SOLAR ENERGY FARMS

Karl H. Bergey

School of Aerospace, Mechanical and Nuclear Engineering, University of Oklahoma, Norman, Oklahoma

Solar energy sources, though attractive from an environmental standpoint, suffer from intermittency and low power densities. Because of the need for back-up or energy storage, the capital costs are high and, as a consequence, the cost of power is also high. This paper suggests a method for developing solar and conventional energy sources in combination so as to avoid the need for energy storage and to provide a load-following capability which will be compatible with normal demand curves. The cost of such energy generation is calculated and appears to be competitive with current energy costs.

The current energy crisis has encouraged both government and industry to take a new look at nonfossil energy sources. Of the various alternatives, solar-related energy offers a unique combination of unlimited supply, environmental benignity, and a natural harmony between the increasing demands for energy and the complex ecological balance of the world in which we live.

Despite its attractive features, solar-related energy is not without its own set of problems. The sun does not always shine and the wind does not always blow. Furthermore, solar energy density is relatively low, so that large land areas and high capital investments are required to support large-scale solar power generation.

In Oklahoma, we are particularly fortunate in our solar energy resources and, in particular, in the availability of strong steady winds. Of all solar-related energy sources, wind power appears to be the most promising for immediate use. It draws on existing technology, is compatible with existing use patterns, and can provide a significant share of our nations energy needs without adverse environmental consequences.

Approximately 2% of all solar radiation to the earth is converted to kinetic energy in the earth's atmosphere (1). The resulting circulation and its interaction with land and water masses determine the nature of the wind patterns in any given part of the world. In the United States, the coastal margins and the Great Plains, from Texas through the Dakotas, are the most promising geographic locations for the development of energy from the wind. In both regions, the average winds are high and the periods of zero wind are infrequent.

The total kinetic energy flux of a wind column with a cross section of one square meter is:

$$K.E._{flux} = \frac{WV^2}{2g} = \zeta \frac{V^3}{2g} = .0624\ V^3 kg\ m/sec$$

Since the air cannot be brought to zero speed by rotating blades which are extracting energy from the air column, the ideal efficiency for a wind-powered rotor is approximately 60%. The actual kinetic energy flux which is available from a unit area is therefore:

$$K.E._{flux} = 0.0375\ V^3 kg\ m/sec$$
$$= 0.00037\ V^3 kw$$

It is important to recognize that the mean velocity as normally reported should not be used in calculating the long-term wind power potential for a specific location. Mean wind velocity is defined as the arithmetic mean, the sum of the observations divided by the number of observations. Since we are interested in a quantity which is a function of velocity cubed, the *mean-energy velocity* must be used for other than instantaneous energy calculations.

Column 3 of Table 1 shows the frequency distribution of the wind for the year 1966 in the central Oklahoma area. It is based on research carried out by the National Severe Storms Laboratory located in Norman (2). The mean annual wind velocity for that year was 11.34 knots, (5.84 m/sec). The annual mean-energy wind velocity, however, was 14.07 knots (7.25 m/sec), an

Proc. Okla. Acad. Sci. 55: 72-78 (1975)

TABLE 1. *Mean annual wind velocity and annual mean-energy wind velocity for central Oklahoma.*

Average Velocity knots	Average Velocity m/sec.	Frequency Distribution	(1) X (3)	V^3 (knots)^3	(3) X (5)	(3) X (5) Flat Rate to 22k
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0	0	0.009	0	0	—	—
1	0.515	0.023	0.023	1	—	—
3	1.545	0.056	0.168	27	1.5	1.5
5	2.575	0.091	0.455	125	11.4	11.4
7	3.605	0.141	0.987	343	48.4	48.4
9	4.635	0.133	1.197	729	97.0	97.0
11	5.665	0.145	1.595	1331	193.0	193.0
13	6.695	0.116	1.508	2197	254.8	254.8
15	7.725	0.080	1.200	3375	270.0	270.0
17	8.755	0.062	1.054	4913	304.6	304.6
19	9.785	0.050	0.950	6859	343.0	343.0
21	10.815	0.037	0.777	9261	342.6	342.6
23	11.845	0.025	0.575	12167	304.2	266.2
25	12.875	0.014	0.350	15625	218.8	149.0
28	14.420	0.018	0.504	21952	395.1	191.7
		1.000	11.343		2784.4	2473.2

1. The annual mean wind velocity is 11.34 knots (5.84 m/sec)
2. The annual mean-energy wind velocity is $\sqrt[3]{2784.4}$ = 14.07 knots (7.25 m/sec)
3. The annual mean energy wind velocity with a flat rate speed of 22k is $\sqrt[3]{2473.2}$ = 13.52 knots (6.96 m/sec)

increase of 24%. Since the output varies with the cube of the wind velocity, the calculated energy outputs differ by a factor of two.

