Energy Resource* (NSF/NASA Solar Energy Panel Report, Washington, D.C., 1973) which states: "It is calculated that the power potential in the winds over the continental U.S., the Aleutian arc, and the Eastern seaboard is about 10^{11} kilowatts electrical." Even if one assumes 100 percent efficiency in converting wind energy into electrical energy, this 10^{14} W amounts to more than 7.5 percent of the global near-surface dissipation over an area of only 2 percent of the globe and is approximately 80 percent of the global limit suggested in this article. In the absence of some basis for the United States using such a large share of the world's wind energy and ways to ameliorate the probable climatic effects, this estimate appears excessive.
40. This estimate is based on "natural" geothermal assets. Successful development of hot dry rock technology or other advances may increase the usable potential of this resource.

41. This article is adapted from a paper presented at the 1978 Annual Meeting of the AAAS held in Washington, D.C.