The above relationship is true, however, only if the generating system is capable of absorbing all the wind energy at the maximum wind speeds. In the central Oklahoma area, this would require an installed generating capacity of about 1.10 kw per square meter of swept rotor area.

$$\text{Capacity} = 0.00037\ (14.4)^3 = 1.10\ \text{kw/m}^2$$

From a cost-effectiveness standpoint, this would be an excess of capacity, however, since the generator would be operating at maximum output less than two percent of the time. Using a more realistic installed capacity of 0.55 kw/m^2, the flat rate wind speed is just over 22 knots (11.33 m/sec) and the mean-energy wind velocity is reduced to 13.52 knots (6.96 m/sec). Figure 1 shows a plot of specific output for a windmill which starts to generate power at wind speeds of 6 knots and develops a constant output above 22 knots.

Although the start-up speed is not critical from the standpoint of total power output, it does define the period during which no power is being generated, in this case about 18% of the time.

Assuming a combined efficiency of 65% for the aerodynamic, mechanical and electrical components of the windpower system, the annual specific output is:

$$\text{Annual output} = 0.00037\ (6.96)^3 (8760)\ (0.65) = 710\ \text{kwh/m}^2\text{/yr}$$

The annual output for various rotor diameters is shown in Table 2. The two smaller diameters represent units suitable for private homes. The 48-meter unit represents a size which may be the maximum practical diameter for central station units.

TABLE 2. *Wind rotor output vs. diameter.*

Diameter m	Diameter ft	Swept Area m^2	Installed Capacity kw	Power Output kwh/yr
4	13.1	12.6	6.9	9000
8	26.2	50.3	27.7	36000
16	52.5	201.1	101.6	143000
32	105.0	804.2	442.3	571000
48	157.5	1810.0	995.5	1285000

It is interesting to note that the frequency distribution of wind direction in central Oklahoma favors the north-south quadrants, as shown in Figure 2. About 53% of the winds are from the south, 22% from the north, 14% from the east and 10% from the west. The winds are calm during the remaining one percent of the time. This

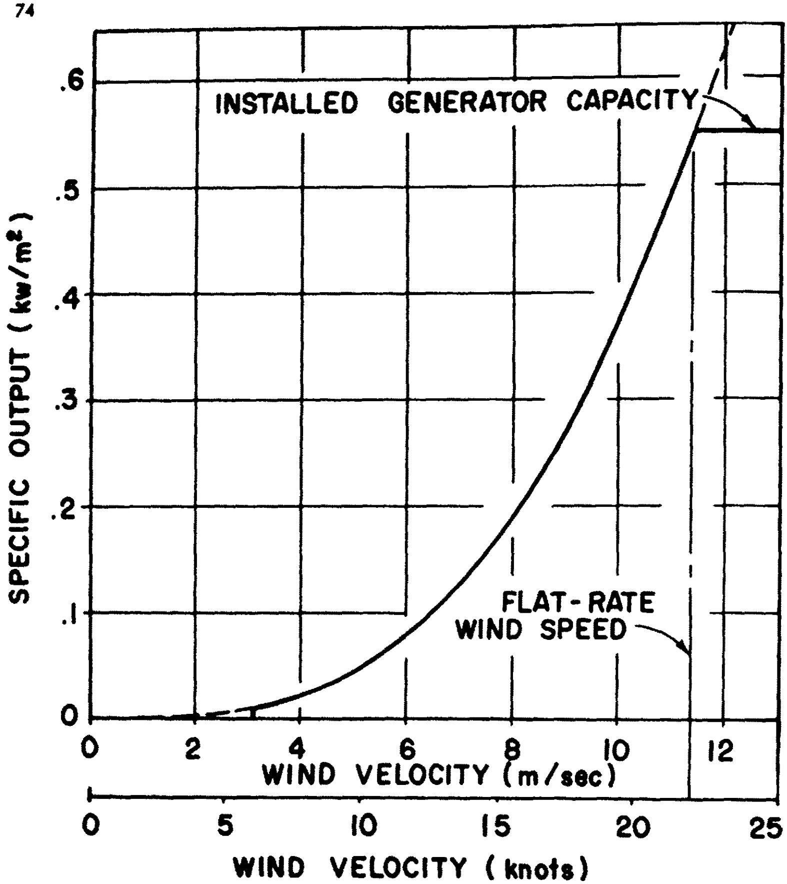

FIGURE 1. Specific output for wind generator.

skewed distribution could be an important factor in optimizing the distribution of windmills in a wind-energy farm complex.

As with any new technology, the initial unit costs for windpower generators will be high. Until the inevitable "bugs" are worked out of the prototype systems, the operating costs will also be high. Assuming that these early hurdles can be passed successfully, it appears that large-scale windpower generating systems can be built for about $200 (1974) per installed kilowatt (3). Some authors have suggested capital costs as low as $150 per installed kw (4). This compares with today's costs of $200-$350 for conventional fossil fuel plants and $500-$600 for nuclear plants. Windpower systems, however, will require three to five times the installed capacity for the same annual output. This relationship is a consequence of the low load factors of solar-related energy systems, 15%-25% as compared to 70%-80% for the more conventional systems.

Assuming 20% load factor, a 40-year payback of capital, a 10% return on investment, and a conservative allowance for operating costs, windpower systems should produce electricity at an average of about 2.5 cents (1974) per kilowatt hour in central Oklahoma.

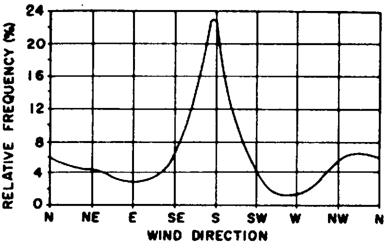

FIGURE 2. Frequency distribution of wind direction.

The intermittent character of the wind leads inevitably to a consideration of energy storage or auxiliary power sources. Both hydrogen and pumped water have been suggested as suitable energy storage methods. Despite some attractive features of both storage techniques, I believe that the associated capital costs will rule them out for other than special situations.

For the more general case, I would like to suggest the possibility of meeting the intermittency problem as well as improving the overall economics of windpower through combination with other energy sources. Specifically, a grid of well-designed wind generators is entirely compatible with high-yield agriculture. Furthermore, either fossil or nuclear power plants could be located in the same area, benefitting from a symbiotic relationship with the other two energy sources.

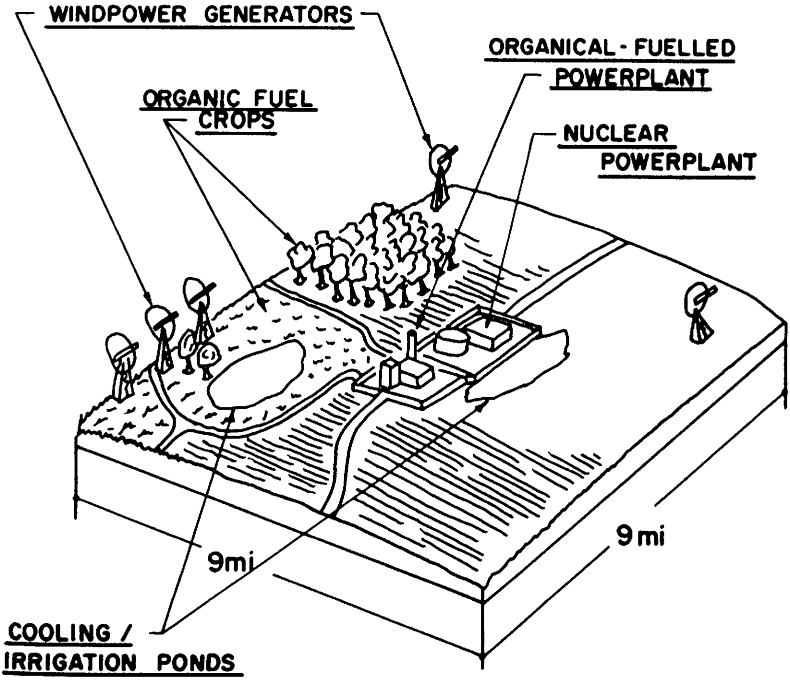

FIGURE 3. Schematic diagram of a solar energyfarm.

Figure 3 shows an idealized model of such a complex. It consists of a rectangular land area of about 80 square miles. A portion of the complex is covered with a grid of large-diameter windmills for generating electrical power. The surface beneath the windmills is devoted to agriculture or forestry. A fossil or nuclear power plant is located in the center of the land area in such a way that the cropland serves as a greenbelt buffer zone.

The relationship between these three energy-generating modes is such that the output can be adjusted to meet normal demand requirements without the need for energy storage.

Looking first at the windpower component, a grid of windmills is capable of installed power densities as high as 50,000 kw per square mile in central Oklahoma. To the first approximation, this potential is independent of rotor diameter. A large number of small units will have essentially the same output as a small number of large units. Thus the optimum grid configuration and the size of the basic windpower unit may be based on other considerations, such as capital costs and joint land use.

Assuming a power density of 40,000 kw per square mile and a capital cost of $200 per installed kilowatt, the capital investment for the mechanical units themselves would be approximately $8,000,000 per square mile or $12,500 per acre.

An obvious use for the land beneath the wind rotors would be to grow traditional food grain crops such as wheat or rye or corn. An alternative use would be to grow high-yield biomass crops which, when harvested and burned in a conventional steam power plant, could furnish fill-in or peaking power for low-wind or high-energy-demand situations.

The heat content of dry organic biomass is about 7500 Btu per pound. Some existing plants, including eucalyptus, sugar cane, and sorghum, can produce 20 tons of biomass per acre per year under favorable growing conditions (5). Tree farming is particularly attractive in arid regions which cannot support high-yield shallow-rooted crops without irrigation, but which have adequate water at levels which can be exploited by the deeper roots of many high-yield trees.

Assuming a productivity of 18 tons per acre per year, a generating plant efficiency of 35%, and an 80% load factor, one square mile of organic energy farm could support an installed capacity of 2500 kw.

An attractive feature of organic energy farming is its potential for producing substitutes for conventional fossil fuel through pyrolysis, hydrogenation and bio-conversion. The resulting products are oil, methanol, medium-Btu gas, and char. Under certain conditions of excess wind power production, the surplus wind energy could be used to provide process heat for pyrolyzing the collected biomass.

This ability of organic fuels to provide either direct heat for generating electricity or acceptable substitutes for fossil fuels is unique among solar-related energy sources. It could be particularly attractive in easing the transition as we move away from energy-use patterns which depend on portable fossil fuels toward a longer-range dependence on essentially inexhaustible solar energy or nuclear fusion.

The provision for a conventional generating plant at the center of the complex recognizes that both fossil and nuclear power will be with us for a long time. It also increases the total output of the energy farm and contributes to the flexibility of the entire complex. At the same time, the power plant can use irrigation water impoundments as cooling ponds, can make joint use of solar farm facilities and, as mentioned before, would be separated from potential public conflicts by a green belt of fields or forests. A nuclear plant would benefit particularly from this isolation and from the relative ease with which security could be enforced.

Clearly, the combination energy farm is an attractive possibility, offering a high degree of environmental benignity and an unparalled flexibility for meeting present and future energy demands. It avoids entirely the need for high-cost energy storage.

A major question remains. Is it economically feasible?

Using the 80-square-mile complex as an example, it is possible to make some approximations of the capital investment and operating expenses, and to compare these costs with the value of the generated energy.

In order to simplify the calculations, it will be assumed that all energy output is in the form of electricity rather than a combination of electricity and substitute organic fuels.

If the total land requirements of the central power plant, along with the organic generating plants, the service areas and the roads are assumed to be 15 square miles, the land available for organic farming and windpower is 65 square miles. The total cost of the land at $500 per acre is approximately $26 million.

The wind generator units are assumed to have an installed power density of 40,000 kw per square mile, an average load factor of 0.20, a capital cost of $200 per installed kw, and an annual operating cost of $16 per installed kw. A list of the assumptions is shown in Table 3.

TABLE 3. *Energy farm assumptions.*

Total land area	80 sq. mi.
Productive land area	65 sq. mi.
Land cost	$500/acre
Windpower	
Power density	40,000 kw/sq. mi.
Load factor	0.20
Capital cost	$200/kw
Annual operating cost	$16/kw
Organic power	
Power density	2500 kw/sq. mi.
Load factor	0.80
Steam power plant	$250/kw
Planting & land prep	$800/acre
Annual operating cost	$60/kw
Nuclear power	
Installed capacity	500,000 kw
Load factor	0.80
Capital cost	$550/kw
Annual operating cost	$35/kw

The organic power system has a productivity and an installed capacity of 2500 kw per square mile at an average load factor of 0.80. The capital cost for the steam power plant is $250 per installed kw and the total annual operating cost for all aspects of planting, harvesting, and power generation is $60 per installed kw. The initial land preparation and planting, a capital expenditure, is assumed to be $800 per acre.

The conventional power plant portion of the energy farm is assumed to be a light-water-reactor nuclear plant with an installed capacity of 500,000 kw. This represents a conservative cost assumption with respect to an equivalent fossil plant. The capital cost is $550 per installed kw. The average load factor is 0.80 and the total annual operating costs are $35 per installed kw.

Finally, in calculating the annual costs of operating the energy farm, the capital costs are amortized over a 40-year period and provisions are made for 10% return on investment.

The total annual output for all three components of the energy farm is 9.20 X 10^9 kilowatt hours per year as shown in Table 4.

The total capital investment for the entire energy farm, exclusive of the power distribution network, is $970 million as shown in Table 5.

TABLE 5. *Capital investment for energy farm.*

Land	$ 26,000,000
Windpower units	520,000,000
Organic steam plants	41,000,000
Initial planting & prep	33,000,000
Nuclear plant	275,000,000
Controls & misc.	75,000,000
	$970,000,000

In the first year of steady-state operating conditions, the annual costs of the energy farm are $198 million as shown in Table 6. Based on an annual output of 9.20 X 10^9 kwh per year, the cost per kilowatt hour is 2.15 cents.

Although this cost is higher than the electrical generating costs in many parts of the country, it is not much higher and is, in fact, encouragingly close. Furthermore, there is a strong likelihood that fossil-fired

TABLE 4. *Annual power output of the energy farm.*

Wind	65(40000)(0.20)(8760) = 4.55×10^9 kwh/yr
Organic	65(2500)(0.80)(8760) = 1.14×10^9 kwh/yr
Nuclear	500,000 (0.80)(8760) = 3.51×10^9 kwh/yr

TABLE 6. *Annual operating and overhead costs for energy farm.*

Return on investment	$ 97,000,000
Amortization	24,250,000
Windpower operations	41,600,000
Organic power operations	9,750,000
Nuclear power operations	17,400,000
Miscellaneous	8,000,000
	$198,000,000

power will increase in cost more rapidly when the utility industry's long-term (and low-cost) fuel contracts will have run out or when the pollution control costs associated with new fossil fuels are fully realized in the generating costs.

Although solar-organic farms appear to be environmentally attractive when compared with strip mining or oil shale operations, they are not without foreseeable problems. Fertilizer availability and runoff, for example, will require considerable study, as will the availability of water and the long-term effect on the water table. Even though forests and croplands may be aesthetically pleasing, long lines of tall wind towers marching across the landscape may be distasteful to a large number of people.

On the other hand, the possibilities for recreational use of energy forests for hunting, fishing, and camping appear promising and could go a long way toward enlisting public support.

Finally, I do not mean to suggest by this simplified model that the solar energy farm should be a rigidly defined rectangle of dedicated land. The practical difficulty of carving out such large tracts in most parts of the country would be prohibitive. Realistically, a solar energy farm could consist of both public and private lands, not all contiguous, so long as the interconnect and transportation problems are not excessive. It could possibly be structured in the same way as existing farm coperatives, in which the lands are privately held and operated, but the crops, by pre-arrangement, are sold to a common processor.

The variations within the general outline are almost limitless and could be tailored to the specific needs and resources of each geographic region.

REFERENCES

1. D. BRUNT, *Physical and Dynamic Meterology,* Cambridge, University Press, 1941, p. 285-288.
2. K. C. CRAWFORD and H. R. HUDSON, *Behavior of Winds in the Lowest 1500 feet in Central Oklahoma, June 1966-1967,* ESSA Technical Memorandum ERLTM-NSSL 48, August 1970.
3. K. H. BERGEY, *Wind Power Potential for the United States,* Norman, Oklahoma, Report to the Committee on Science and Astronautics (Subcommittee on Energy), House of Representatives, U.S. Congress, June 10, 1974.
4. W. L. HUGHES, J. D. PARKER, H. J. ALLISON, R. G. RAMAKUMAR and D. D. LINGELBACH, *Basic Information on the Economic Generation of Energy in Commercial Quantities from Wind,* Stillwater, Oklahoma, Report to the Committee on Science and Astronautics (Subcommittee on Energy), House of Representatives, U.S. Congress, Engineering Energy Laboratory Report ER74-EE-7, Oklahoma State University, May 21, 1974.
5. J. A. ALICH, JR., and R. E. INMAN, *Effective Utilization of Solar Energy to Produce Clean Fuel,* Final Report of Research under NSF Grant No. 38723, Stanford Research Institute, June, 1974.